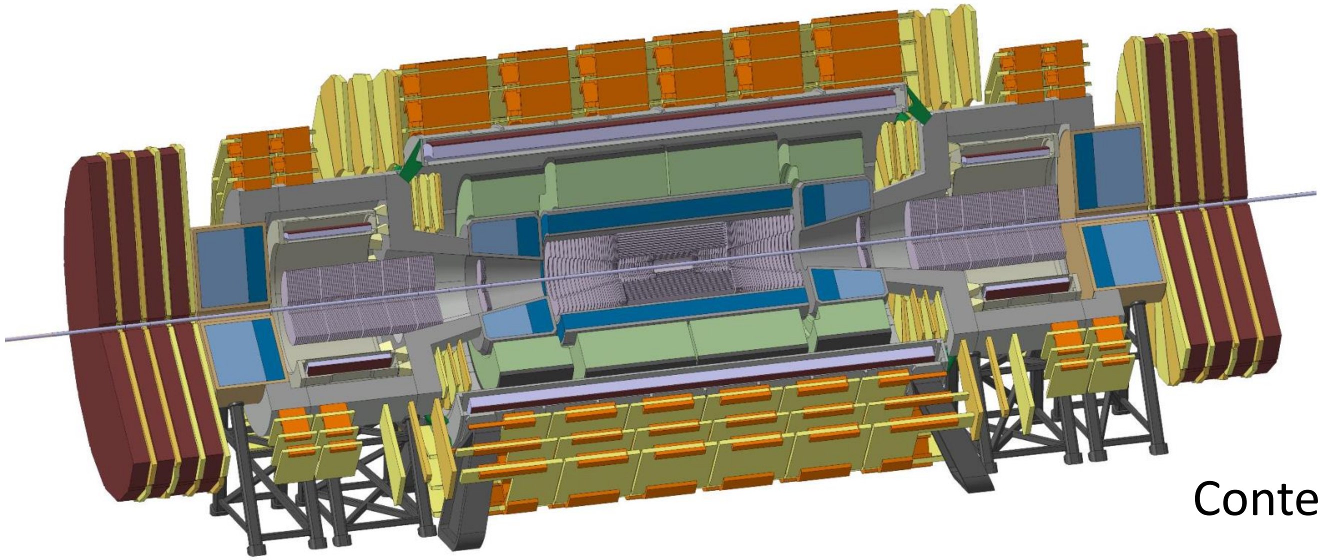
FCC-hh Detector Magnet

- Evolution and New Baseline Design -



Herman ten Kate, Matthias Mentink

for the FCC Detector Magnets Working Group: A. Dudarev, E. Bielert, B. Cure, A. Gaddi, V. Klyukhin, H. Gerwig, C. Berriaud, U. Wagner, H. Filipe Pais da Silva

Content

1. Initial requests and designs
2. New Baseline Detector Magnet
3. Ultra-thin & transparent Solenoid
4. Summary and outlook

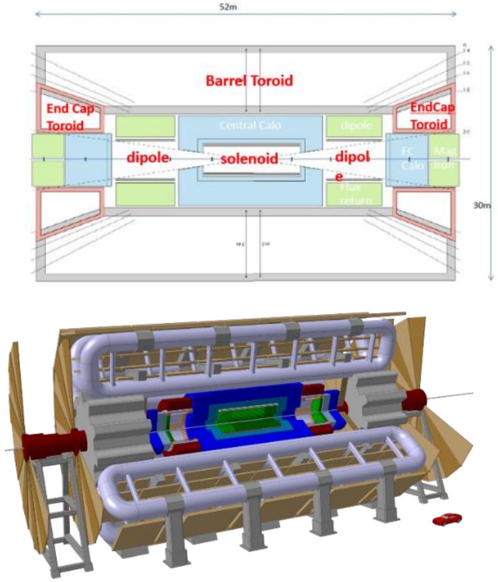
1. Initially 2014-2015: Collecting requirements and probing designs

FCC 100 TeV = 7x the 14 TeV of LHC, consequences?

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$

Initial thoughts for 2 detectors:

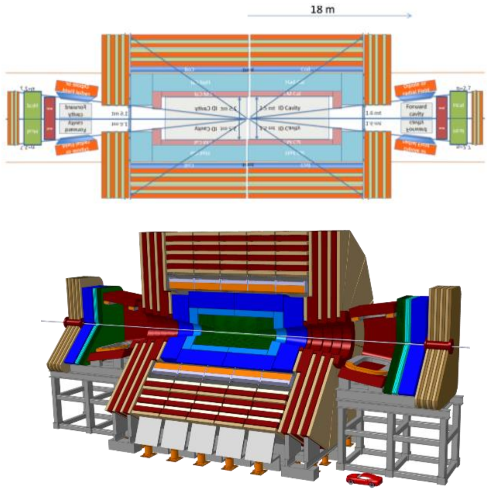
- Define CMS+ and ATLAS+ designs, but for 100 TeV
- And add magnets in forward directions for 10 Tm (dipoles, solenoids)
- For same tracking resolution, same σ, BL^2 has to go up by factor 7, in combination with thicker calorimeter, this leads to a 6T/12m bore solenoid
- Similar arguments for a toroid leads to a gigantic 30m dia, 50m long system
- All not affordable, too expensive (≈1 B€ magnets)!



