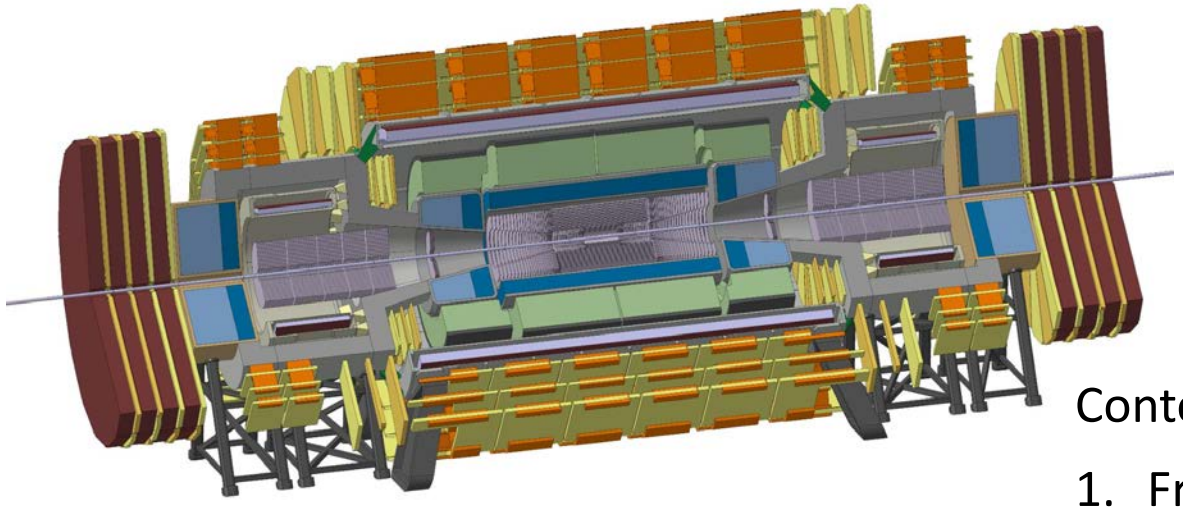
MT25

Detector Magnets for the Future Circular Collider

- Evolution and New Baseline Design -



Herman ten Kate

for the FCC Detector Magnets Working Group
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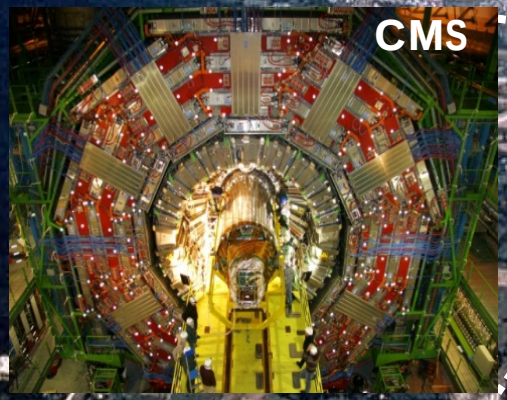
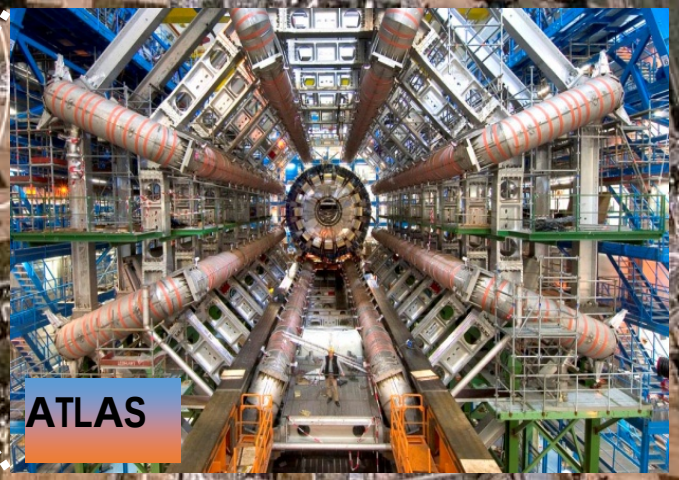
Content

1. From today's LHC to FCC next
2. Initial requests and designs
3. New Baseline Detector Magnet
4. Ultra-thin & transparent Solenoid
5. Summary and outlook

Large Hadron Collider

Exploring the energy frontier at 14 TeV, but what is next, option FCC?





