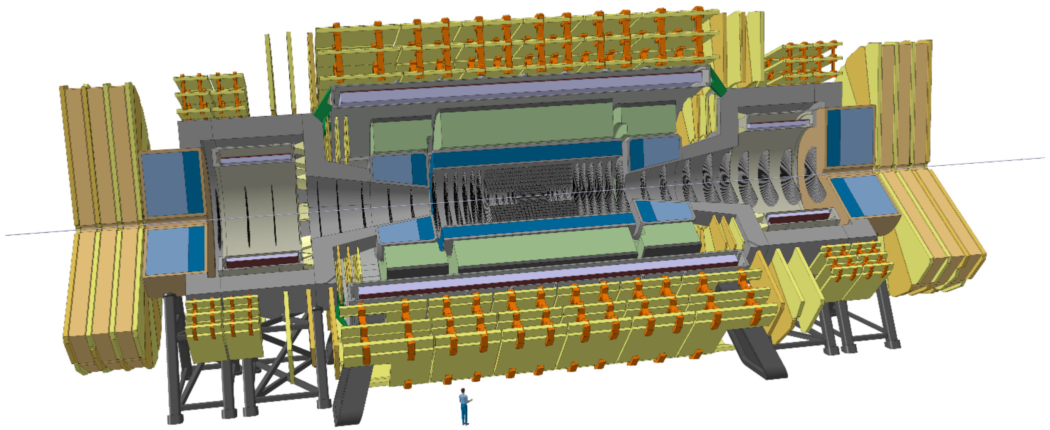
Detector Magnets for FCC-ee-eh-hh

- CDR baseline designs -



Herman ten Kate

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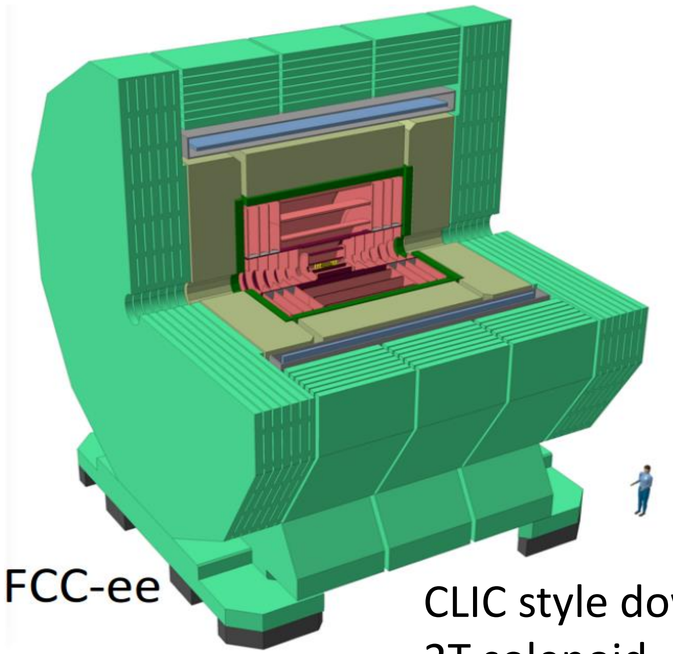
Content:

1. **FCC-ee, 2 detector designs**
2. **FCC-hh, 1 design with options**
3. **FCC-eh**
4. **Conclusion**

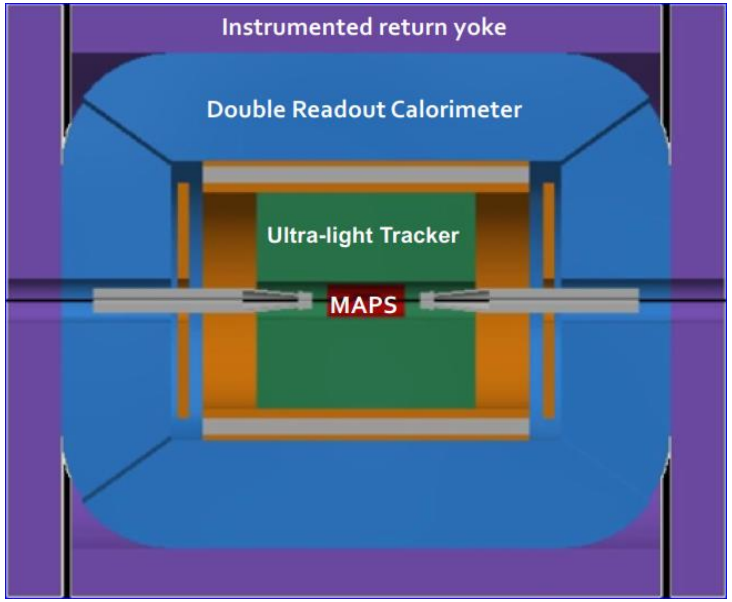
1. Detector magnets for FCC-ee

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

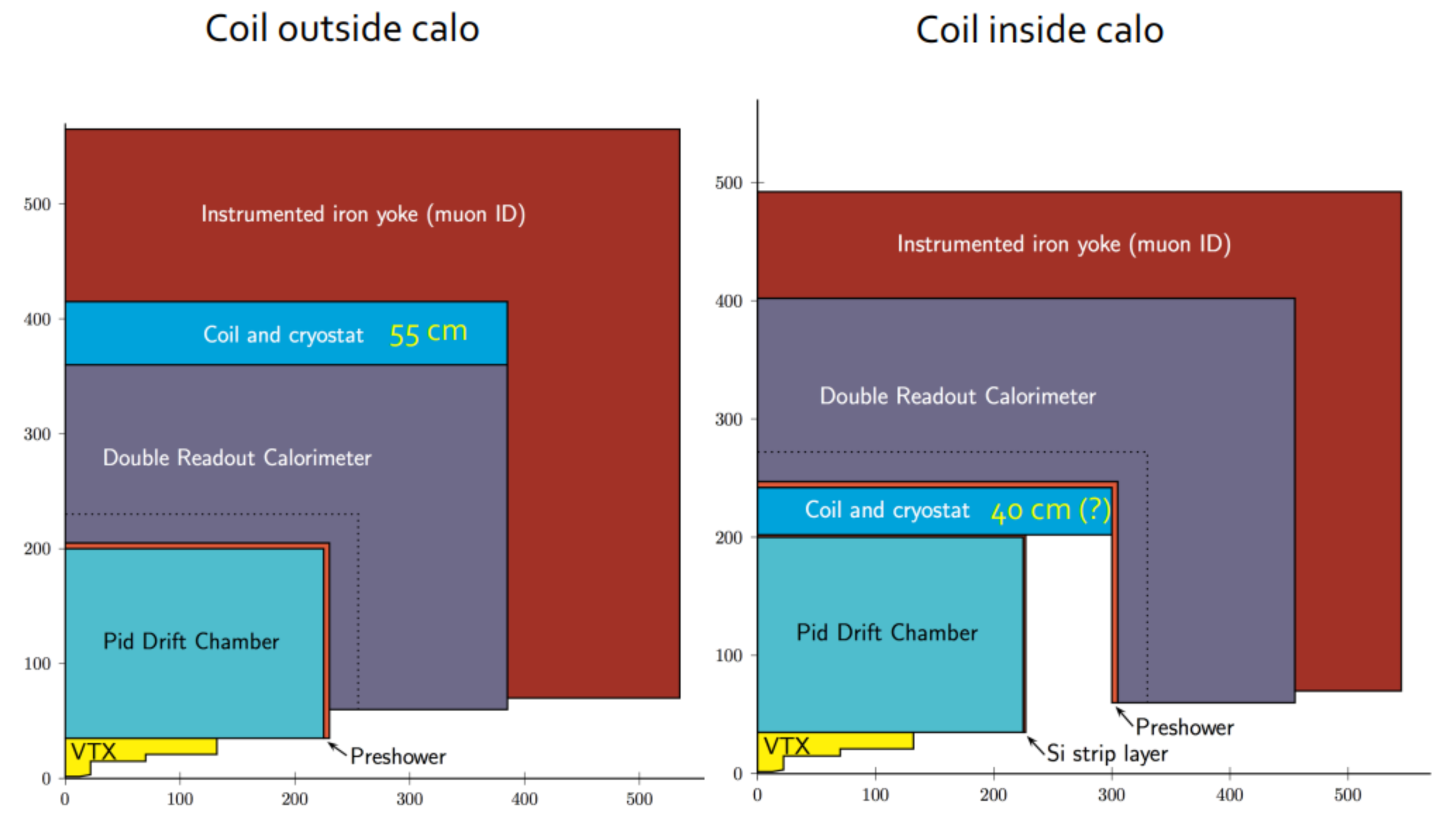
Motivation:

- 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?

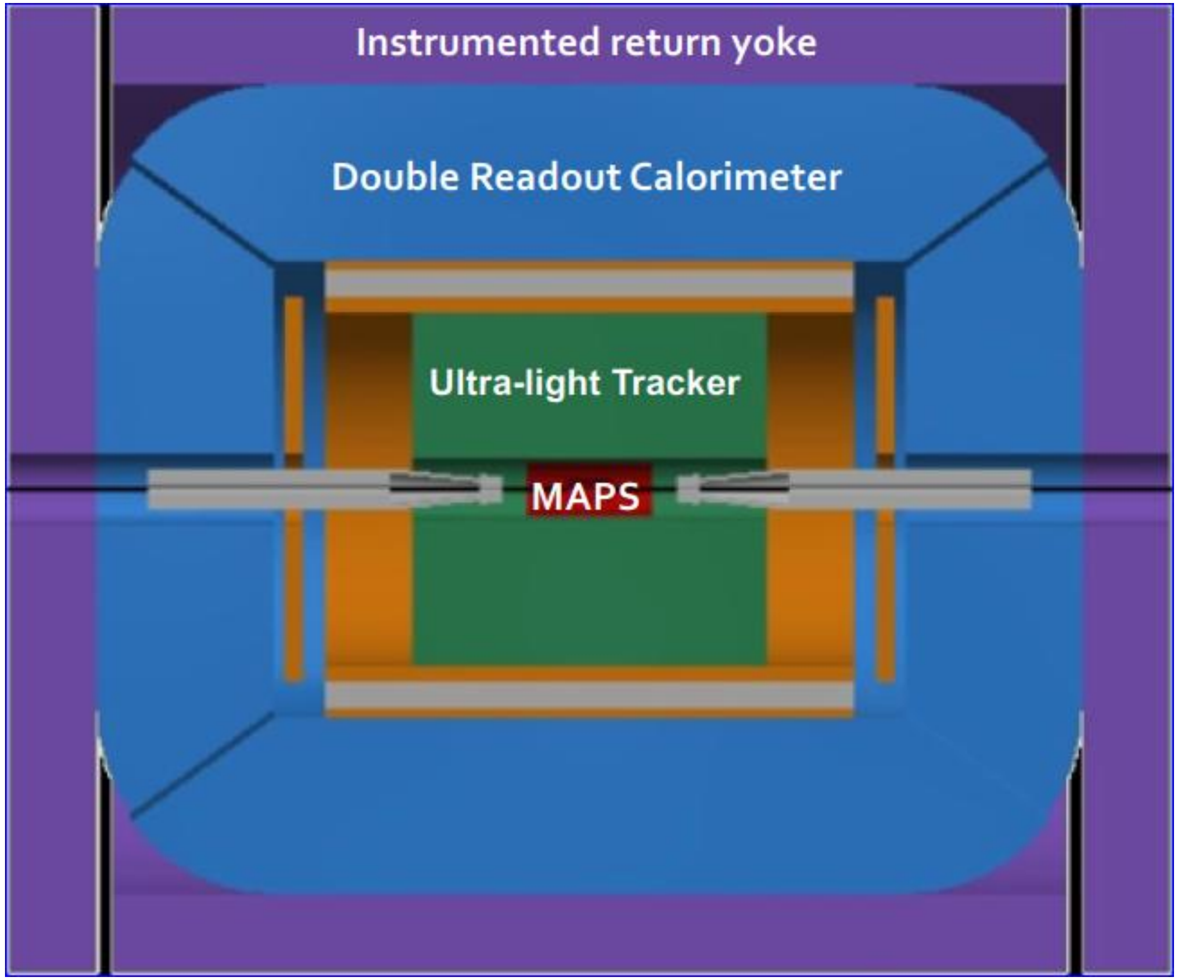
Solenoid for IDEA detector

Requirements:

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

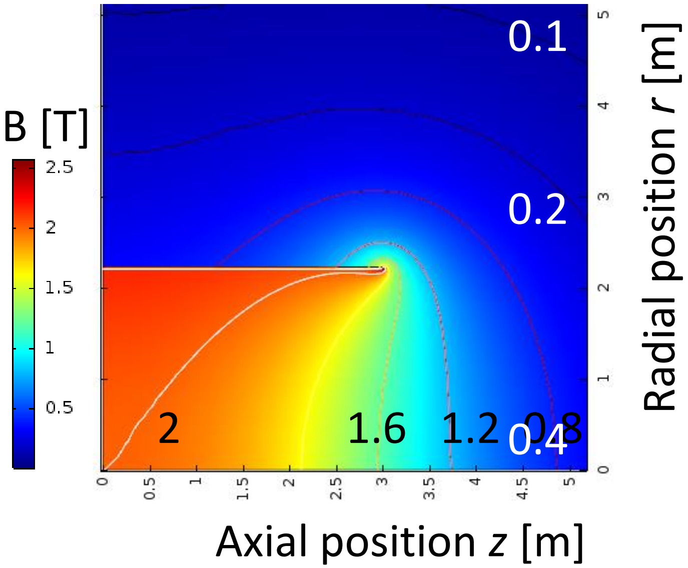
Strategy:

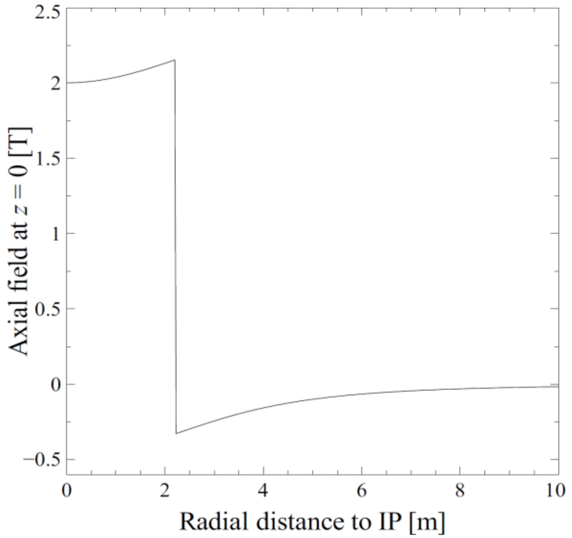
- Reduce thickness of cold mass.
- Reduce thickness of cryostat.
- Magnetic flux return by a light return yoke.

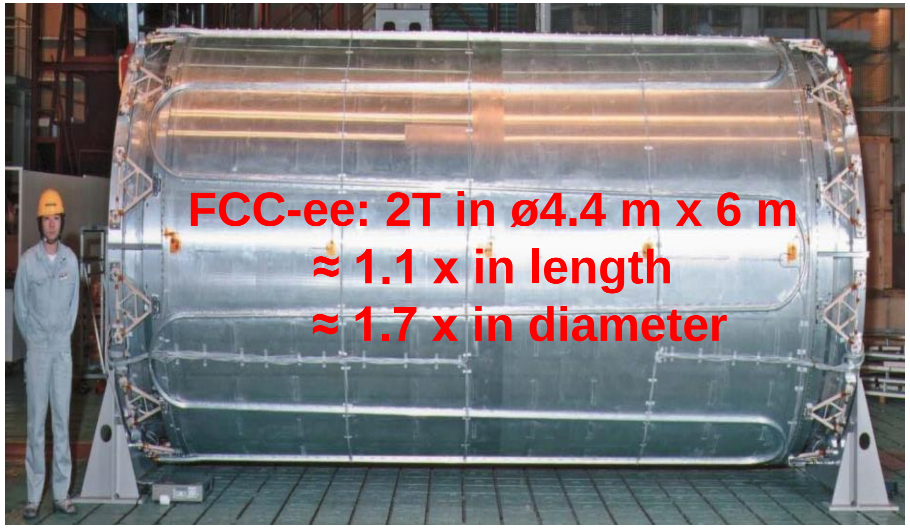


IDEA detector (***I***nternational ***D***etector ***E***lectron ***A***ccelerators), an innovative thin solenoid around tracker

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 $X_0 = 0.8 < 1$!**

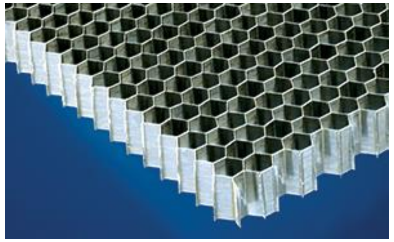
R&D for a Thin & Transparent Solenoid

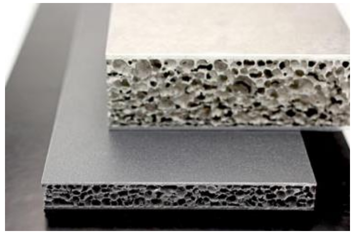
Crucial technologies to be developed:

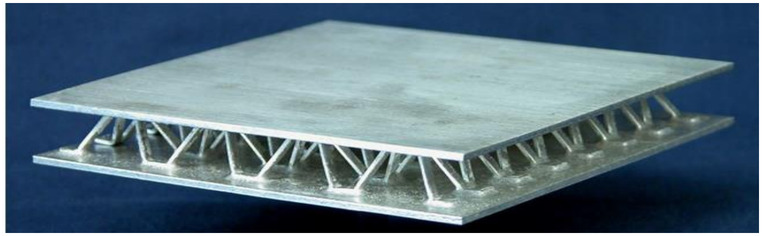
- High YS Super-Conductor allowing self-supporting coil windings.
- Maximum energy extraction at quench to minimize cold mass hot spot temperature.

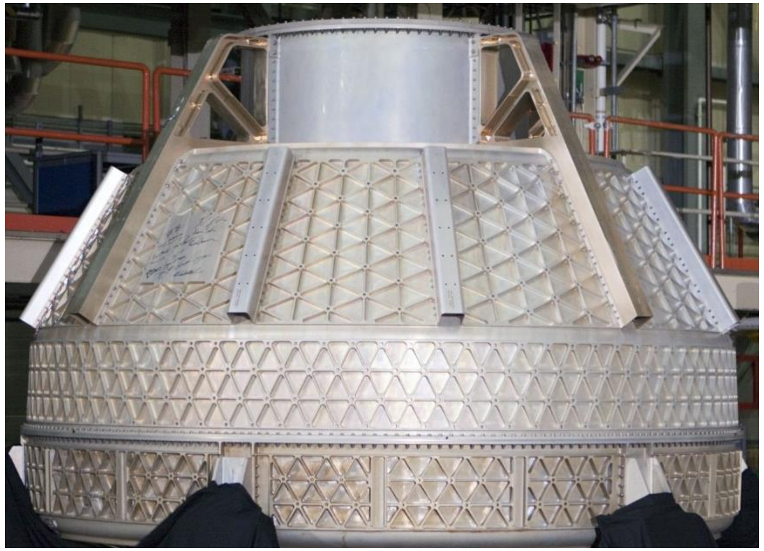
- New ultra-light cryostat design following two routes:
  - high level of thermal insulation and mechanical support through metal foil sealed glass spheres or permaglass under vacuum (not presented here).
  - lightest possible metallic-vacuum cryostat using honeycomb structures or corrugated plate-sandwich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

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





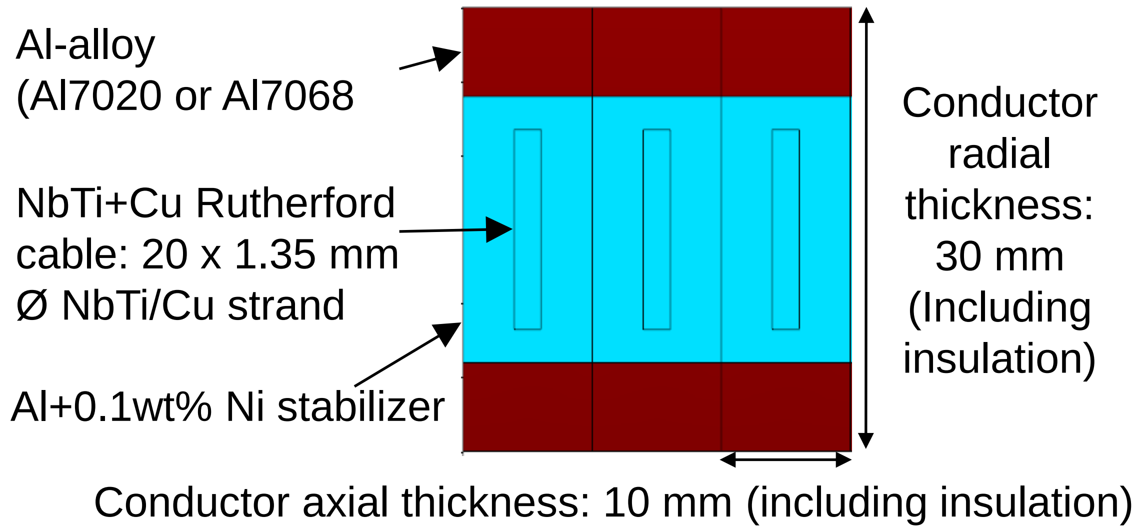


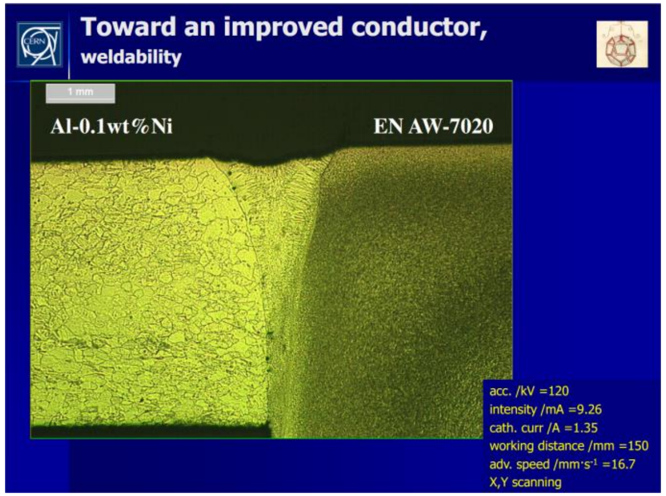


R&D on Conductor – Reinforced conductor

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.