1st ATLAS+ sketch and design

Cure:

- Standalone muon tracker not needed --> drop toroid design, define 1 detector
- Assume higher tracker resolution, expected well possible (factor ≈3) --> less BL^2
- Limit calorimeter depth, not 12 but 11λ --> less radial thickness
- Accept no magnetic shielding (cavern at -300 m) --> no iron, no shielding coil

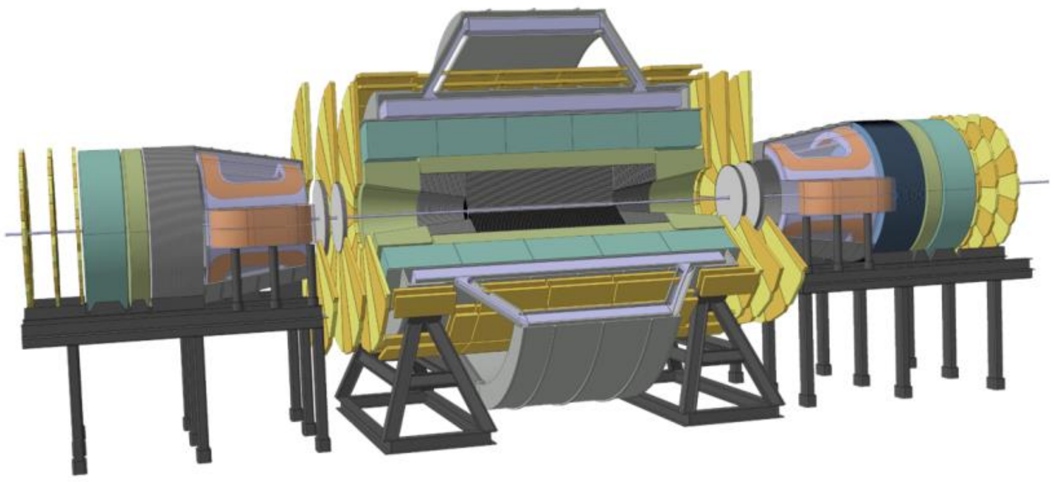


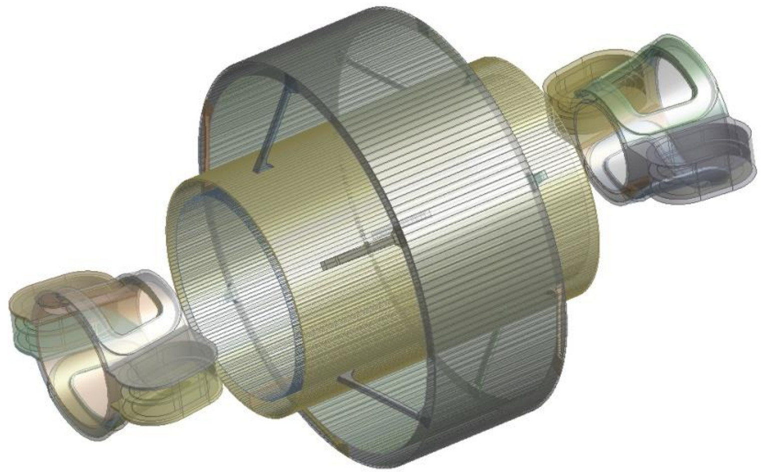
1st CMS+ sketch & design

Result:

✓ **New baseline design for CDR 2018**

FCC week 2016: 6 T / 12 m bore Twin Solenoid with Balanced Forward Dipoles





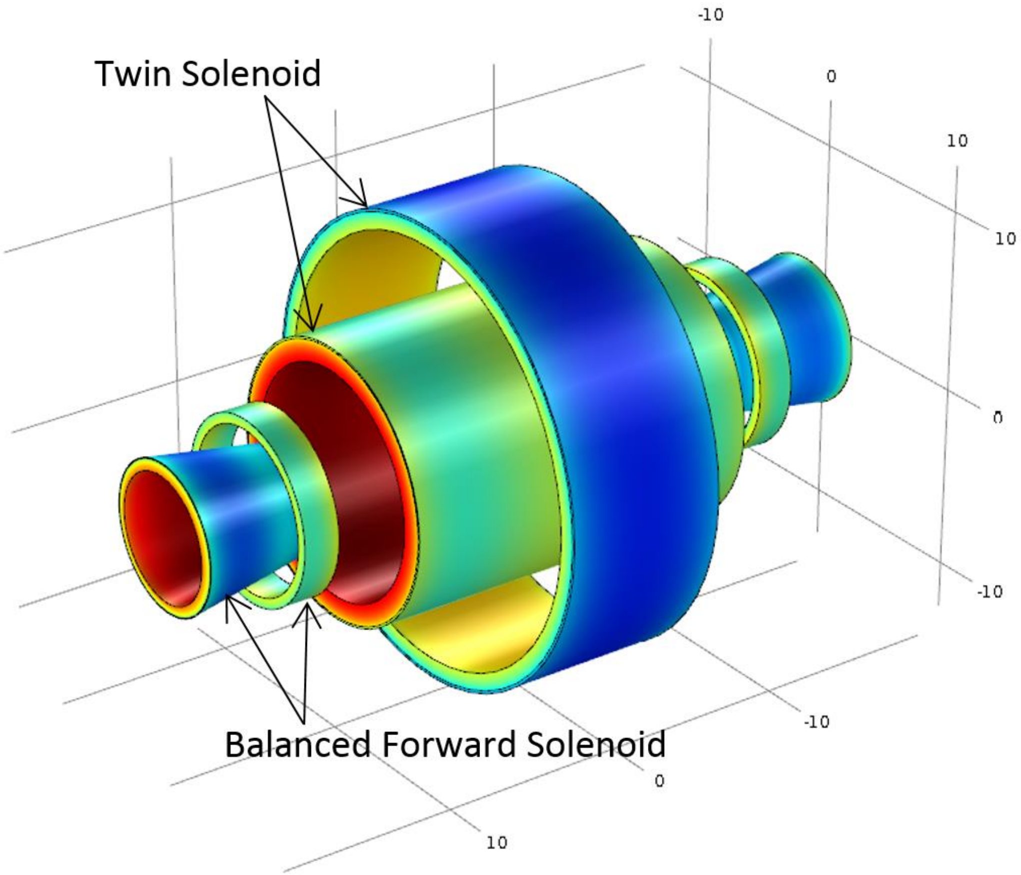
Concept:

- Inner main solenoid generates 6 T in a 12 m free bore
- Outer solenoid returns flux --> Reduced stray field and increased bending power for muons
- Forward dipoles comprise main lateral dipole coils --> Net force and torque on each cold mass is zero