1. FCC: Featuring proton – proton collisions at 100 TeV

Colliding Energy = 0.6 x B x R

B: 1.9 x from NbTi to Nb_3Sn

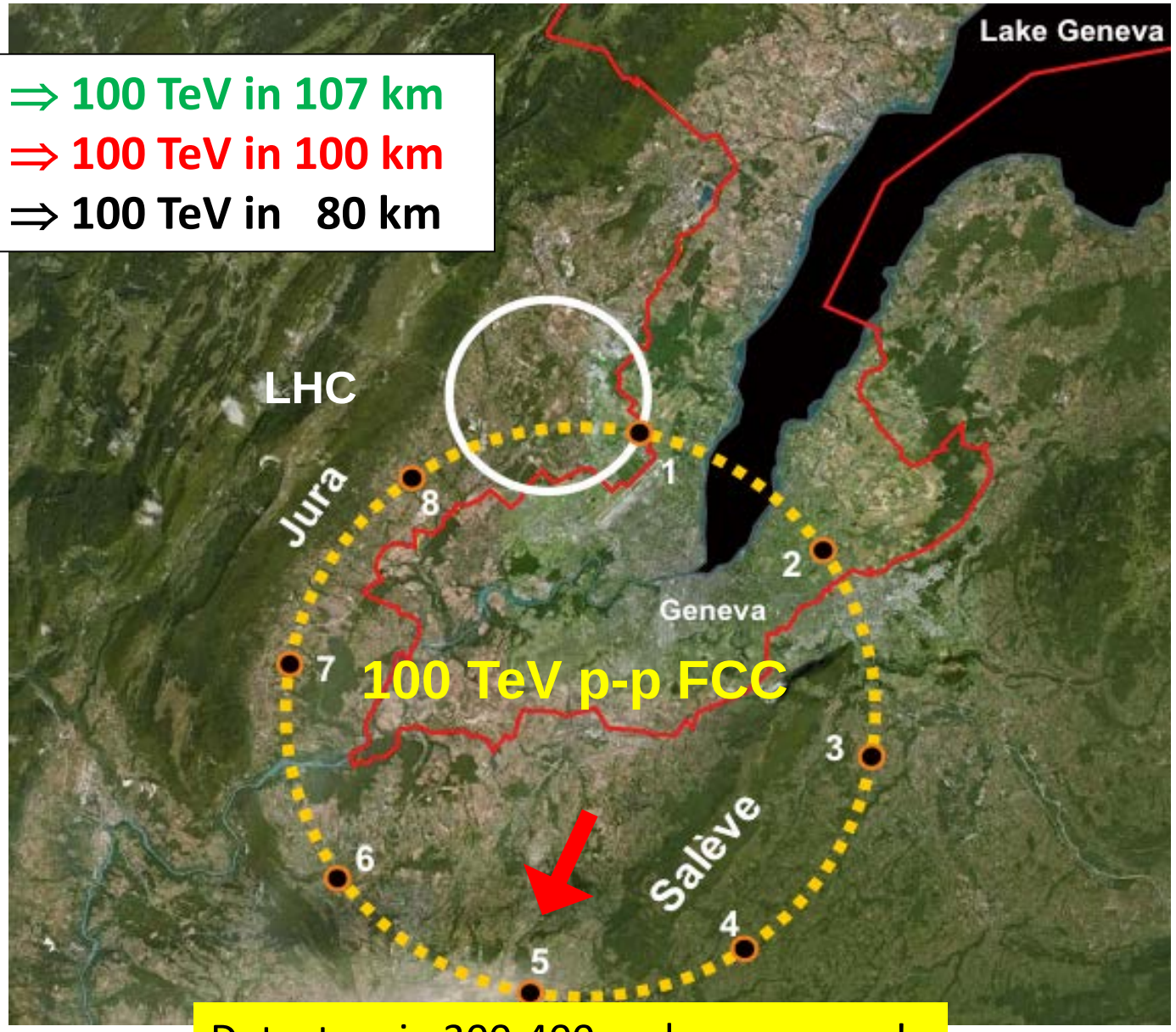
B: 2.4 x from NbTi to HTS

R: 4 x more magnets

- New ≈100 km tunnel in Geneva area
- 100 TeV p-p determines the size
- Options for adding an e+e collider (TLEP) & pe collider (VLHeC)

- An extremely challenging project.
- ✓ **The options shall be explored……**

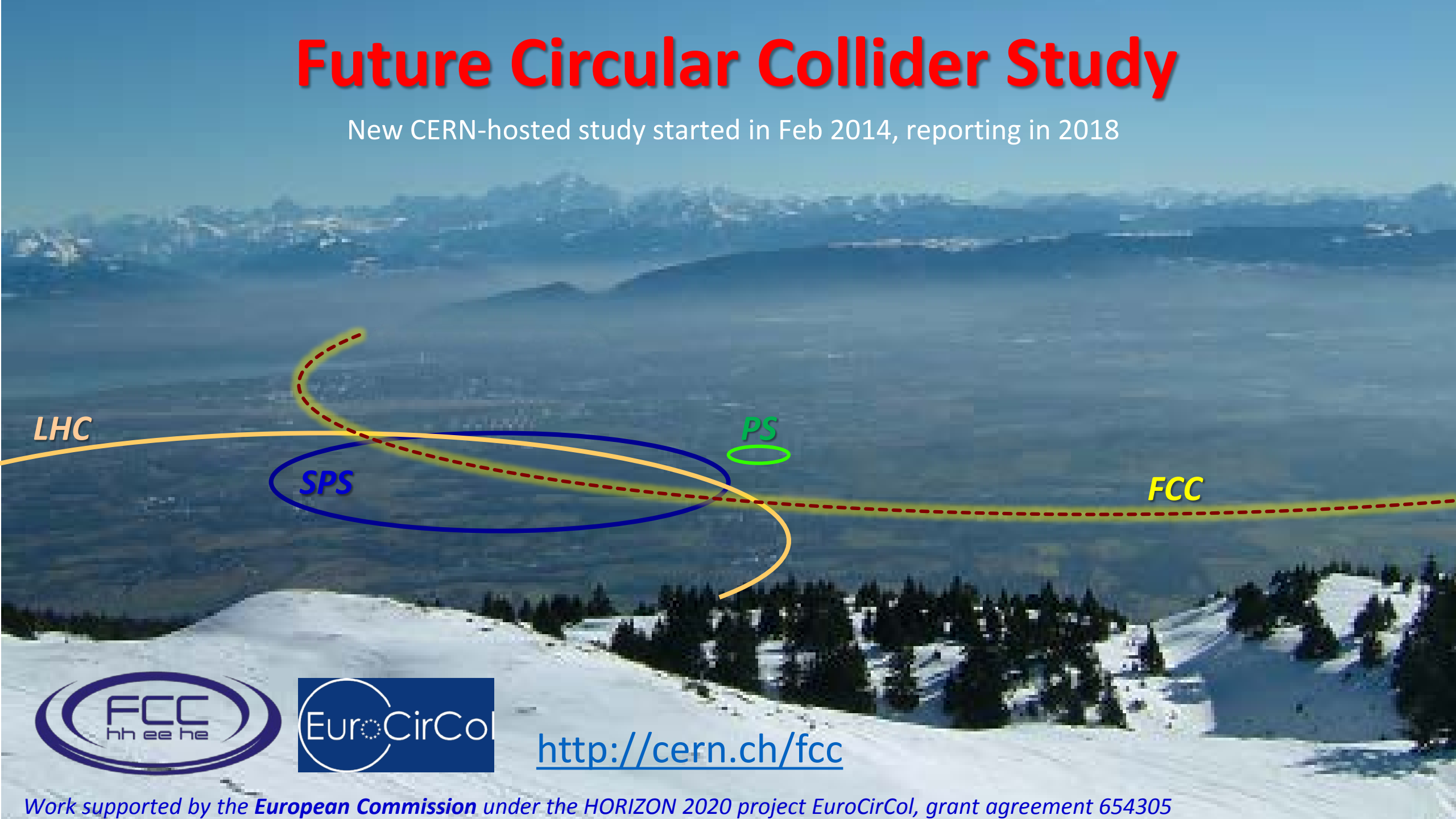
≈ 15 T ⇒ 100 TeV in 107 km
≈ 16 T ⇒ 100 TeV in 100 km
≈ 20 T ⇒ 100 TeV in 80 km



Detectors in 300-400 m deep caverns!