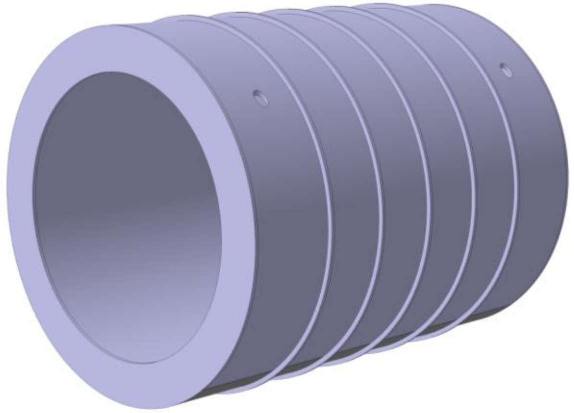


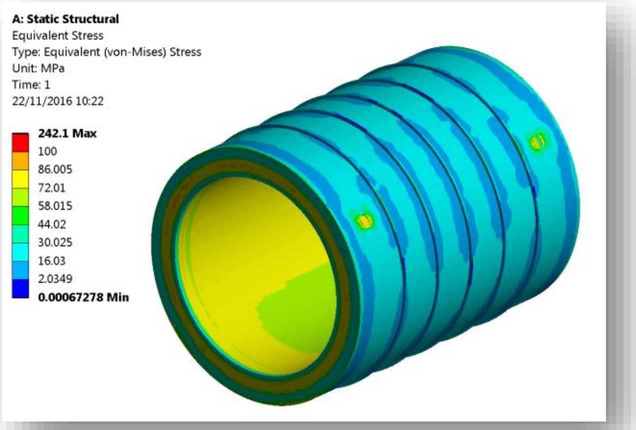
EB welded reinforcement, Sgobba [2010]

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

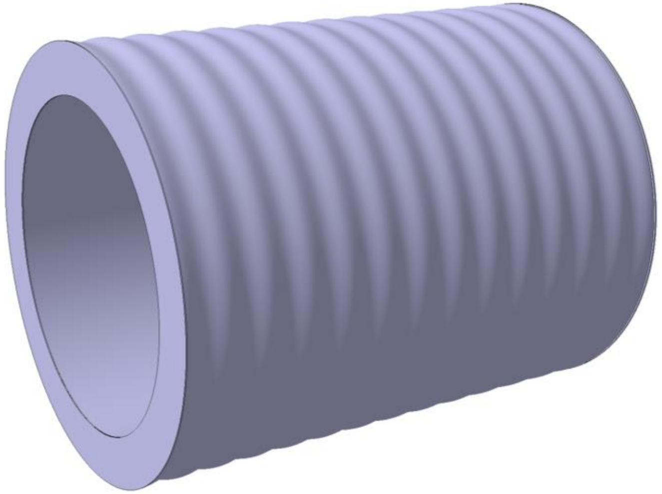
* Initial estimate is 3 times the weight of the cold mass

	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

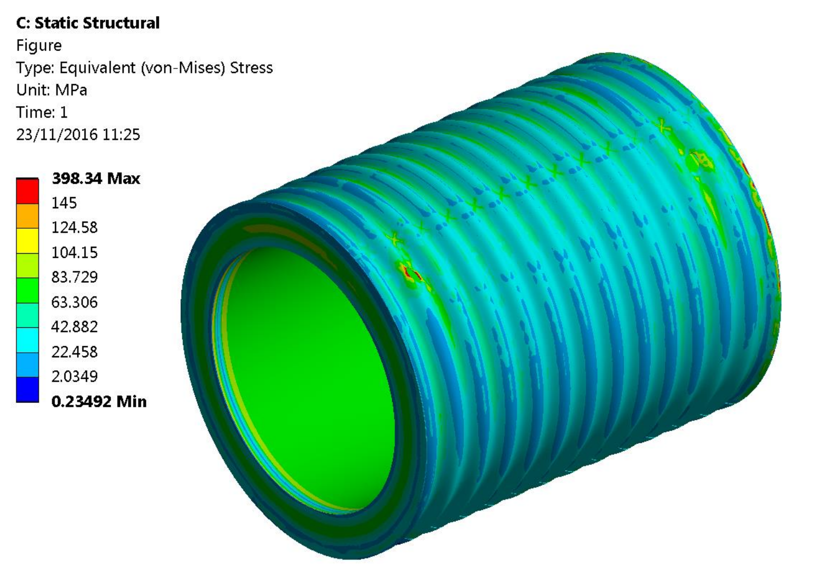
Option for the external shell, use corrugated plate:

- 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

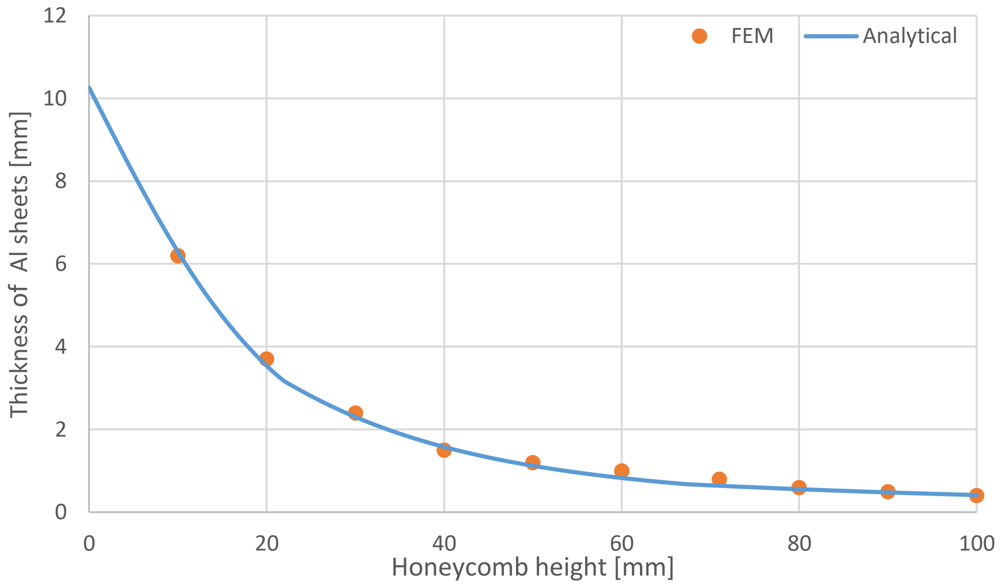


Best cryostat option – Use honeycomb-like plate

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**

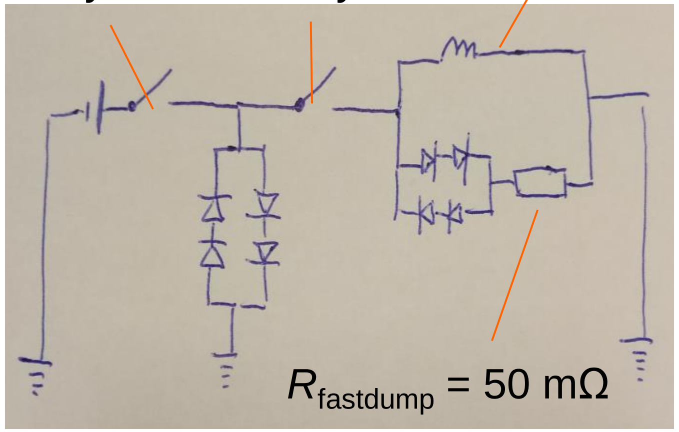
Quench Protection and Hot-spot temperature

Quench protection:

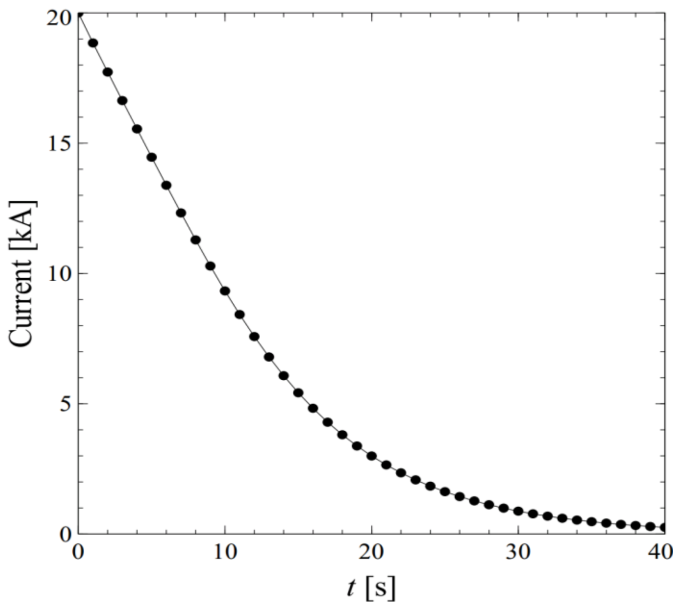
- Relies on high percentage of extraction to reduce cold mass enthalpy
- And relies on quench heaters
- 1000 V peak extraction voltage accepted to yield 76% extraction
- Required conductor RRR> 400
- **Normal quench scenario:**