Result:

- Bending power for particle products at all pseudorapidities
- Stored energy: 65 GJ
- But: Complex combination of magnets --> implies relatively high cost and technical risk

6 T / 12 m Twin Solenoid with Balanced Forward Solenoids



Twin Solenoid + Balanced Forward Solenoid:
Net force and torque on each coil is zero

Concept:

- Very similar to Twin Solenoid + Forward dipoles
- Combination of larger inner forward solenoid and smaller outer forward solenoid results in force and torque neutrality on every coil

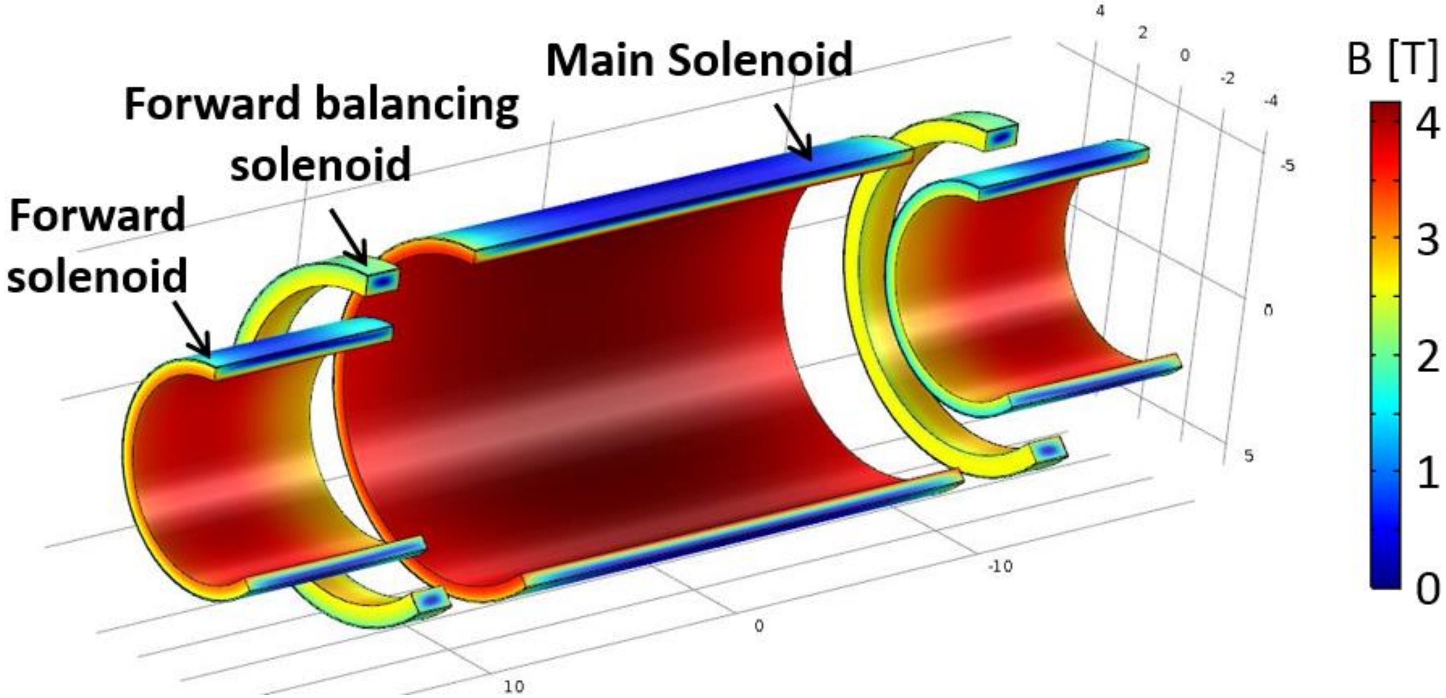
Result:

- Stored energy: 68 GJ
- Bending power comparable to forward dipole in pseudorapidities up to 4
- Radially symmetric detector magnet --> Easier particle tracking
- Less complex forward magnet system implies reduced cost and reduced technical risk

4 T / 10 m Main Solenoid with Balanced Forward Solenoids

Concept:

- 4 T in 10 m free bore instead of 6 T over 12 m and removal of outer solenoid --> 5x lower stored energy and thus much lower cost
- Removal of outer solenoid --> Significantly enhanced stray field but more compact, less complex, and more cost-effective detector magnet
- Straight rather than conical forward solenoid to reduce blind spots
- Each coil is force and torque neutral