Future Circular Collider Study

New CERN-hosted study started in Feb 2014, reporting in 2018



FCC hh ee he

EuroCirCol

http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

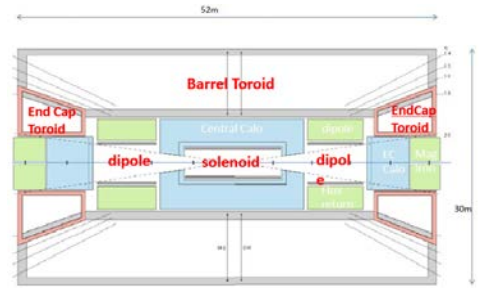
2.1 Initially 2014-2015: Collecting requirements and probing designs

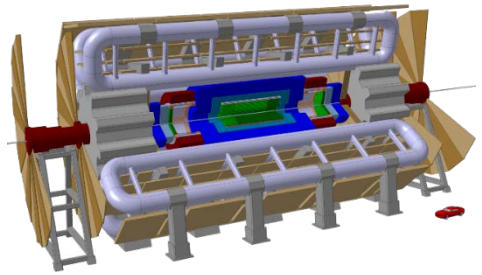
FCC 100 TeV = 7x the 14 TeV of LHC, consequences?

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

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)!

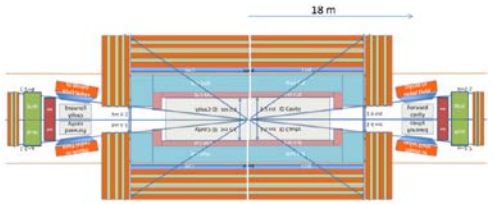


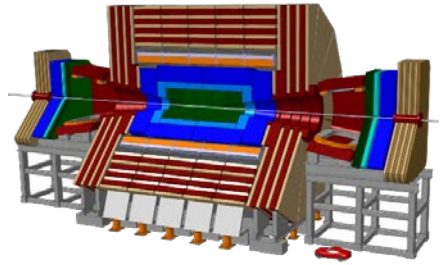


1st ATLAS+ sketch and design

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



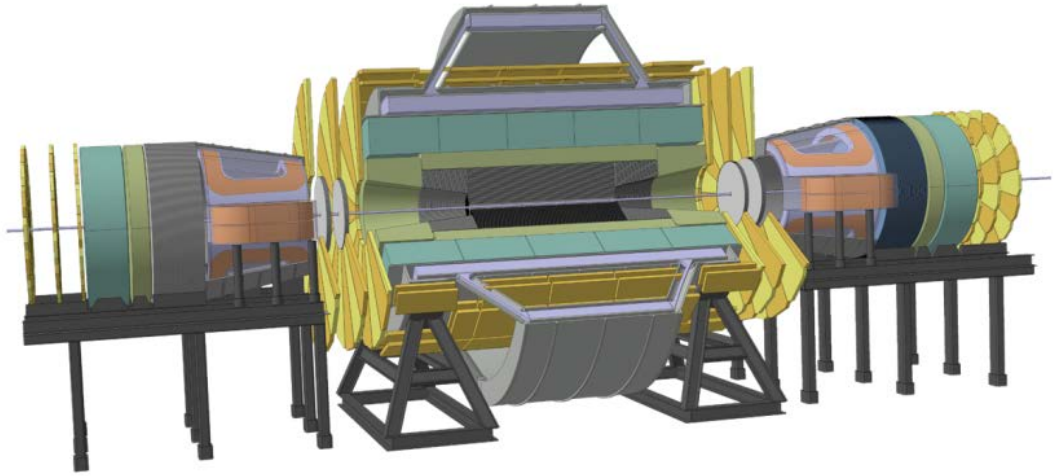


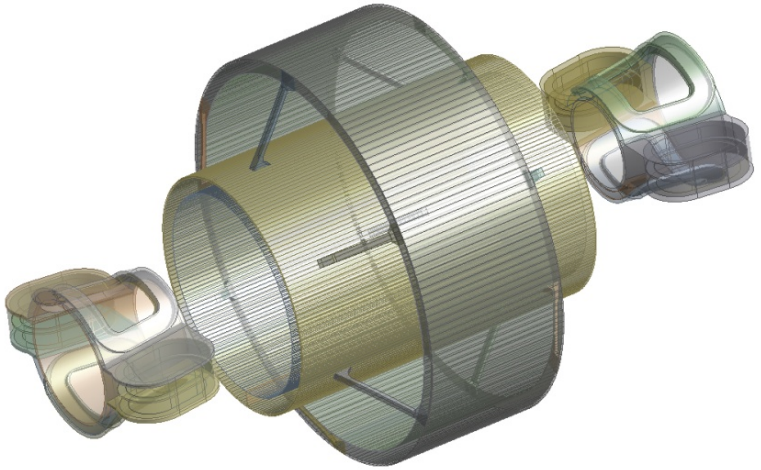
1st CMS+ sketch & design

Result:

✓ **New baseline design for CDR 2018**

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





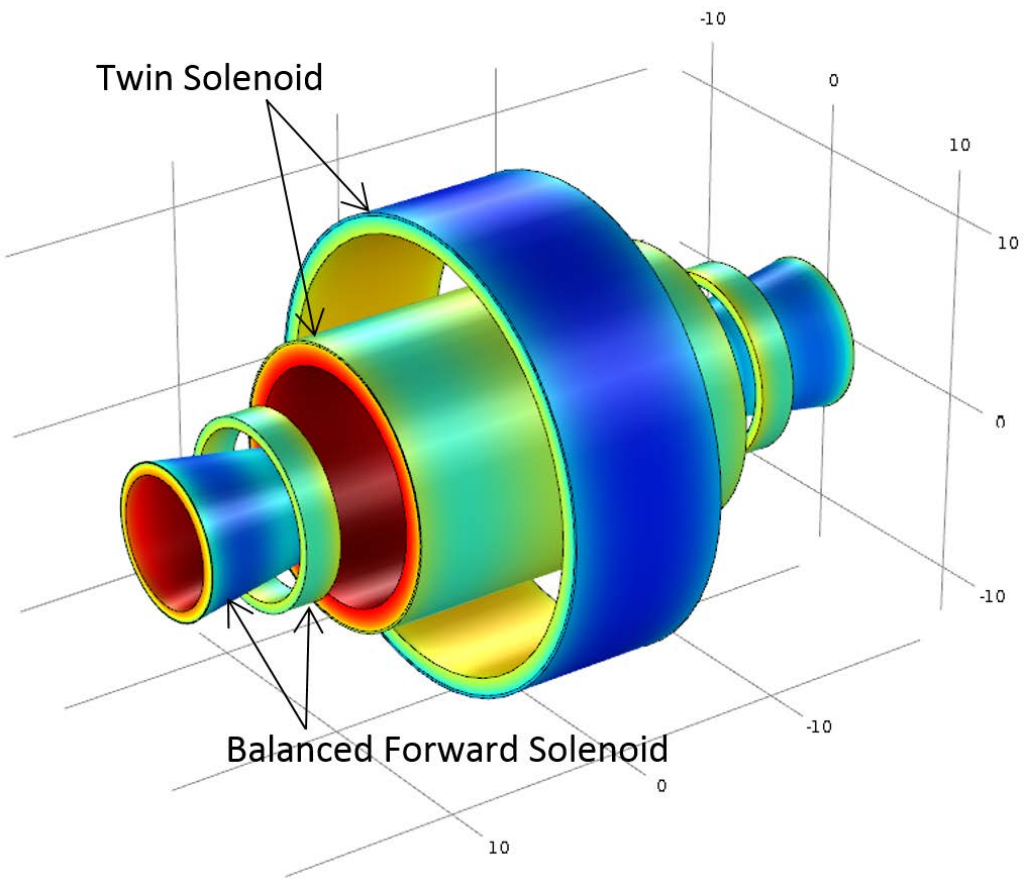
Concept:

- 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 in 12 m bore 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

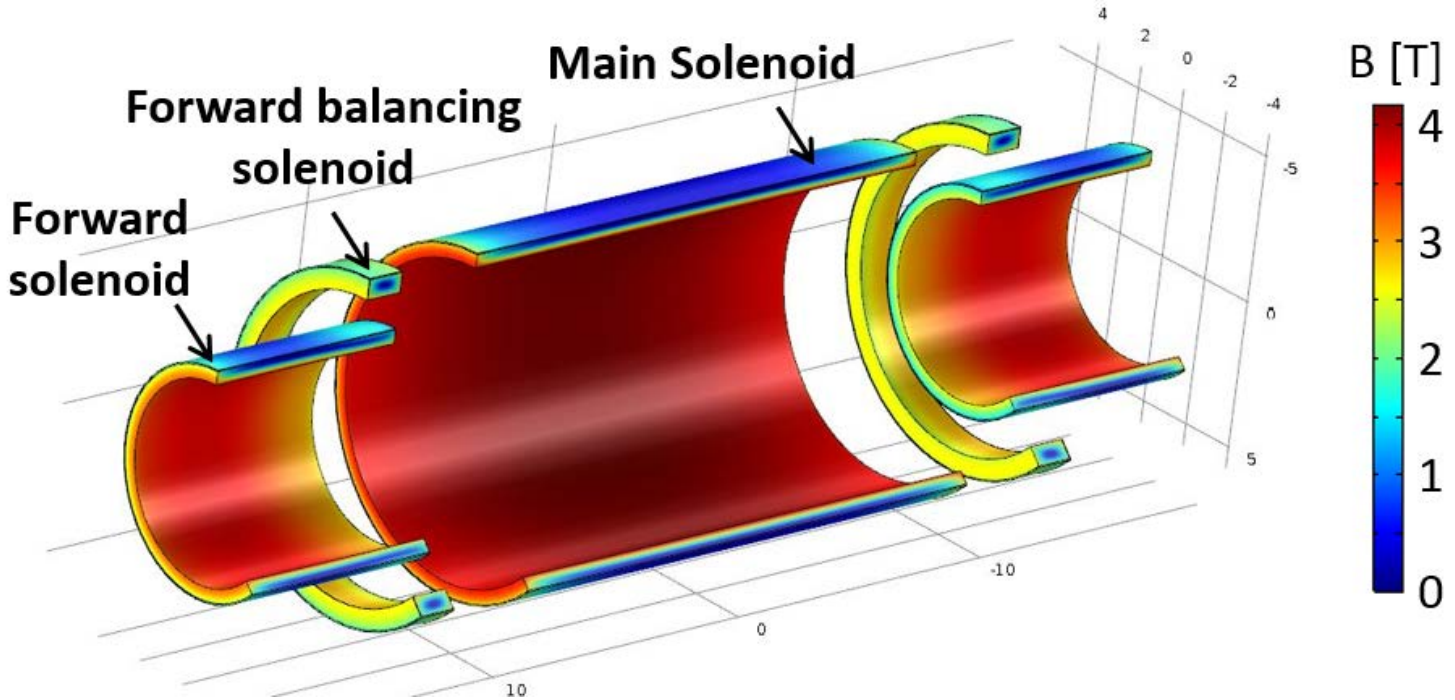
Result:

- 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 in 10 m bore 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



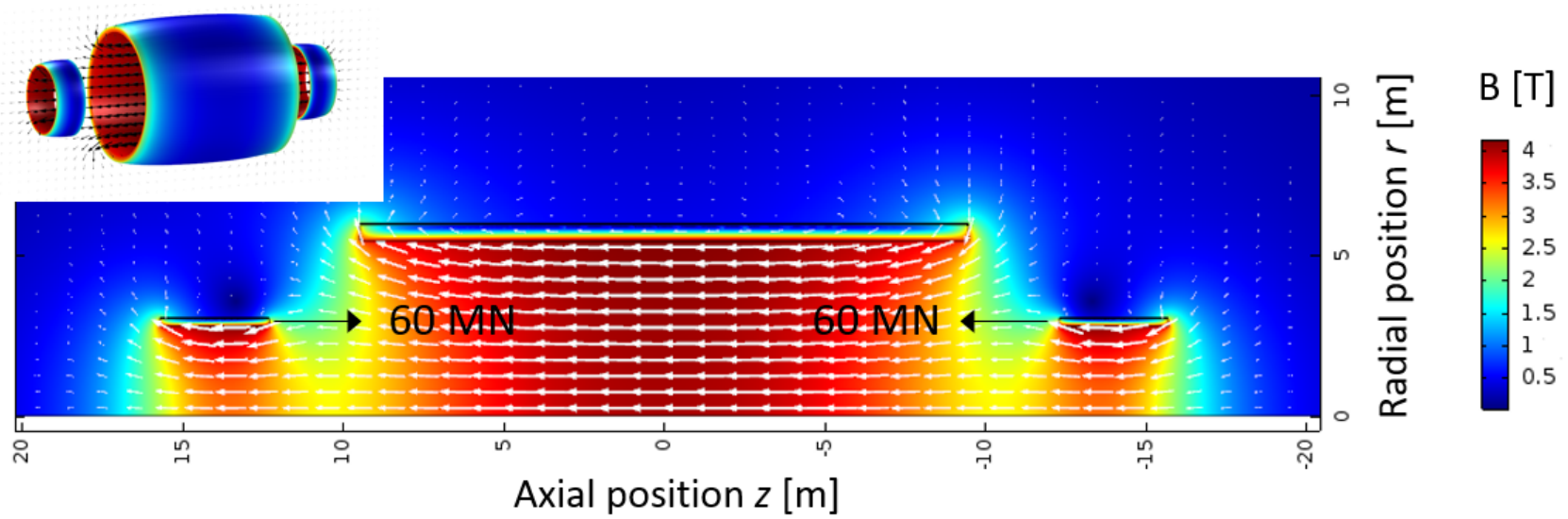
Solenoid + Balanced Forward Solenoid:
Net force and torque on each coil is zero

