HE-LHC and FCC Detector Magnets for eh, ee and hh collisions

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1. LHeC-CDR Detector magnet design, a reminder
2. Adjustments for eh versions for HL-LHC and FCC
3. Example FCC-ee detector magnet
4. Evolution of FCC-hh detectors
5. Conclusion

1. LHeC, magnets at the eh interaction region

Beams in interaction region:

3 beams: e + p1 + p2, also heavy ions

Obviously a Solenoidal Detector Magnet is present

but also

Dipole magnets are required around the collision point:

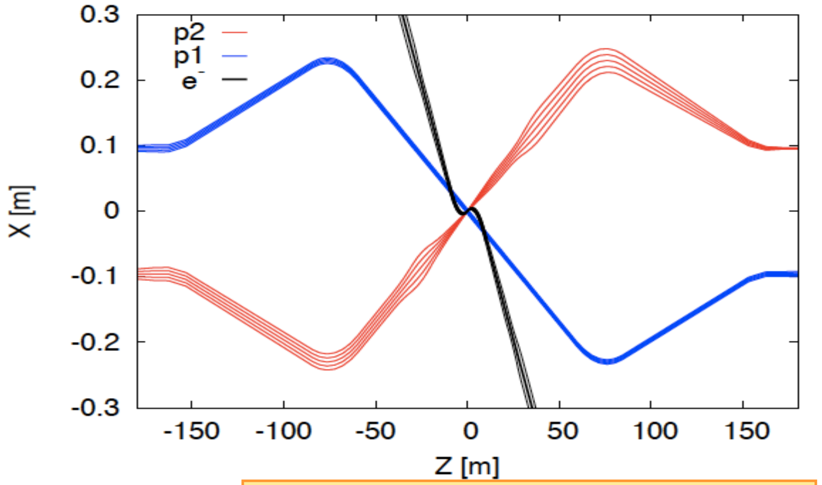
- to guide the e-beam in and out
- for making electrons to collide head-on with *p-beam 2*
- to safely extract the distorted electron beam

Solution:

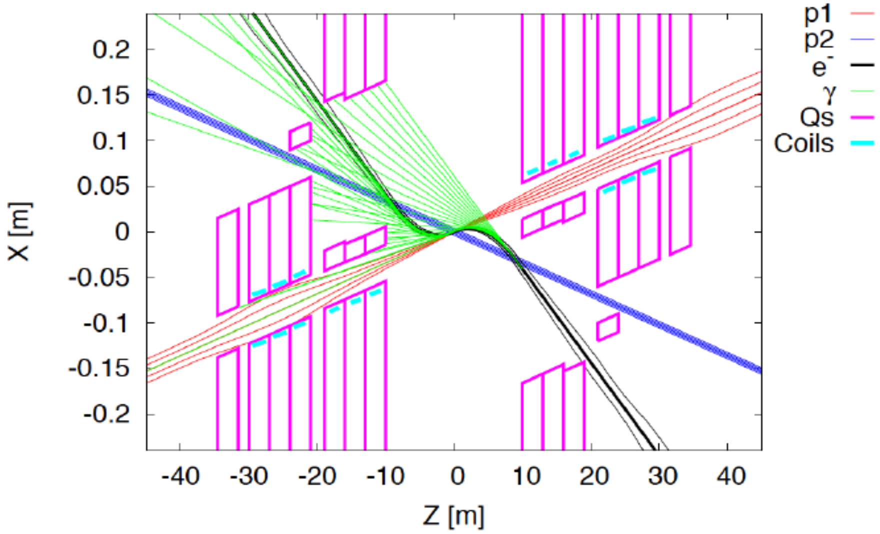
Detector Solenoid making some 3-4 T

2 dipole magnets making some 1 Tm (LHeC)