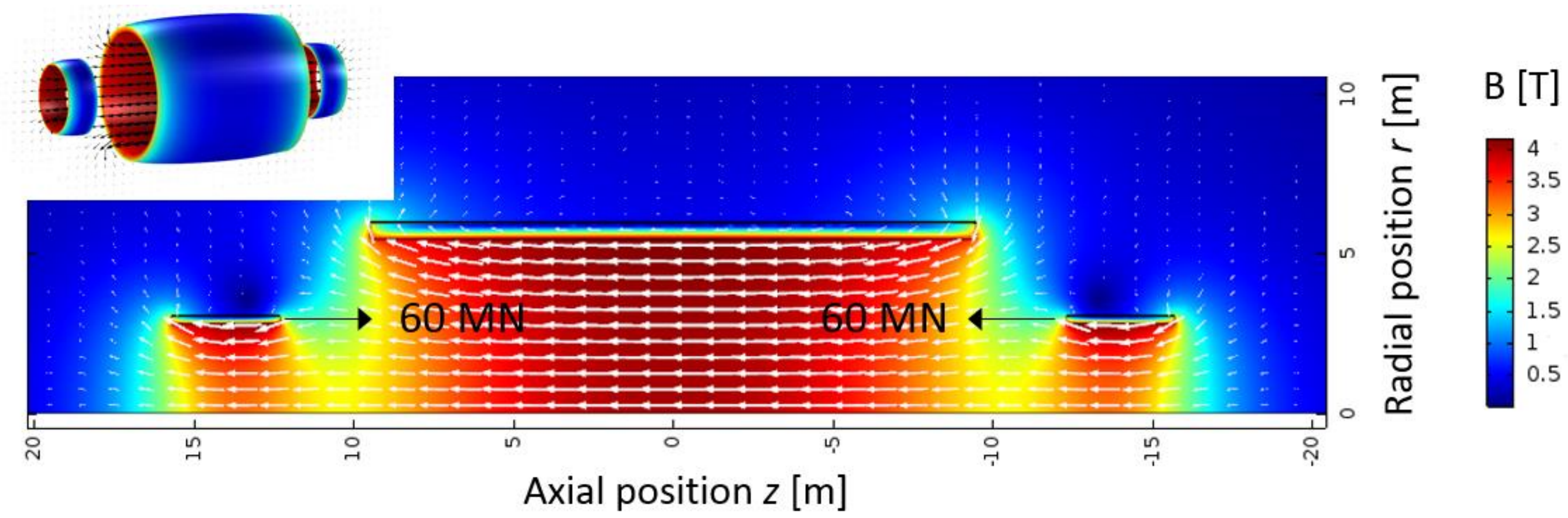


Solenoid + Balanced Forward Solenoid:
Net force and torque on each coil is zero

Result:

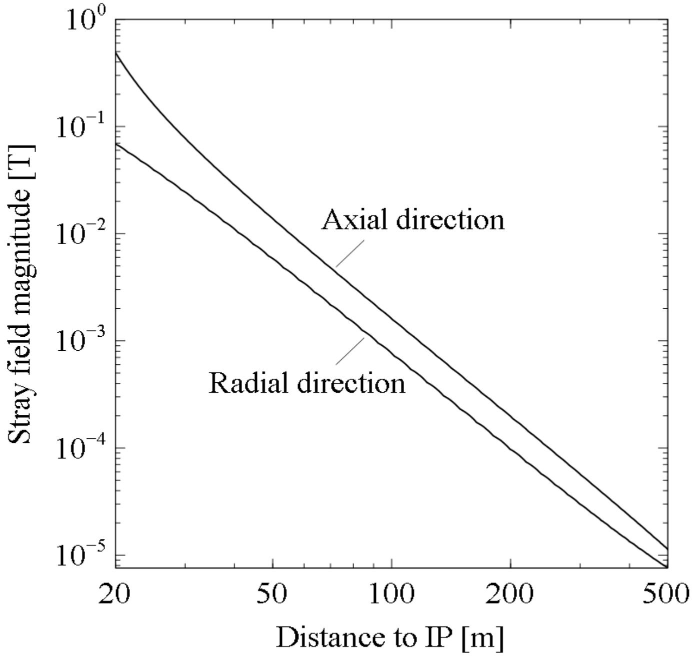
- Stored energy: 14 GJ
- Provides sufficient bending power for muon tagging

2. New Baseline: 4 T / 10 m Solenoid with Forward Solenoids

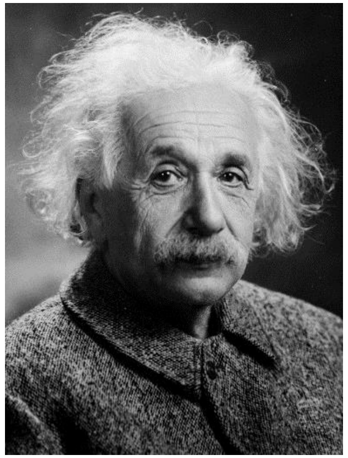


Concept:
- 4 T in 10 m free bore
- Removal of outer forward solenoids, magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods

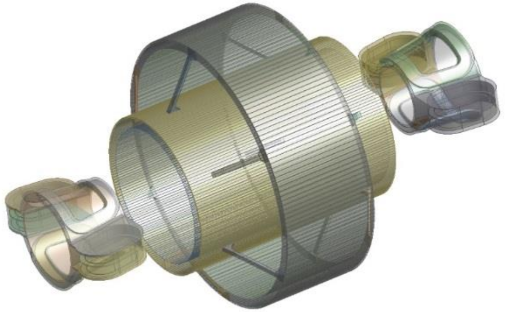
Result:
- Stored energy: 13.8 GJ
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field



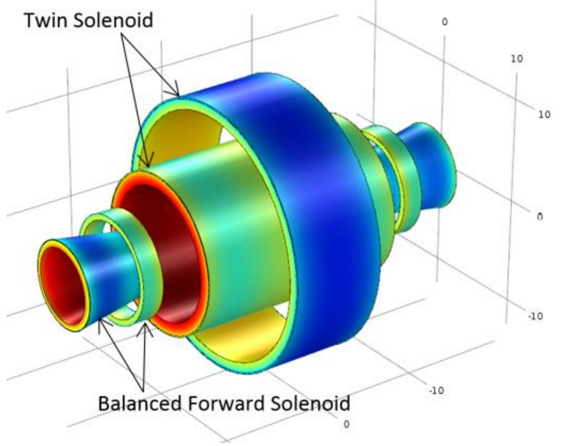
Summary: Design evolution of the FCC detector magnet baseline



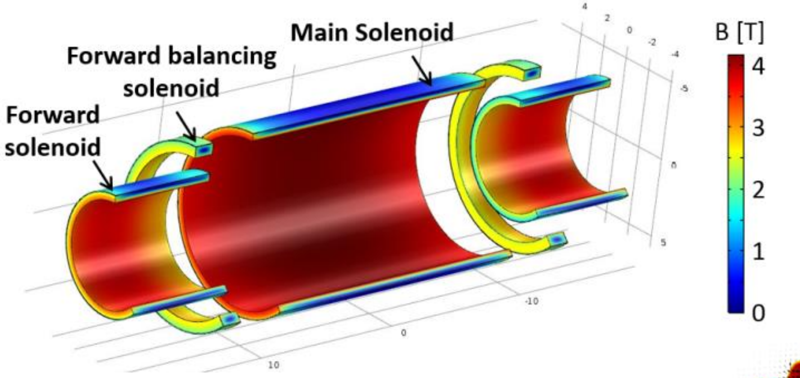
Everything should be made as simple as possible, but not simpler (Quote attributed to Einstein)