- Straight rather than conical forward solenoid to reduce blind spots
- Each coil is force and torque neutral

Result:

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

3. 2017, the new Baseline: 4T/10m Solenoid with Forward Solenoids

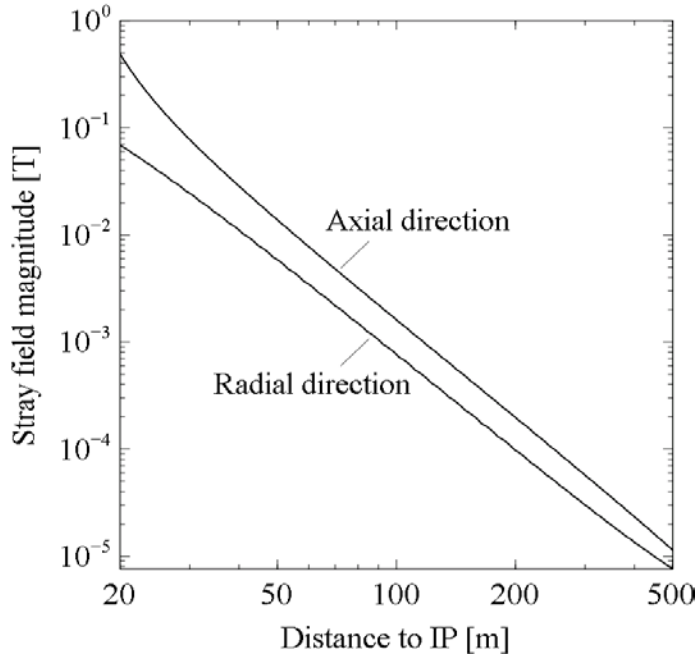


Concept:

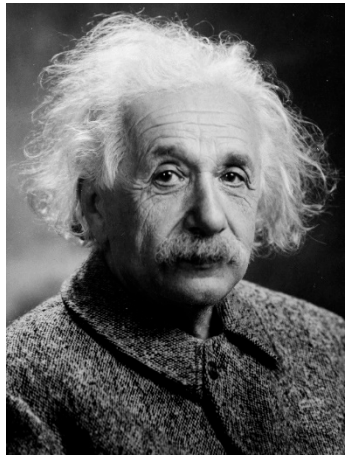
- 4 T in 10 m free bore
- Removal of outer forward solenoids, magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods

Result:

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



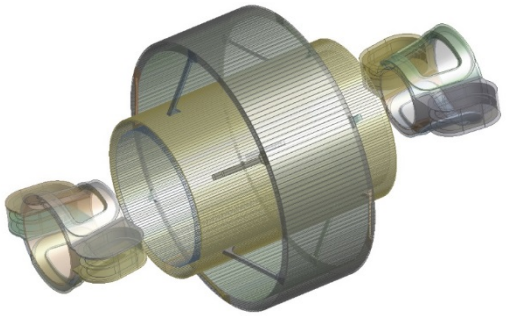
Design evolution of the FCC detector magnet baseline



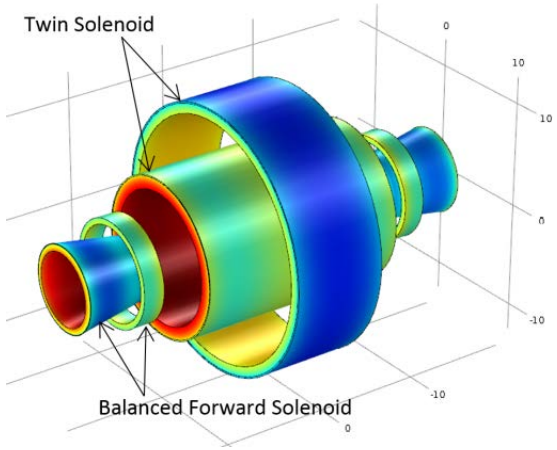
Everything should be made as simple as possible, but not simpler (Quote attributed to Einstein)

Design evolution towards:

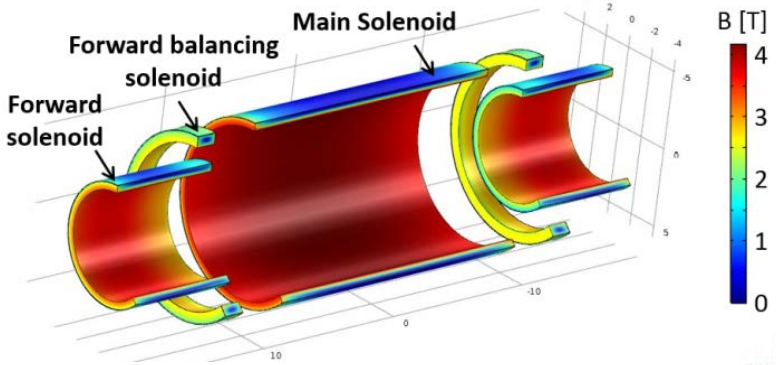
- Lower stored energy, smaller, lighter designs
- Less complexity, size reduction, fewer coils
- More cost-effective!



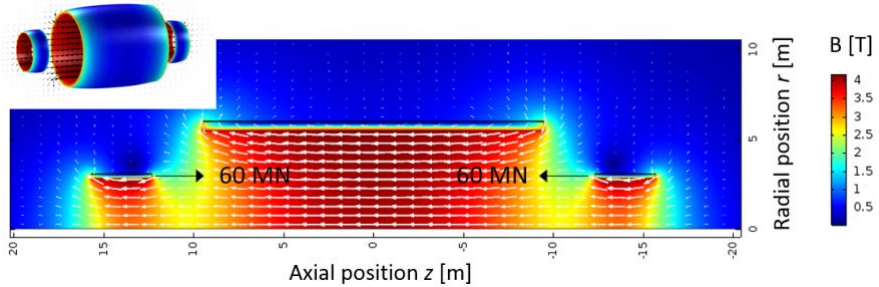
Twin Solenoid + Balanced Forward Dipoles