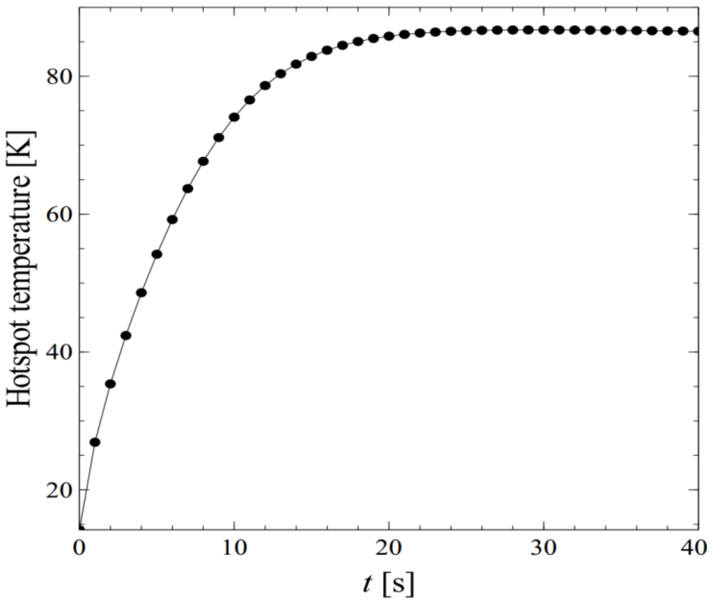
  $T_{hotspot} < 100$ K

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

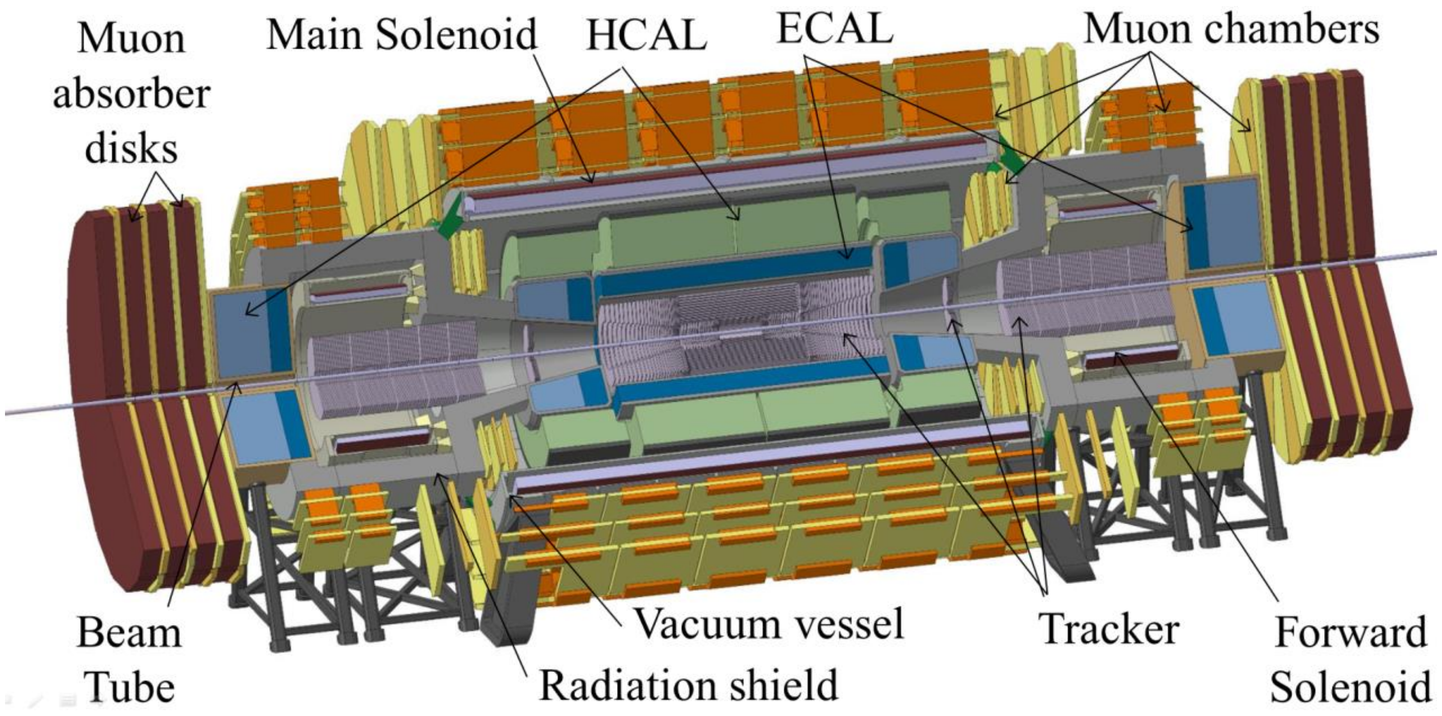


Scenario	Hot spot temperature [K]
Regular	87
Malfunctioning heaters	150
Malfunctioning extraction	118





2. FCC-hh Detector - Baseline



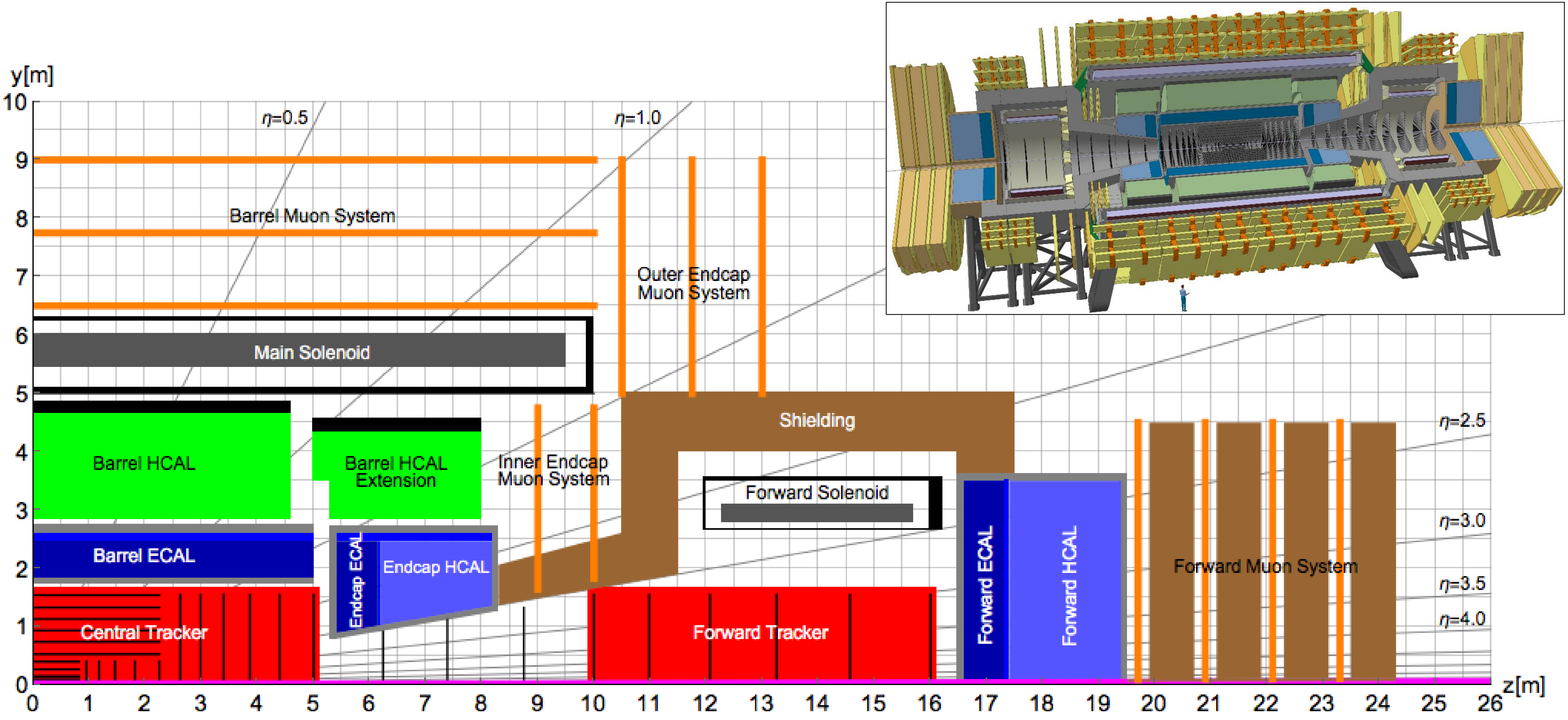
Main solenoid:

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

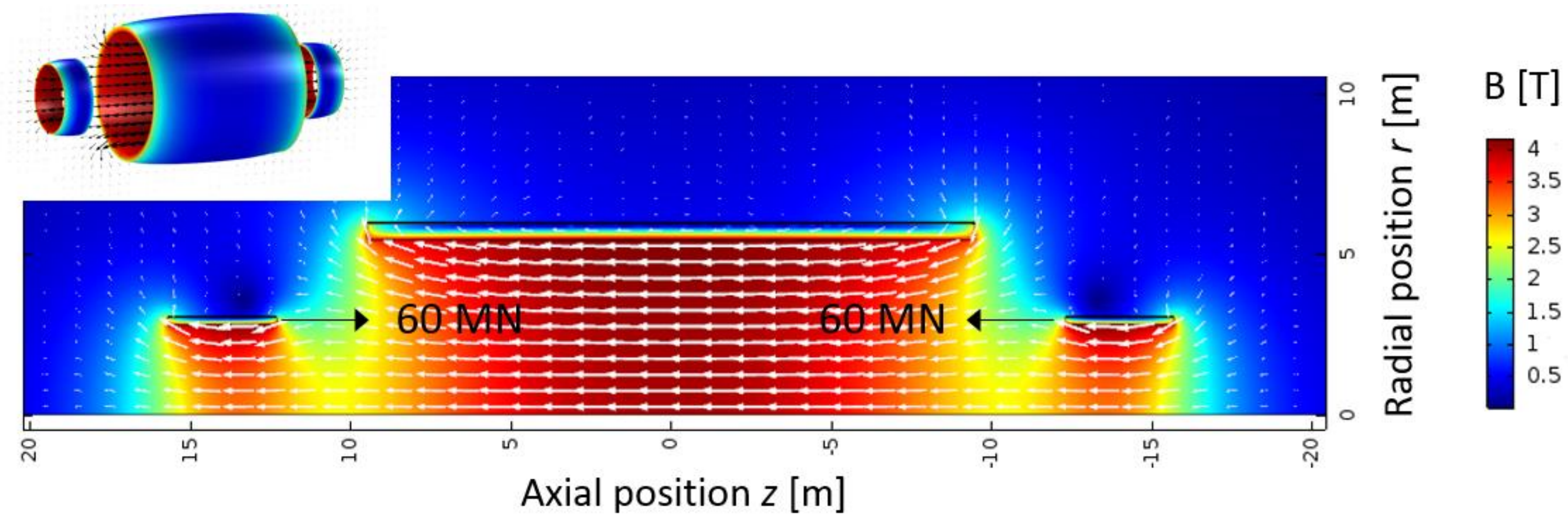
Forward Solenoids (forward dipole is an option):