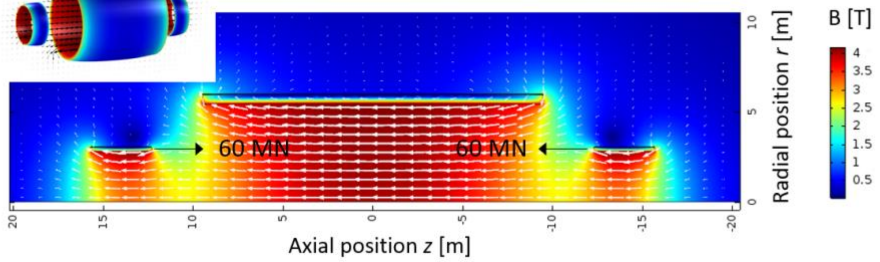
Twin Solenoid + Balanced Forward Dipoles



Twin Solenoid + Balanced Forward Solenoids



Solenoid + Balanced Forward Solenoids

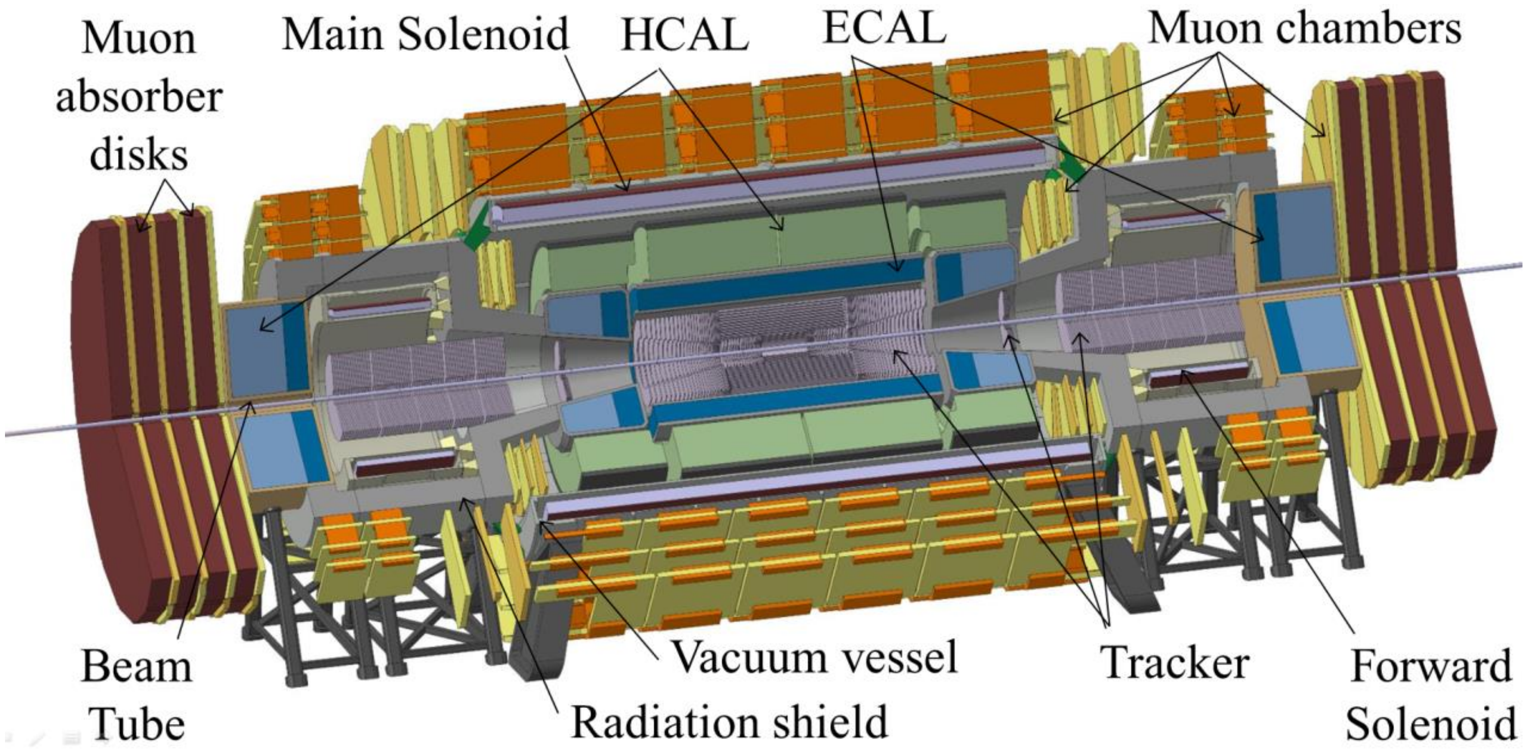


Solenoid + Forward Solenoids

Design evolution towards:

- Lower stored energy, smaller, lighter designs
- Less complexity, size reduction, fewer coils
- More cost-effective!