Twin Solenoid + Balanced Forward Solenoids

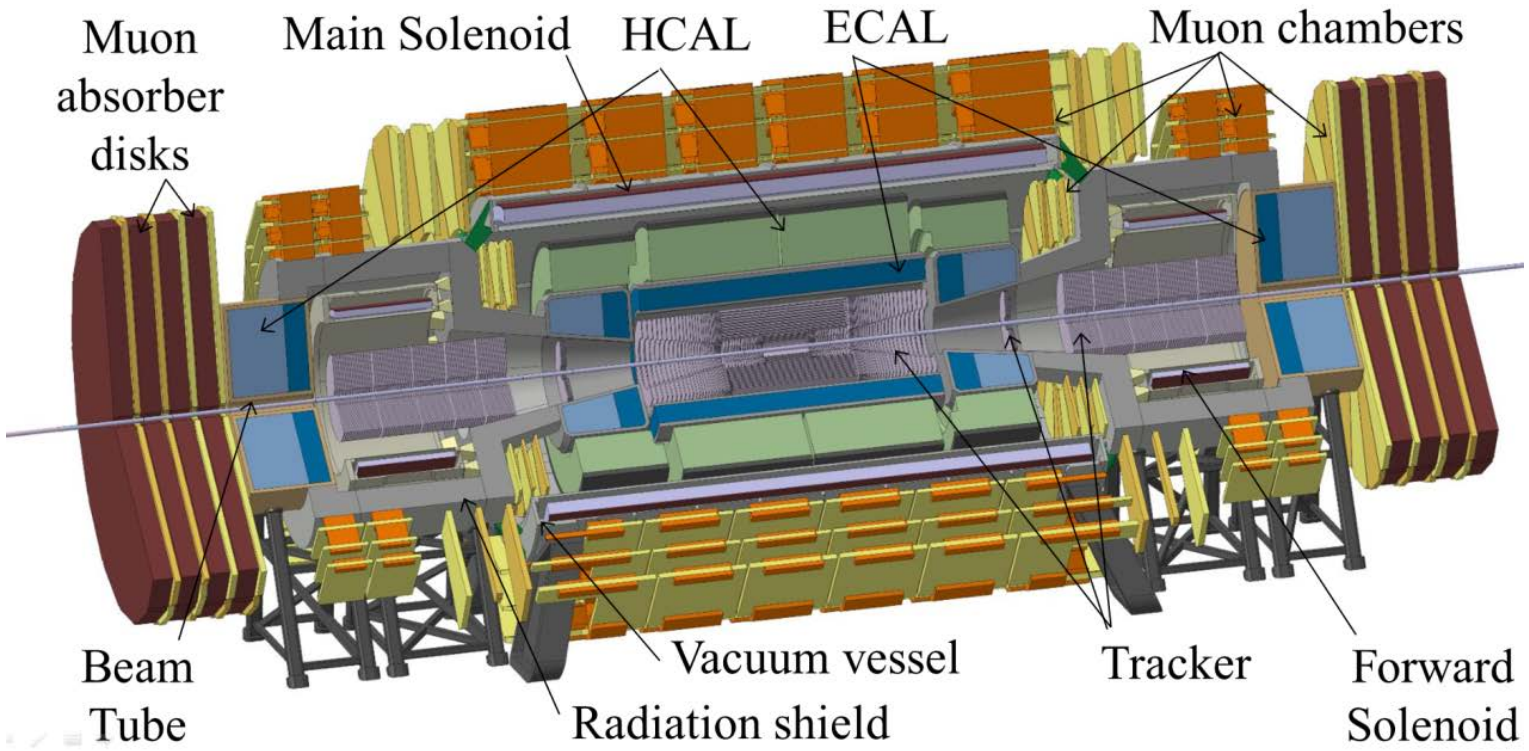


Solenoid + Balanced Forward Solenoids



Solenoid + Forward Solenoids

In 2017: New FCC-hh Detector Baseline



Main solenoid:

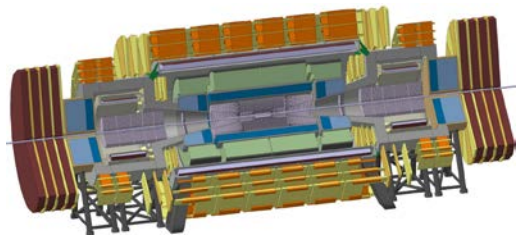
- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) on outside of main and forward solenoids
- Assembly and Services see next talk

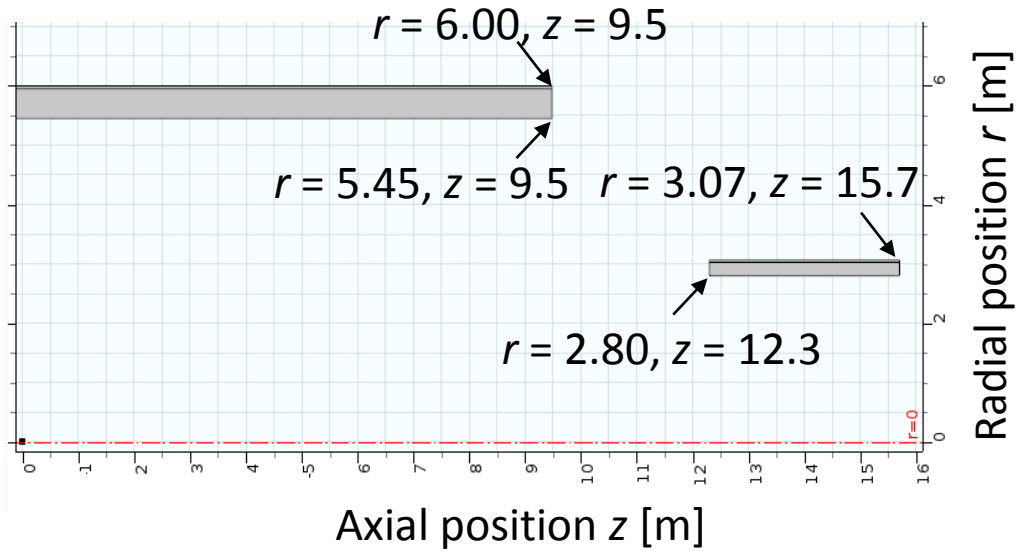
Forward solenoid:

- 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 4T/10m Main Solenoid + 4T/5m Forward Solenoids