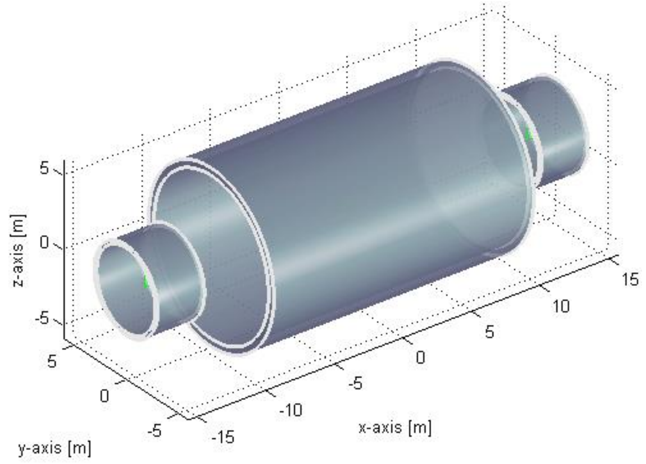
- Tracker inside solenoid
- Forward calorimeters after forward solenoids
- Enclosed by radiation shield
- Muon station behind

2d Layout of reference detector - *baseline*



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



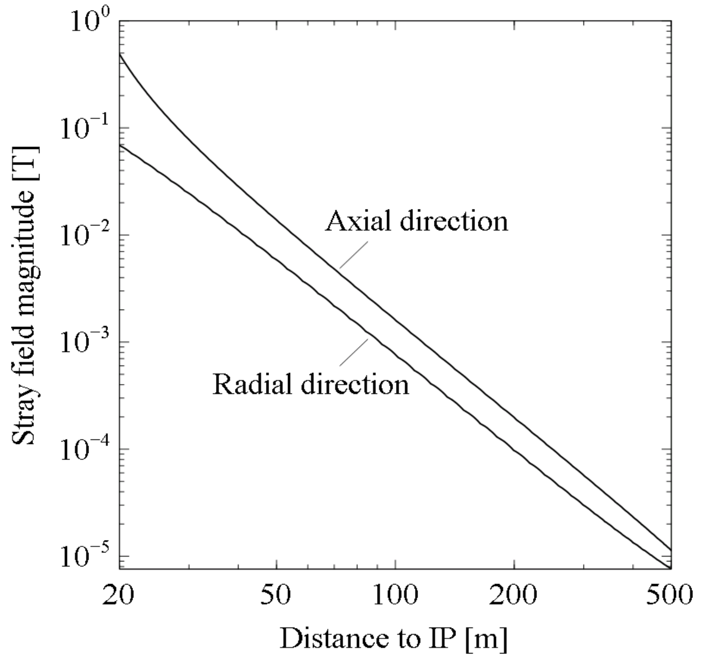


Concept:

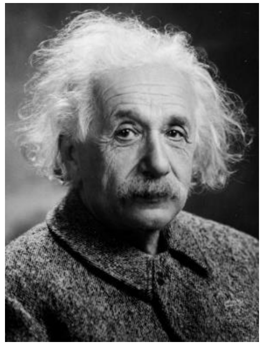
- 4 T in 10 m free bore
- Magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods

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



Design evolution of the FCC detector magnet baseline

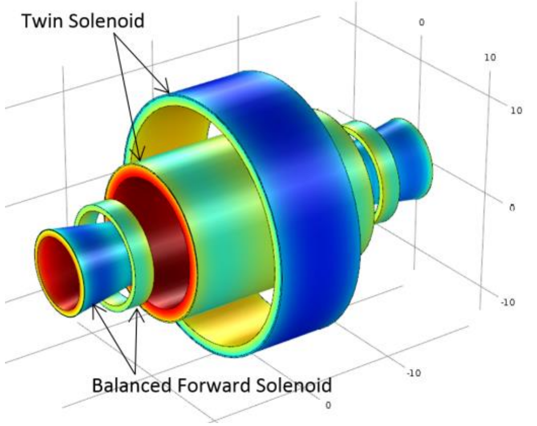


"Everything should be made as simple as possible, but not simpler"

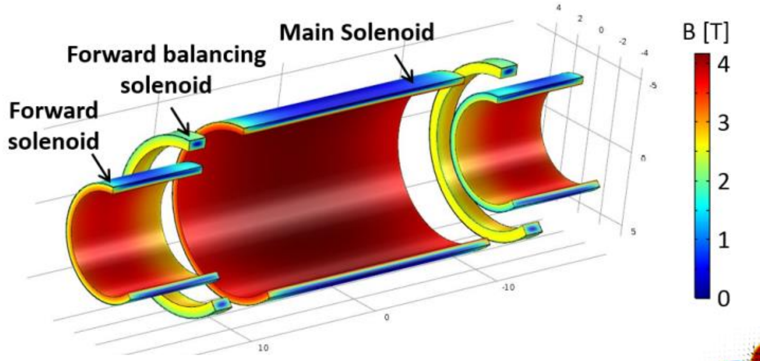
Design evolution towards:

- Lower stored energy, smaller, lighter designs
- **Less complexity, size reduction, fewer coils**
- **Much more cost-effective, from ≈ 0.9 M€ down to ≈ 0.35 M€**

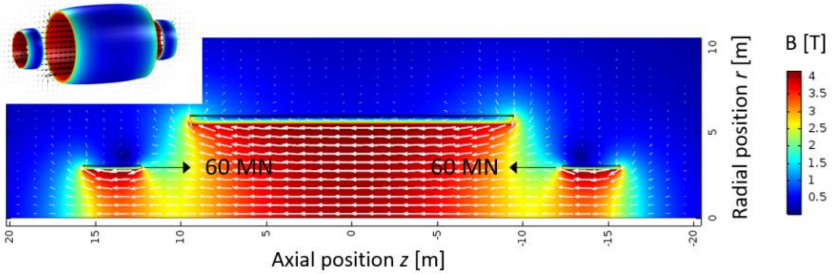
6T/12m bore Twin Solenoid + Balanced Forward Dipoles



Twin Solenoid + Balanced Forward Solenoids

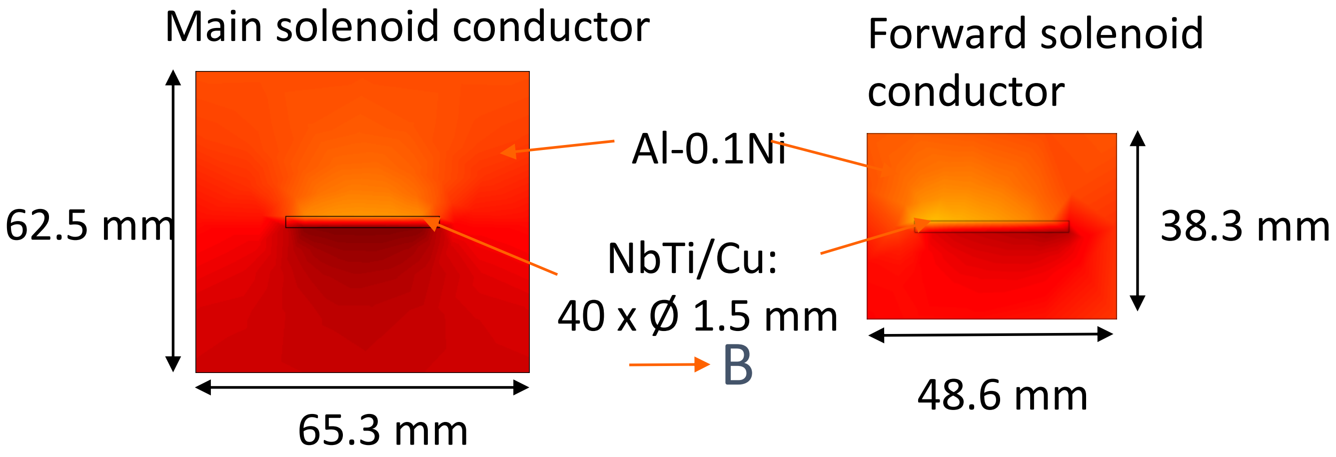


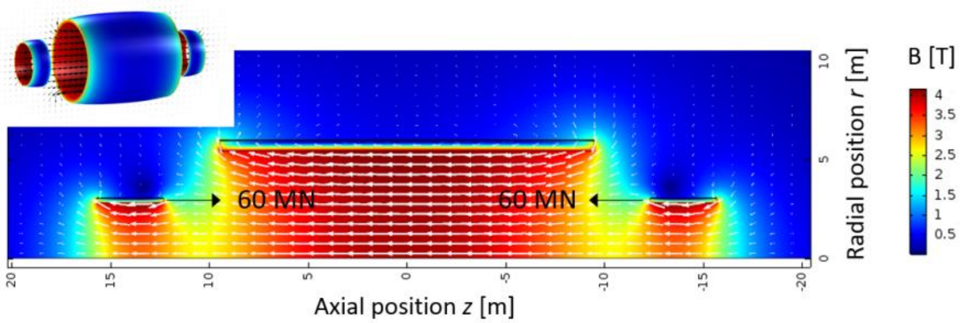
Solenoid + Balanced Forward Solenoids



4T/10m bore Solenoid + Forward Solenoids

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!**

Magnet System - Main and Forward Cryostats

Heat loads

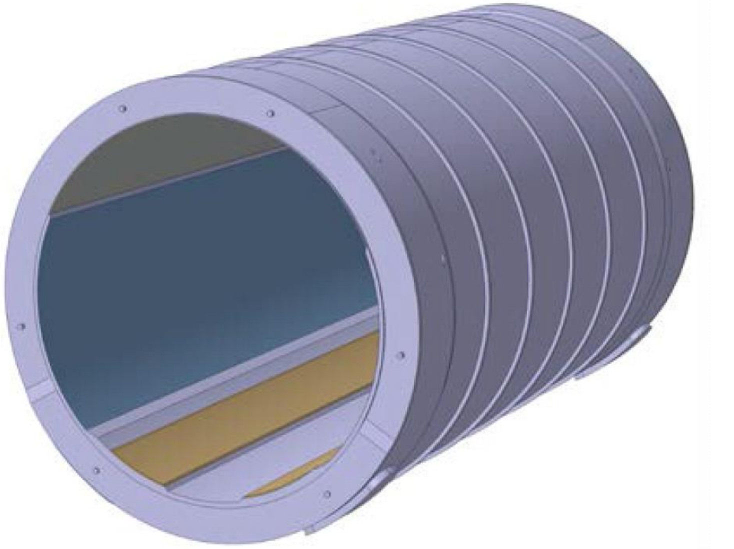
- Radiation: 360 W on cold mass, 6.8 kW on thermal shields
- Tie rods (Ti6Al4V rods, thermalized at 50 K):
  20 W on cold mass, 1.4 kW on 50 K thermalization points
- Acceptable heat loads, despite 60 MN force on forward solenoids

Materials and masses

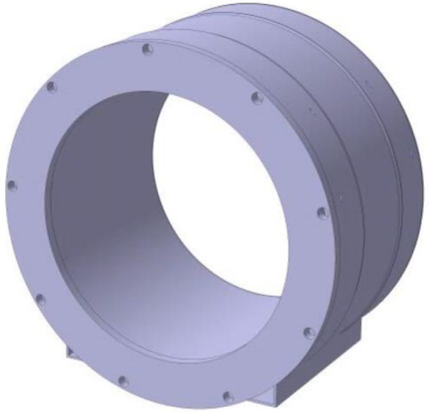
- Main solenoid cryostat: ss 304L (high strength, min. space), 875 t
- Forward solenoid cryostat: Al 5083-O (minimal mass), 32 t
- Main cryostat mass 2 kt, forward cryostat mass 80 t

Mechanical aspects

- Bore tube of main cryostat supports 5.6 kt (Calorimeters & Tracker)
- Bore tube of forward cryostat supports 15 t (Forward tracker)
- Cryostats sufficiently strong to withstand: 60 MN net Lorentz force, mass of the calorimeters & trackers, gravity, seismic load of 0.15g, buckling load with multiplier 5.