FCC week 2017: New FCC-hh Detector Baseline



Main solenoid:

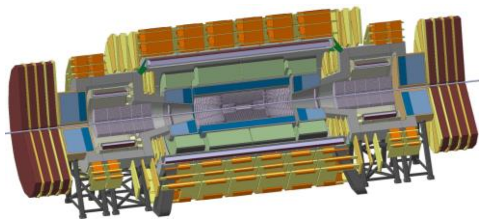
- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) on outside of main and forward solenoids
- Assembly and Services see next talk

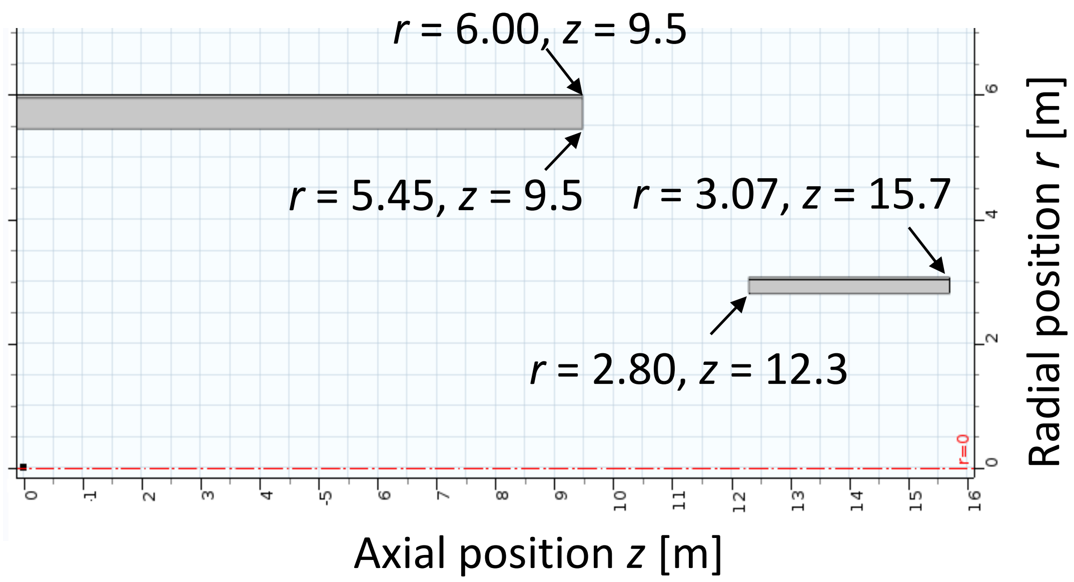
Forward solenoid:

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

(to shield muon chambers from neutrons emanating from forward calorimeters)

Cold mass budget of 4 T / 10 m Main Solenoid + 4 T Forward Solenoids



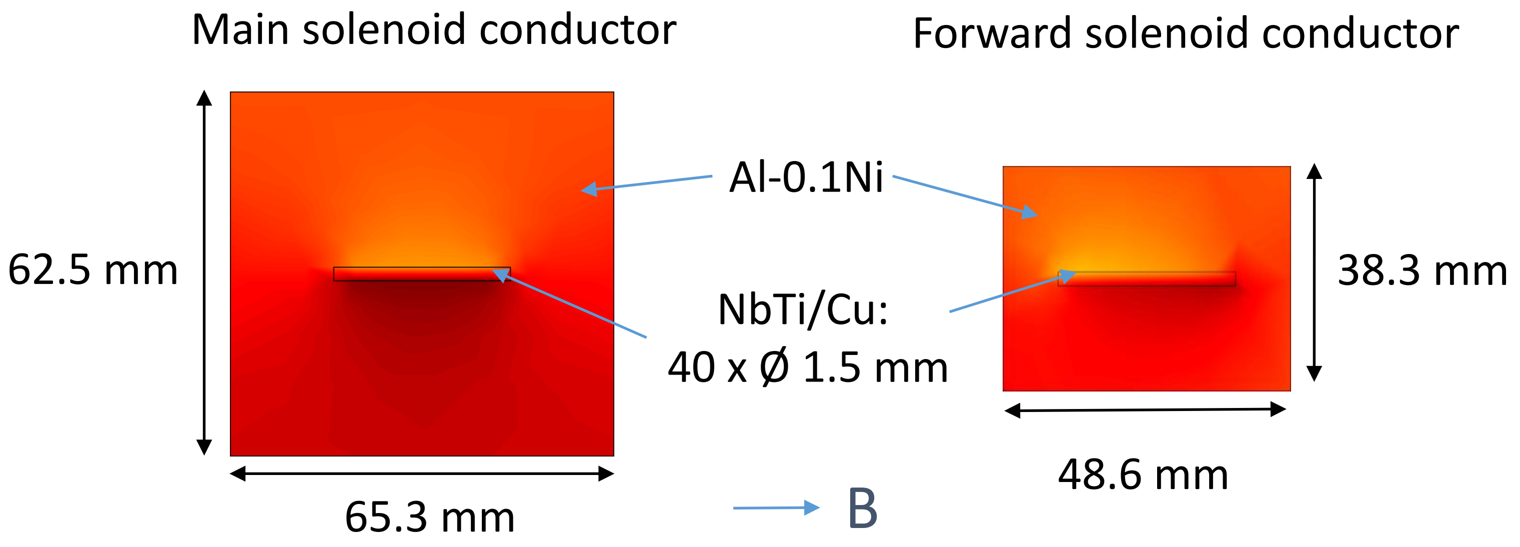


Composition [vol.%]	Main Solenoid	Forward Solenoid
Aluminum	95.4	92.3
Copper	0.8	1.6
Niobium	0.4	0.8
Titanium	0.4	0.8
G10	3.1	4.5

- Numbers refer to the cold mass solely (i.e. not the thermal shields, vacuum vessel, and support structure)
- Cold mass is radially symmetric and symmetric over z = 0
- The main solenoid cold mass is 1070 tons, and each of the forward solenoids cold masses weighs 48 tons
- Total stored energy = 13.8 GJ
- Cold Mass Energy density = 11.9 kJ/kg

Mass per m^3 cold mass [kg/m^3]	Main Solenoid	Forward Solenoid
Aluminum	2590	2508
Copper	75	140
Niobium	33	62
Titanium	17	32
G10	56	81
Total	**2771**	**2823**