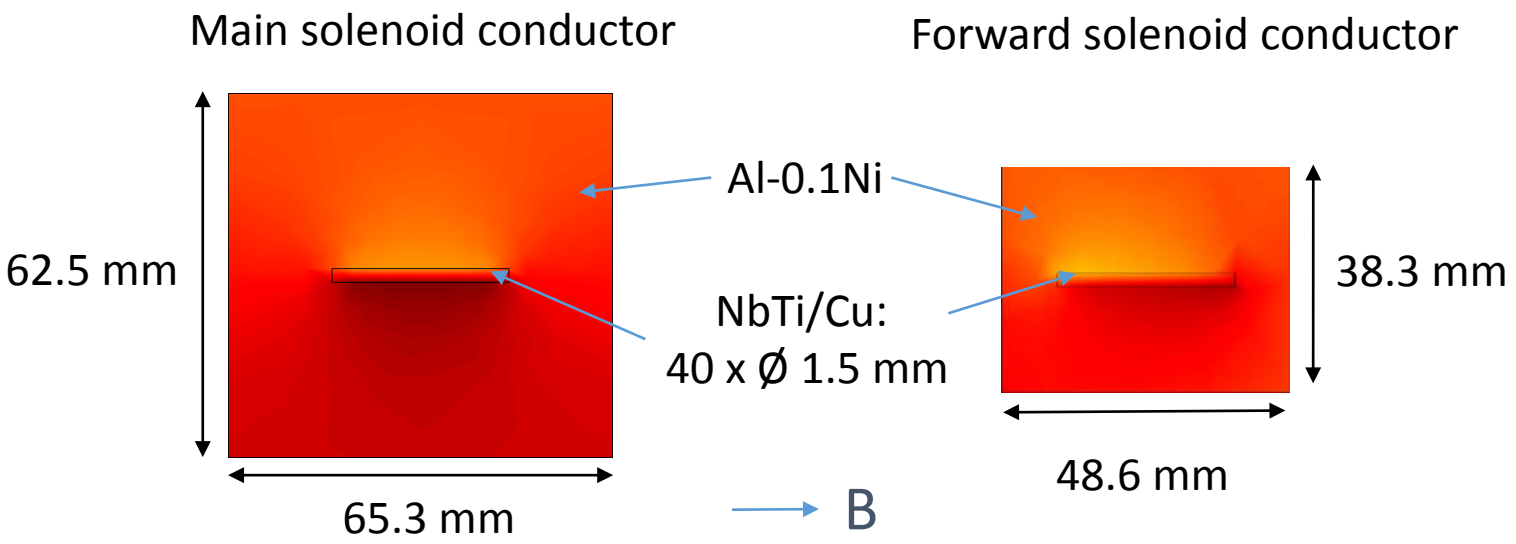


Composition [vol.%]	Main Solenoid	Forward Solenoid
Aluminum	95.4	92.3
Copper	0.8	1.6
Niobium	0.4	0.8
Titanium	0.4	0.8
G10	3.1	4.5

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**

- 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 = 14 GJ
- Cold Mass Energy density = 12 kJ/kg

“Super” - Conductor assumed in baseline design



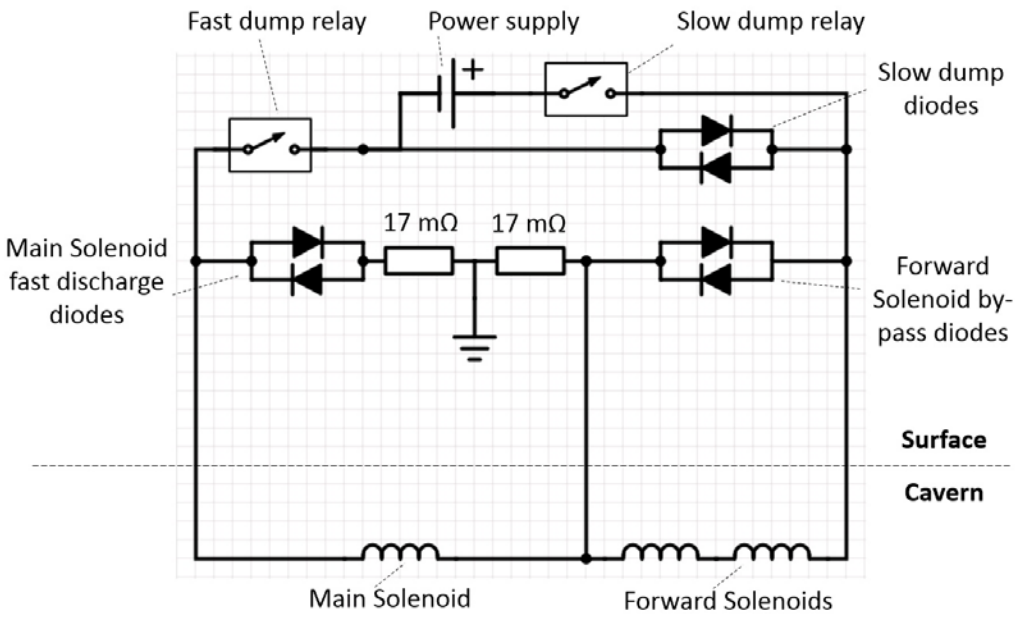
	Main Solenoid	Forward Solenoid
Current [kA]	30	30
Self-inductance [H]	28	0.9
Layers x turns	8 x 290	6 x 70
Total conductor length [km]	83	2 x 7.7
Bending strain [%]	0.57	0.68

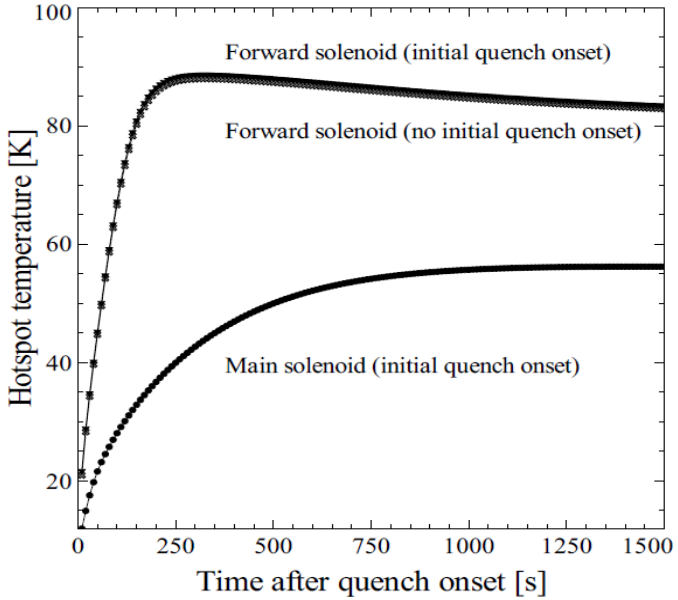
Aluminum-stabilized Rutherford conductors for 30 kA nominal

- 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

- 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, still safe

Cryostat and heat loads

Heat loads:

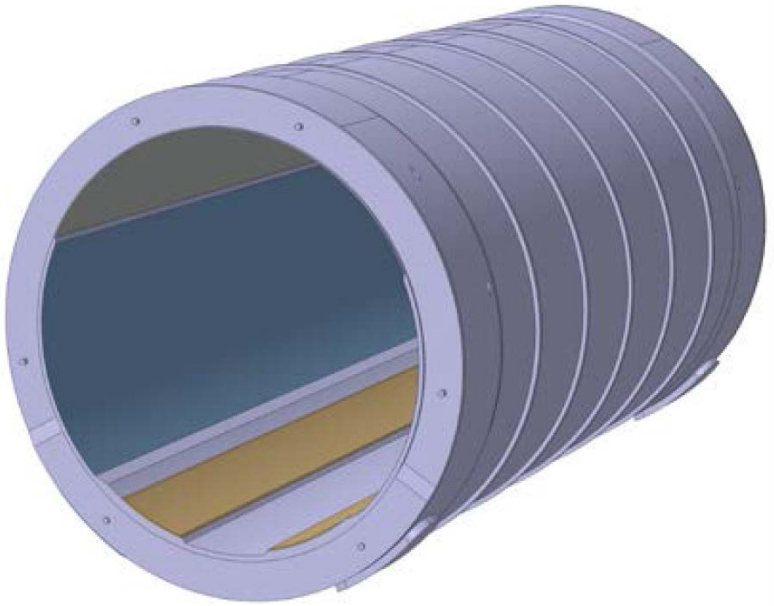
- Radiation: 360 W on cold mass, 6.8 kW on thermal shields
- Tie rods (Ti6Al4V rods, thermalized at 50 K):
  20 W on cold mass, 1.4 kW on 50 K thermalization points
- Acceptable heat load in tie rods, despite 60 MN net force on forward solenoids

Materials and mass:

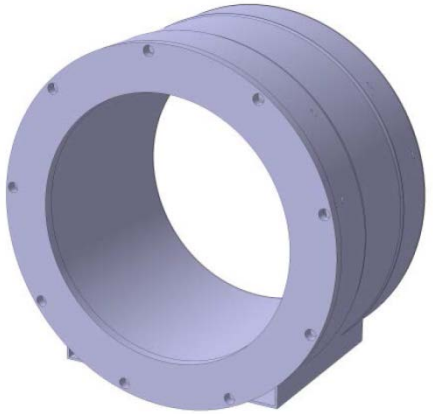
- Main solenoid cryostat: SS 304L (high strength, minimal space), 875 t
- Forward solenoid cryostat: Al 5083-O (for minimal mass), 32 t
- Total solenoid weights: Main 2 kt, forward 80 t (each)

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

4. 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**

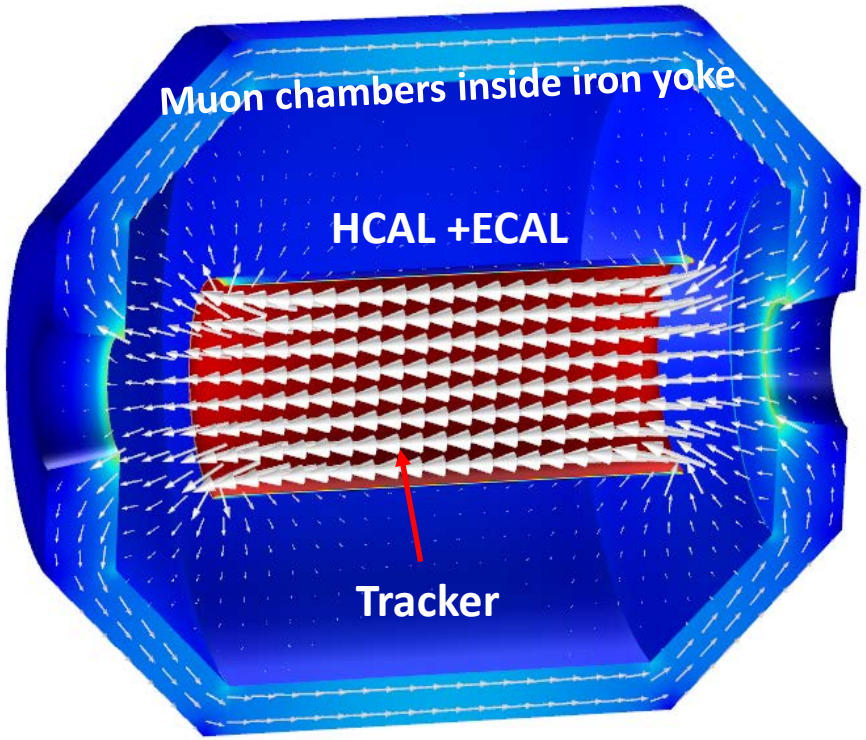
Use an iron yoke (6 kt) for returning flux

- 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

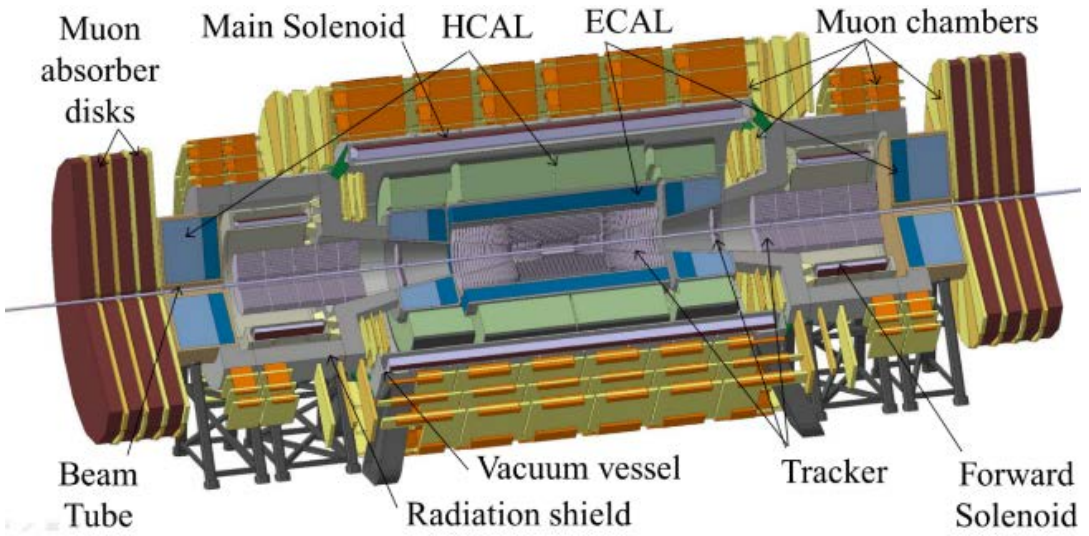
R&D currently in progress (2 PhDs) for maximum transparency of conductor, cold mass and cryostats, for FCC-hh and FCC-ee as well!



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

5. Conclusion & Outlook

- ✓ After 3 years of iterations on physics requirements **a final baseline design for the FCChh Detector 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 the Conceptual Design Report in 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 for high-pseudorapidity particles
  - Designs made for cold mass, vacuum vessel, cryogenics, electrical circuits, quench protection, et cetera. No show-stoppers identified
- ✓ An R&D program for engineering critical parts of the system is being prepared for the next step