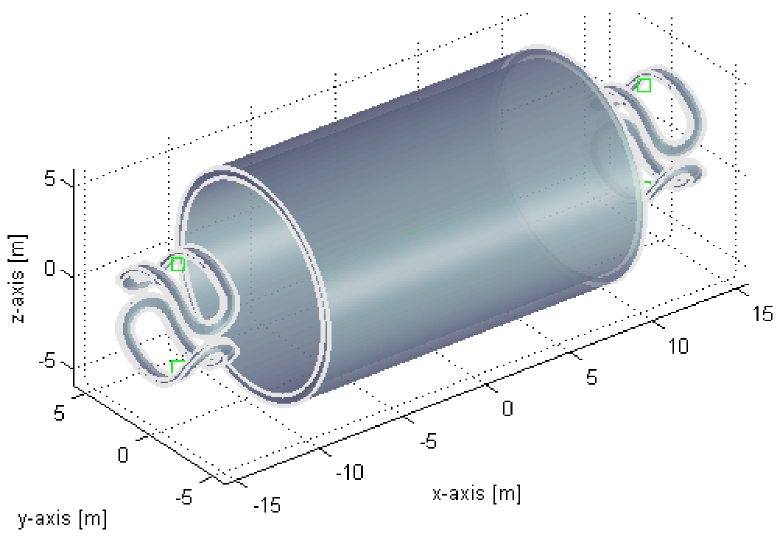


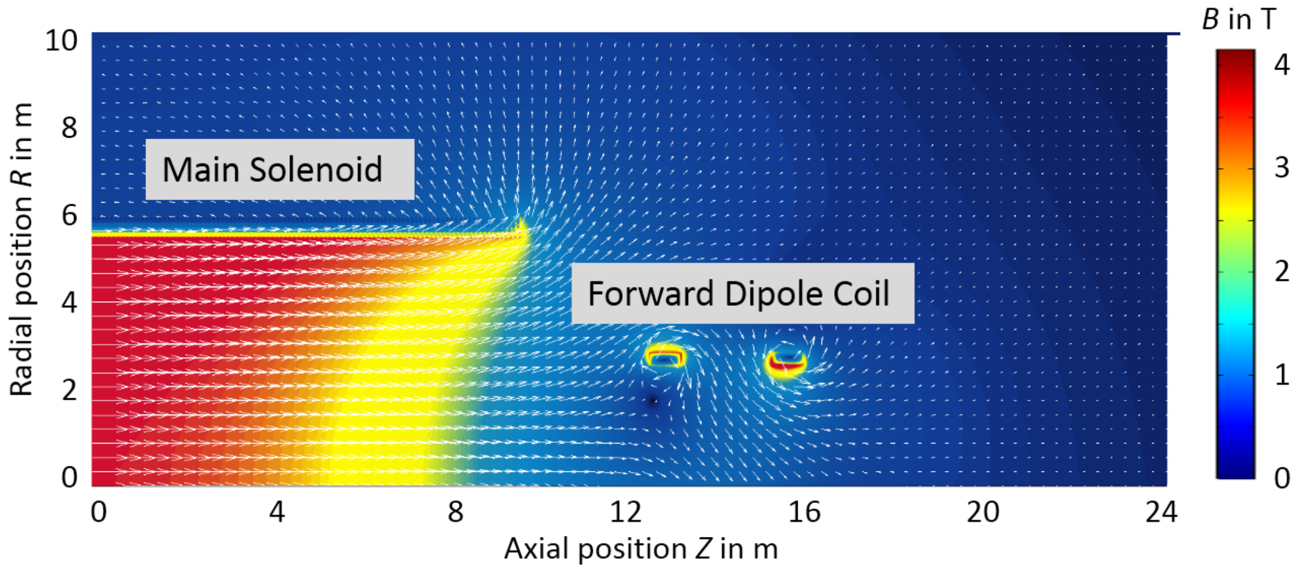
Main solenoid vacuum vessel



Forward solenoid vacuum vessel

Option: 4T/10 m Solenoid & Forward Dipole Coils





Design

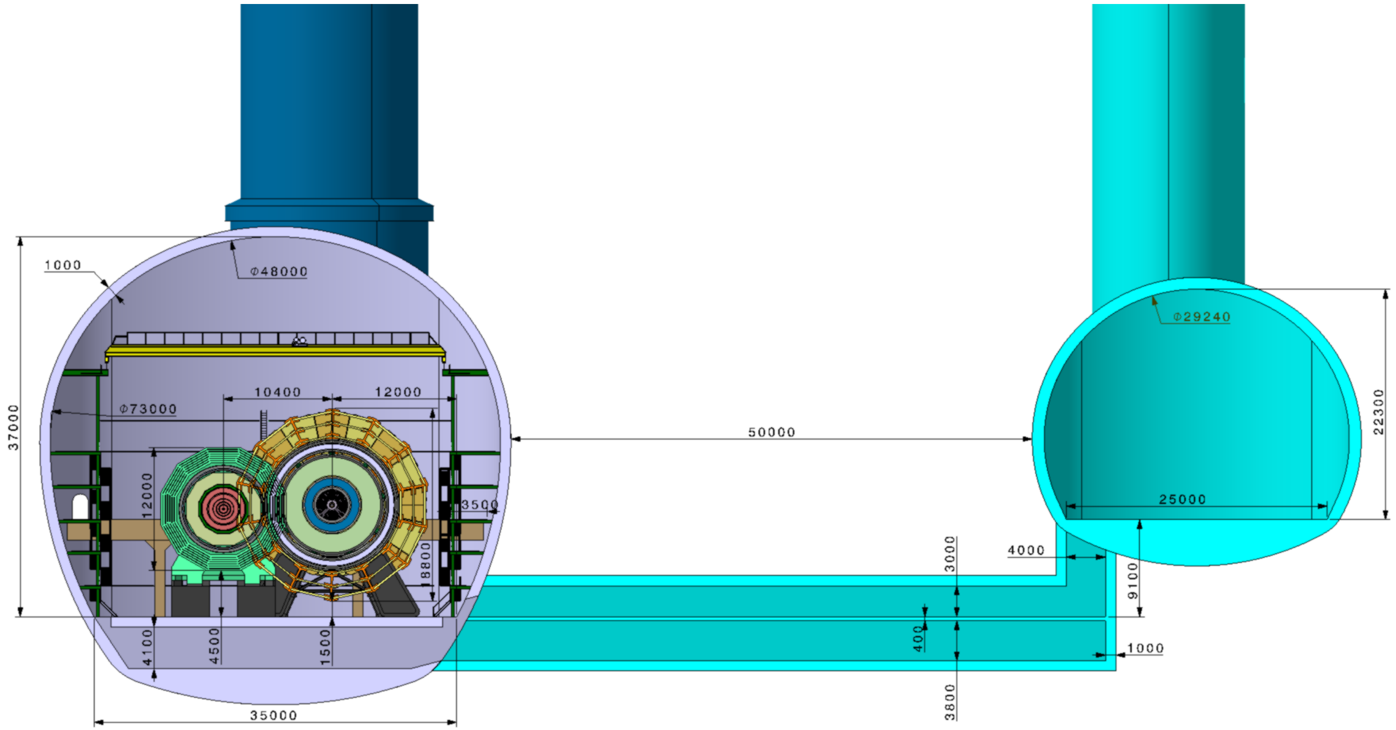
- Main solenoid with 4 T in a 10 m free bore
- Forward **dipole coils**, to **increase** the bending capacity for high eta particles
- Forces **and torques** need to be handled with tie rods and **anchoring to the floor**

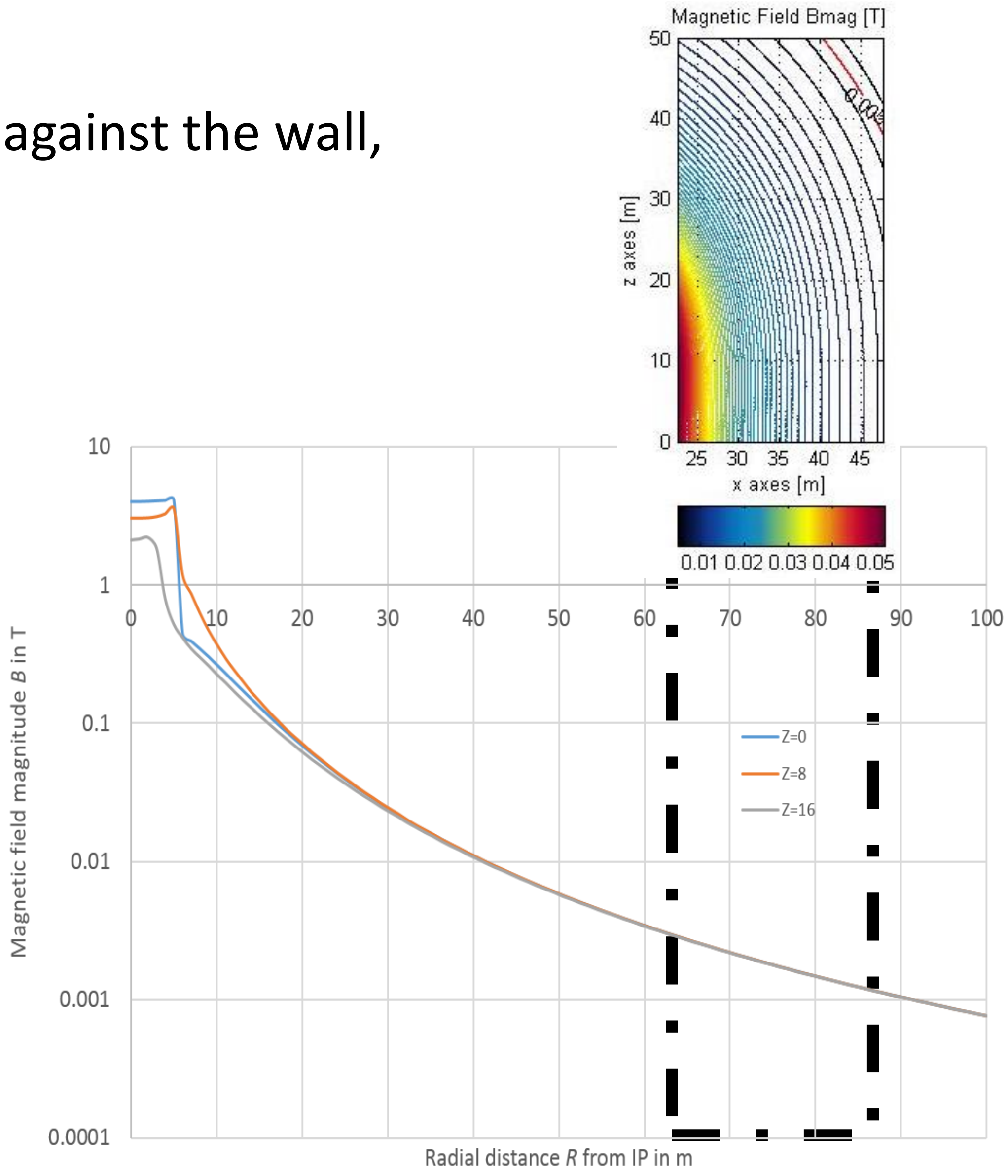
Result

- More complicated cold-mass structure, largest superconducting dipole ever proposed
- Large forces &torques and loss of rotational symmetry, nasty for particle trajectory reconstruction
- Increased bending power for high eta particles, but also impact on crossing beams