"Super" - Conductor assumed in baseline design



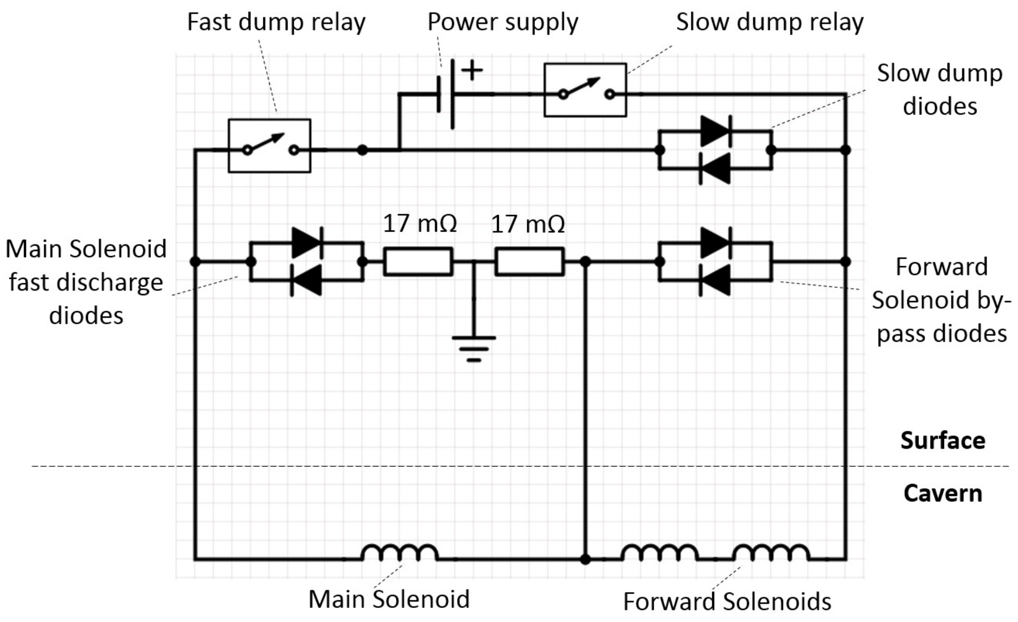
	Main Solenoid	Forward Solenoid
Current [kA]	30	30
Self-inductance [H]	28	0.9
Layers x turns	8 x 290	6 x 70
Total conductor length [km]	83	2 x 7.7
Bending strain [%]	0.57	0.68

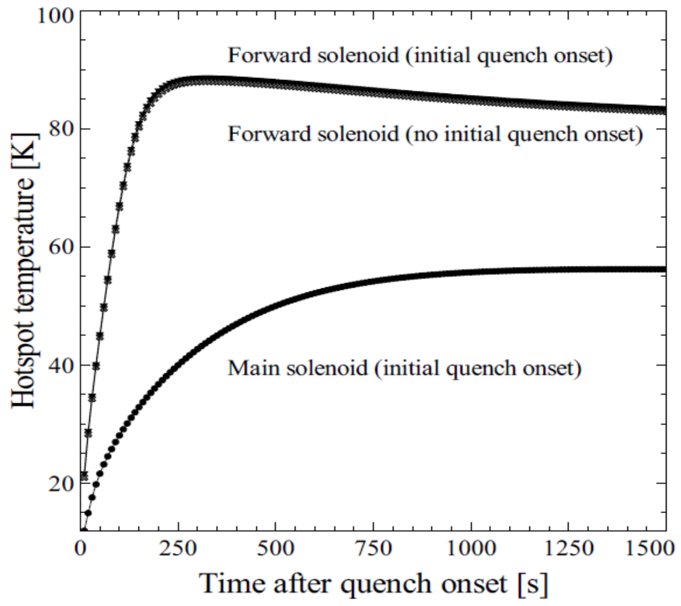
Aluminum-stabilized Rutherford conductors for 30 kA nominal

- 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 on conductor is 100 MPa
- 1 mm insulation between turns, 2 mm to ground

[1] Yamamoto et al., IEEE Trans. Appl. Sup. 9, p. 852 (1999)

Electrical scheme and quench protection





Electrical scheme

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

Quench protection (using Quench code Quench 2.7)

- Conductor RRR = 400
- Main solenoid: Extraction (Quench-back) + Quench heaters
- Forward solenoid: Quench heaters
- Nominal Quench: 56 K in main solenoid, 89 K in forward solenoid, 73% extraction
- Worst case fault (no working heaters): 142 K in main solenoid, 133 K in forward solenoids

Cryostat and heat loads

Heat loads:

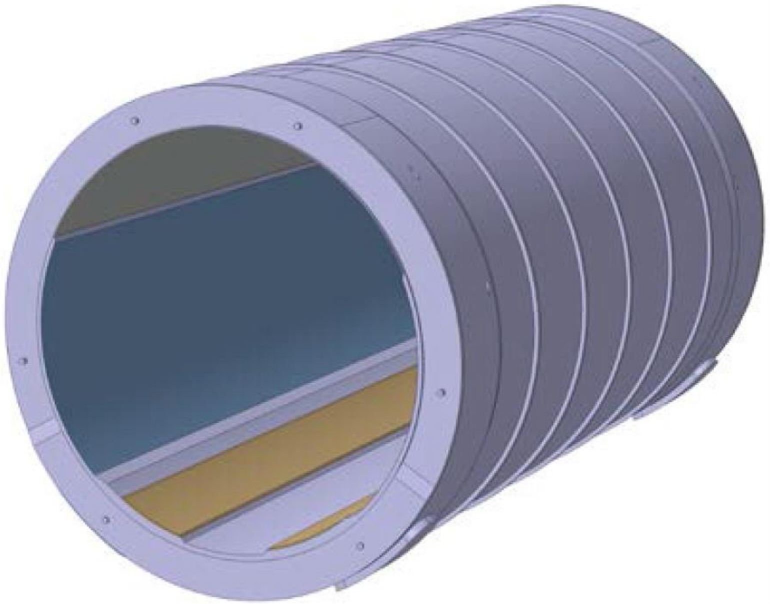
- Radiation: 360 W on cold mass, 6.8 kW on thermal shields
- Tie rods (Ti6Al4V rods, thermalized at 50 K):
  20 W on cold mass, 1.4 kW on 50 K thermalization points
- Acceptable heat load in tie rods, despite 60 MN net force on forward solenoids