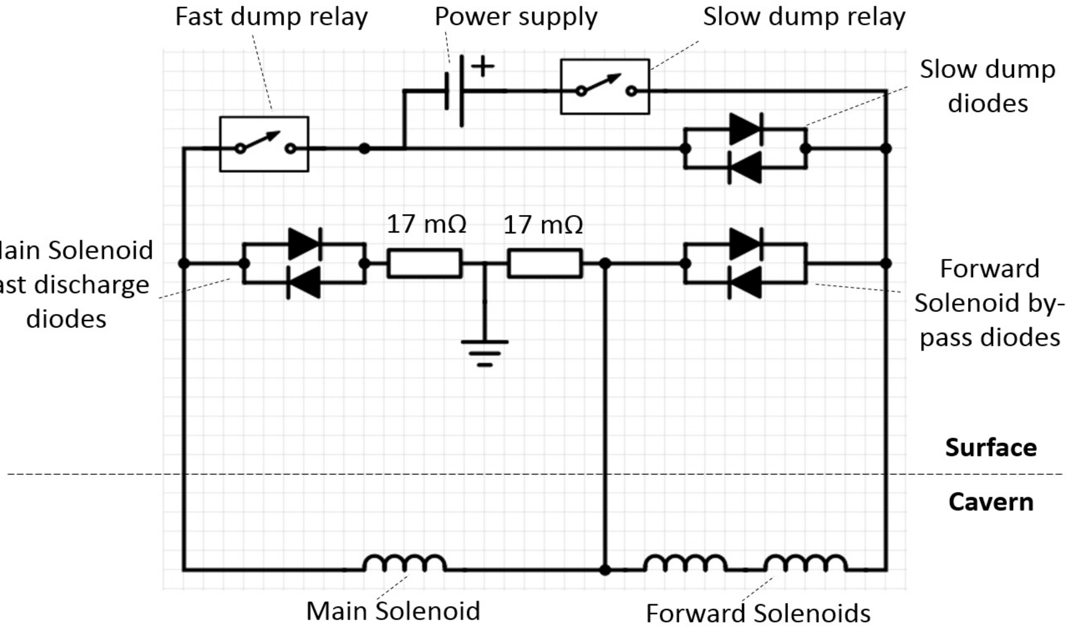
Stray field & shielding - Distance to Service Cavern

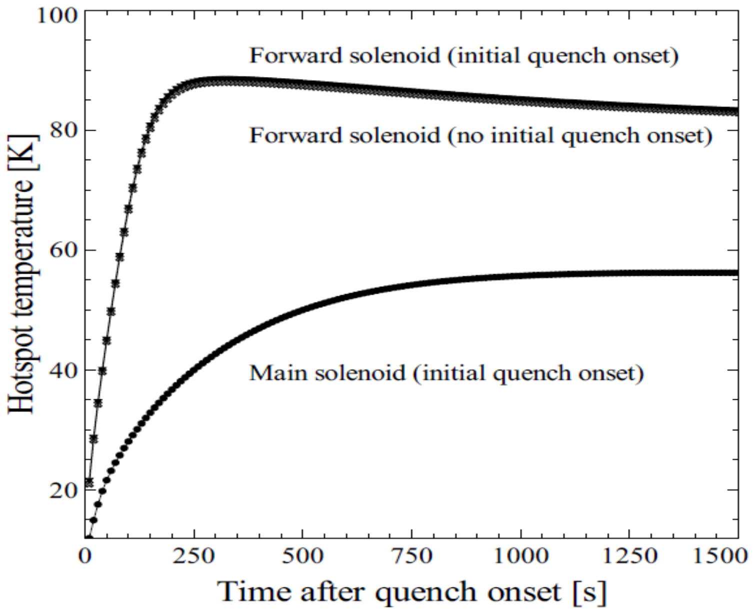
- Side cavern positioned 62 m from IP.
- Stray field of FCChh detector at 4T is 5 mT in small area against the wall, and less everywhere else.
- Good mechanical machine requiring < 5mT.
- For FCCee with iron yoke it will be much less.





Electrical Circuit and Quench Protection





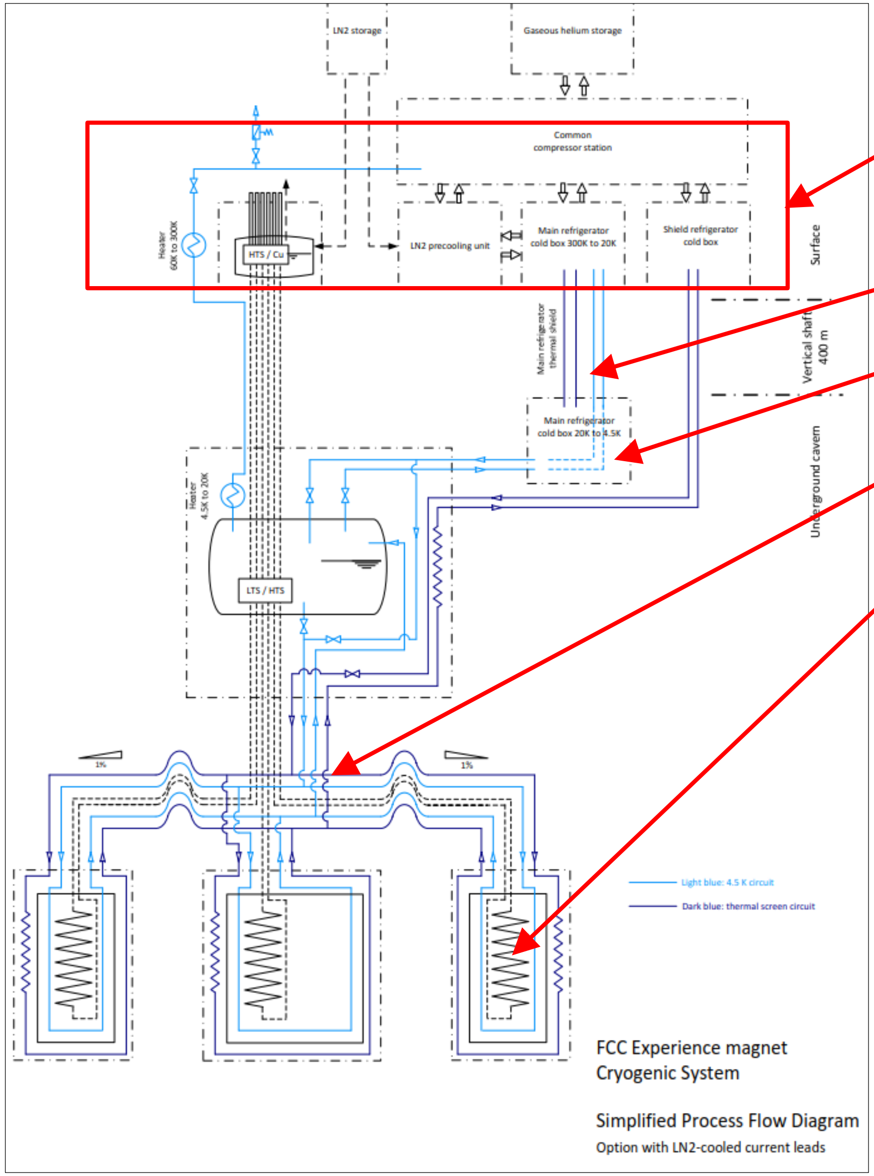
Electrical scheme

- Main and forward magnets are powered in series
- Main solenoid decoupled from forward magnets during quench (bypass diodes parallel to forward solenoids)
- Requires three current leads

Quench protection

- Main solenoid: Extraction + Quench heaters
- Forward solenoids: Quench heaters
- Nominal Quench: **56 K** in main solenoid, **89 K** in forward solenoid, **73% extraction**
- Not-working heaters: 142 K in main solenoid, 133 K in forward solenoids

Cryogenics, Powering and Controls



Main Cryogenics equipment is on surface, not underground

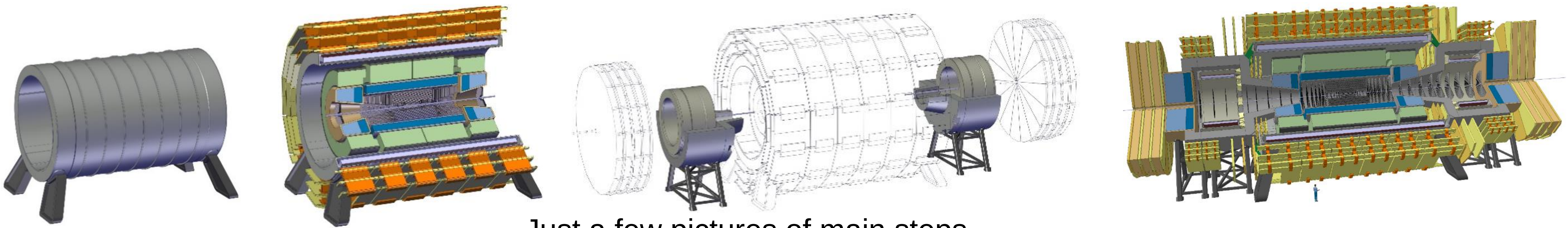
- Intervention on critical installations on surface including Main & Shield refrigerators
- Sending high pressure (20 bar) helium <u>gas</u> down the shaft
- In cavern JT unit producing LiHe and filling dewars
- Distribution of liquid over the main and forward systems
- All coils are conduction cooled 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

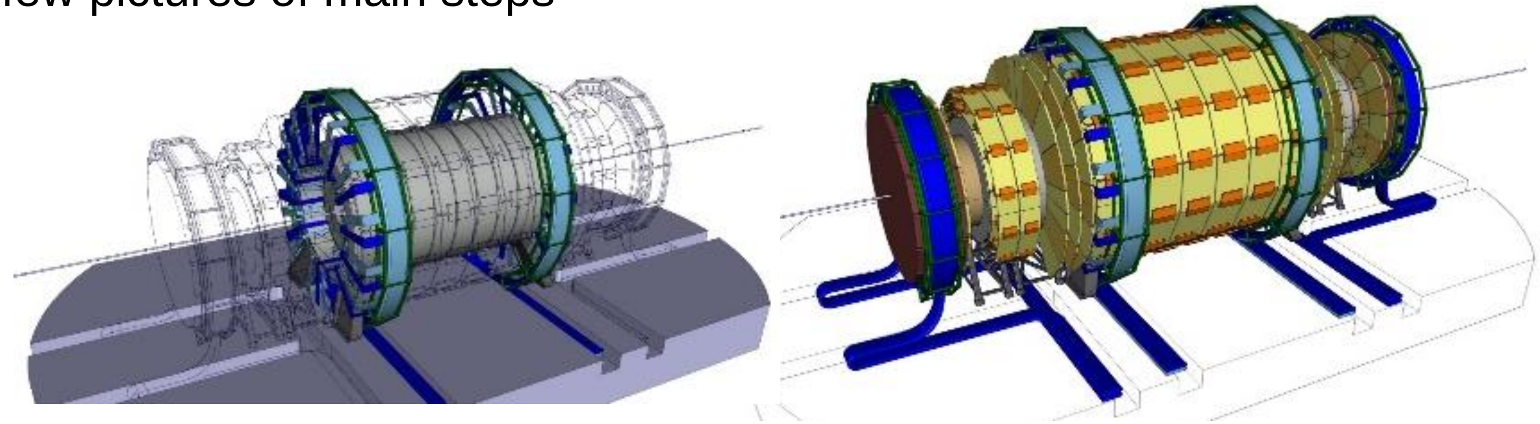
Control and safety systems (MCS and MSS) on surface

Installation – main steps (video available)



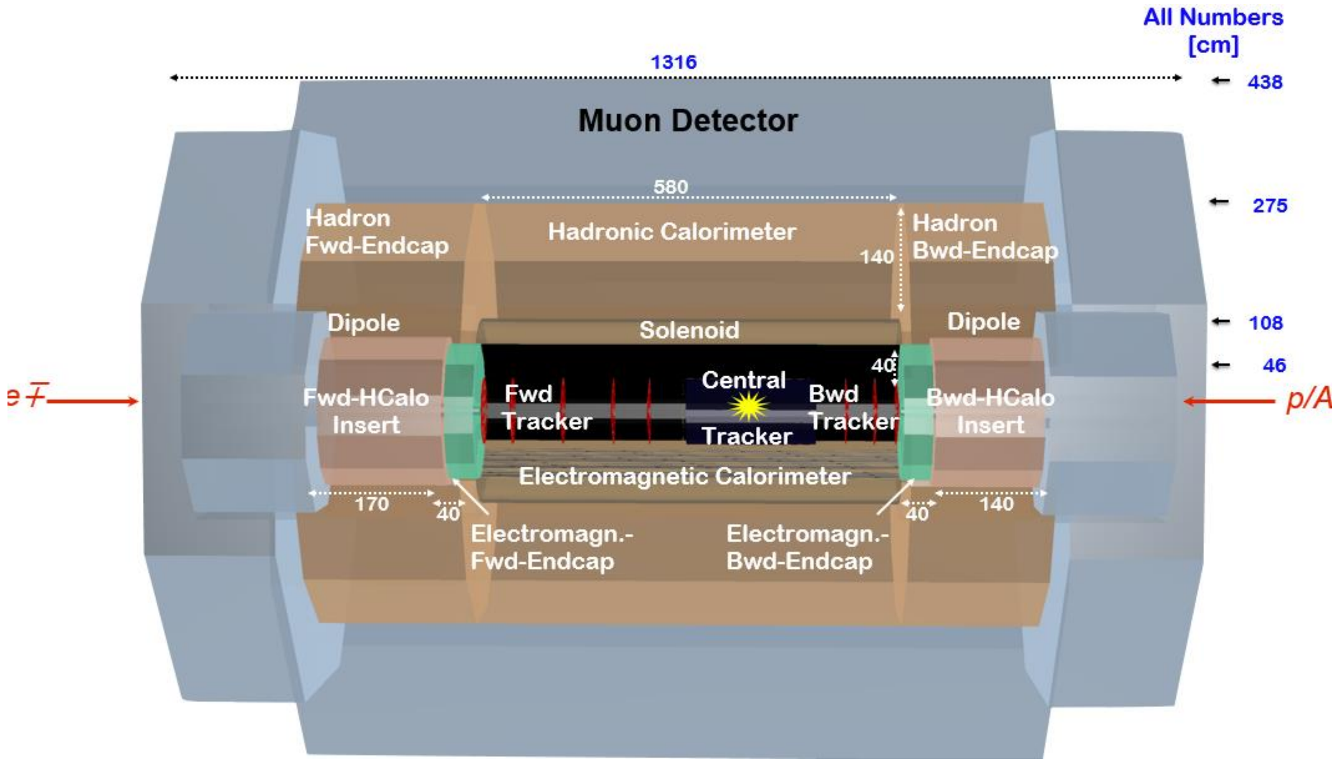
Just a few pictures of main steps

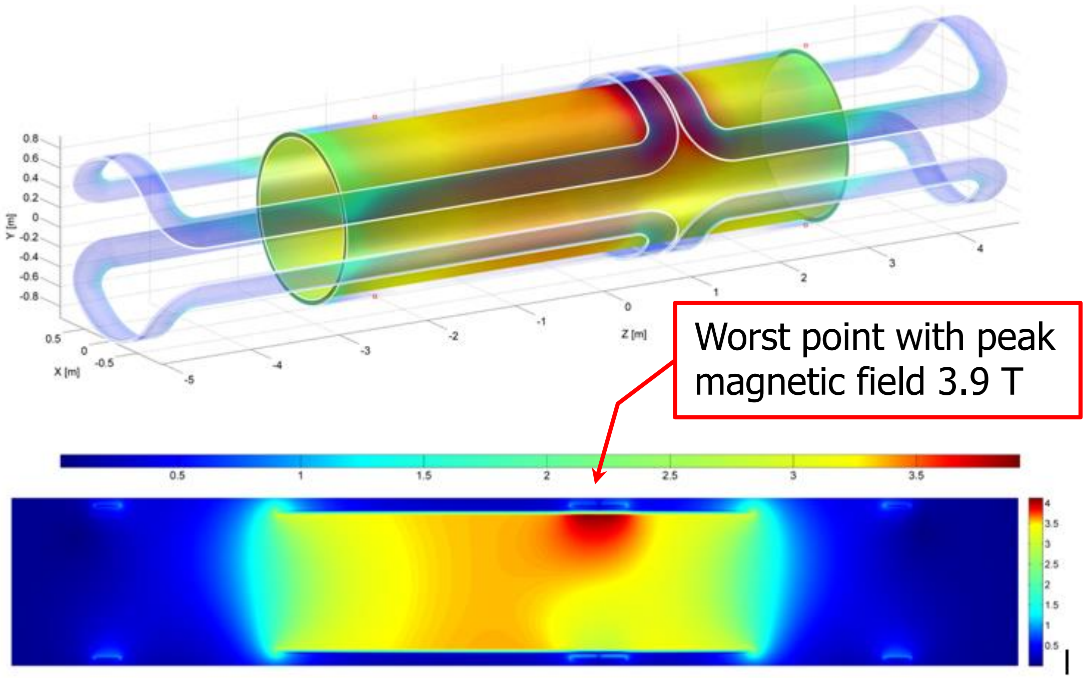
- **Cavern requirement, dimensions and shaft sizes were determined.**
- **Installation scenario of whole detector and service lines studied**



- Full 3d CATIA video film showing main steps of installation is available
- Inner detector cables and lines are routed to the exterior of the detector and then to side cavern
- Forward detectors use flexible chains placed on trenches allowing for longitudinal extraction
- For simplicity, only services routing to muon chambers in forward direction are shown.

3. LHeC Detector Magnet layout, CDR baseline





- Design concept: minimum cost, R&D and risk, relies on present technology for detectors magnets.
- **3.5 T Solenoid & 2 Dipoles** in same cryostat around EMC, Muon tagging chambers in outer layer.
- **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.

Adjustments for LHeC, LHeC+, HE-LHC, FCC-eh

- **Main parameters of the coils in the 4 h-e detectors (A.Polini, Sep 6, 2017)**

	LHeC(2014)	LHeC+	HE-LHeC	FCC eh
Function	CDR design	For comparison	For HE-LHC	For FCC
Location	P2	P2 with L3 magnet	P2 with L3 magnet	Point L
B_solenoid [T]	3.5	3.5	3.5	3.5
B_dipole [T]	0.3	0.3	0.3	*0.15*
Dipole layout	along entire detectors	along entire detectors	along entire detectors	along entire detectors
Free bore/Outer Diam. x length [m]	1.80 - 2.28 x 5.70	*2.16 - 2.86 x 5.78*	*2.42 - 3.14 x 7.20*	*2.63 - 3.35 x 9.18*
Calorimeter	warm	warm	warm	warm

- **From LHeC towards FCC eh, essentially *Increasing system bore and length***
- For 2018 HE-LHC/FCC eh CDR we need to adjust the present design to these new specs
- **Looks all very well doable!**

LHeC (CDR) Solenoid 3.5 T, 2.24 m OD, 7.1 m L

It will look like………a stretched and squeezed ATLAS solenoid,

2 T scaled up to 3.5T (2 layer coil, slightly less free bore but a bit longer)

Relatively small bore but long, and efficient coil with 1.8 m free bore, 7.1 m long

- ≈ 11 km Al stabilized NbTi/Cu superconductor for 10 kA
- ≈ 80 MJ stored energy and ≈ 24 t mass including cryostat.

No specific R&D needed, except detailed analysis of the dipole load case.

Conclusion

- **Baseline Designs for the detector magnet systems for FCC ee, eh and 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 Xo 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.
- Safe Quench Protection design for all magnets was demonstrated.
- 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.
- Cavern and Detector Installation studied, confirming installation feasibility.
- **No show stoppers identified**, **but a serious R&D program is required** on reinforced superconductors and ultra-transparent cold masses and cryostats.