Materials and mass:

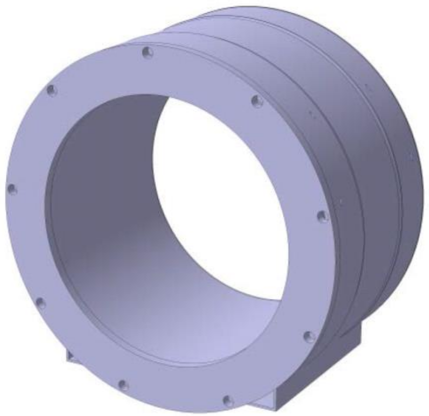
- Main solenoid cryostat: SS 304L (high strength, minimal space), 875 t
- Forward solenoid cryostat: Al 5083-O (for minimal mass), 32 t
- Total solenoid weights: Main 2 kt, forward 80 t (each)

Mechanical aspects:

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



Main solenoid vacuum vessel



Forward solenoid vacuum vessel

3. Challenging alternative - the Ultra-thin & “transparent” Solenoid

Motivation:

In baseline design, useful magnetic field is on the tracker + muon chambers, but most stored magnetic energy goes toward calorimeters, thus enormous “waste” of magnetic field

Solution: (concept of the 2T ATLAS Solenoid):

Generate magnetic field on tracker & muon chambers only
--> **16x lower stored energy**

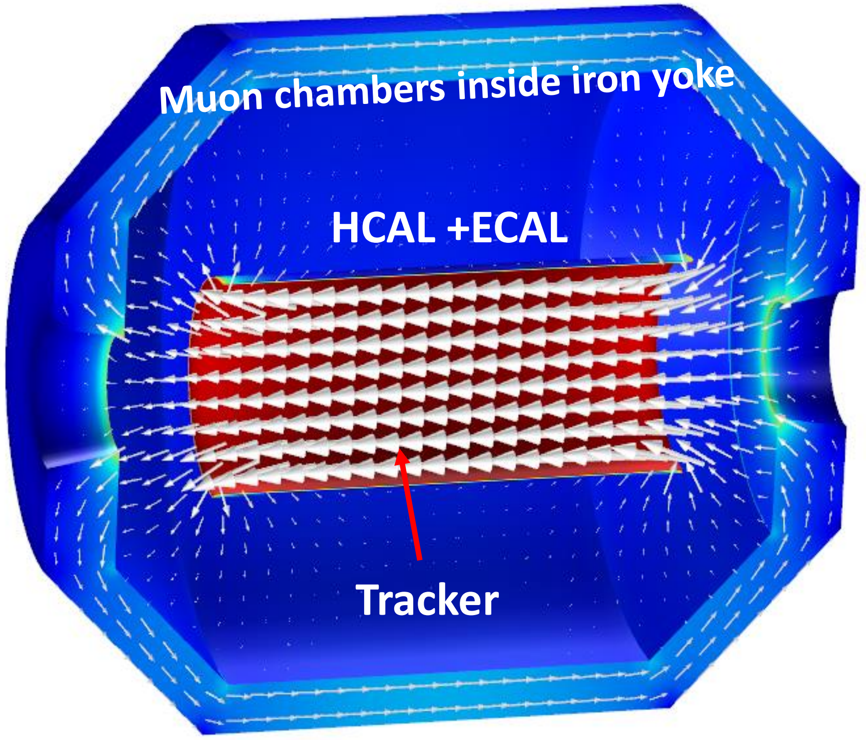
Use an iron yoke (6 kt) for returning flux

- Provides magnetic flux for muon tagging
- And perfect magnetic shielding
- And Lorentz Force decoupling with forward detector magnets

But: particles go through solenoid before reaching calorimeters

- Thin solenoid required for minimal interference
- High-strength conductor needed

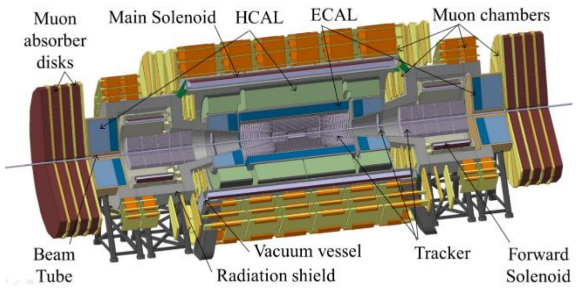
R&D currently in progress (2 PhDs) for maximum transparency of conductor, cold mass and cryostats, for FCC-hh and FCC-ee as well!



Property	4 m bore, ECAL out
Field in center [T]	4
Stored energy [GJ]	0.87
Iron mass [kt]	6
Muon Fl at η = 0 [Tm]	1.2

4. Conclusion & Outlook

✓ After 3 years of iterations on physics requirements (resolution and forward directions), detector technology (tracker resolution and depth of calorimeter), civil engineering (cavern), radiation (shielding), stray field (no field containment), magnet technology and cost, **a final baseline design for the magnet system was accepted by the detector community**



✓ Evolution towards fewer coils, all solenoids, less complexity, less risk, less weight, more space-efficient designs and lower cost (now in-line with an overall detector cost of ≈1 B€)

✓ Baseline for CDR-2018:

- Main solenoid providing 4 T in a 10 m free bore, 20 m long
- Forward solenoids providing 4 T in a 5 m bore, 4 m long, augmenting bending power of main solenoid for high-pseudorapidity particles
- Designs made for cold mass, vacuum vessel, cryogenics, electrical circuits, quench protection, et cetera. No show-stoppers identified

✓ Alternative designs also included in CDR: Main Solenoid with cylindrical Forward Dipoles, Minimum-yoke option, and the Ultra-thin & transparent Solenoid

✓ An R&D program for engineering the critical parts of the system is being prepared