0.3 T transverse field along 2 x 9 m (LHeC)

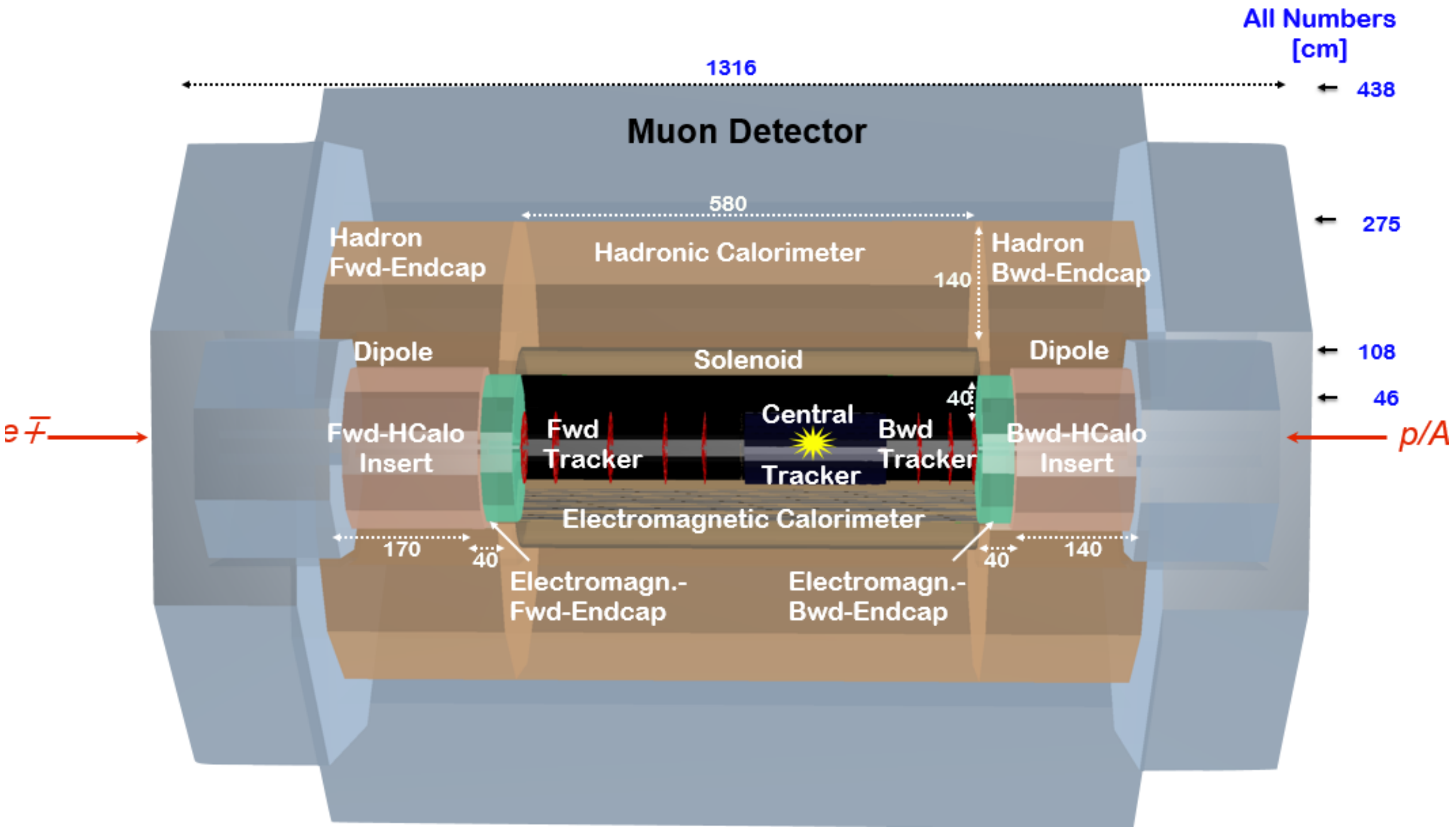


3 beams, head-on collisions



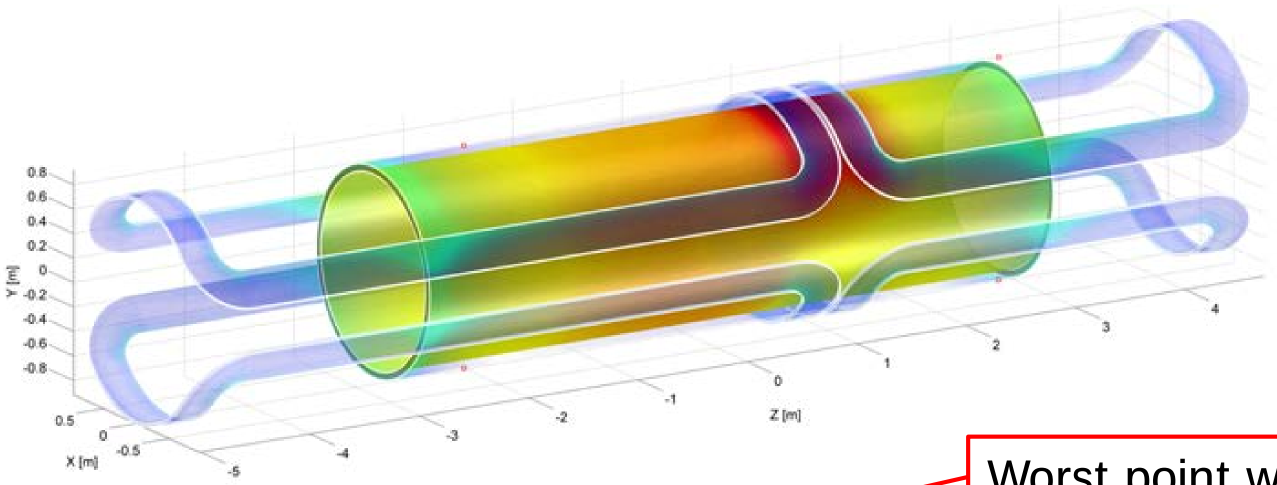
0.3T dipole field to allow head-on collision

LHeC Detector Magnet layout, CDR baseline

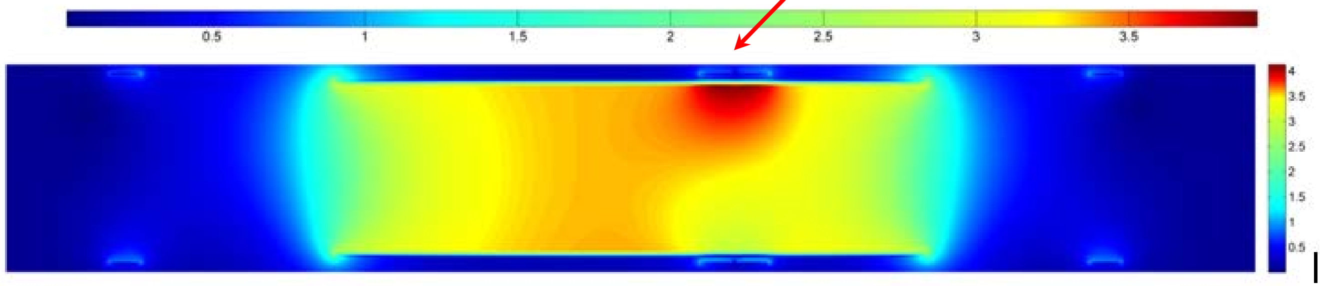


- Design concept: minimum cost, minimize R&D and risk, thus rely on present technology for detectors, magnets and infrastructure
- 3.5 T Solenoid and 2 Dipoles in same cryostat around the EMC
- Muon tagging chambers in outer layer

Magnetic field in Solenoid and Dipoles



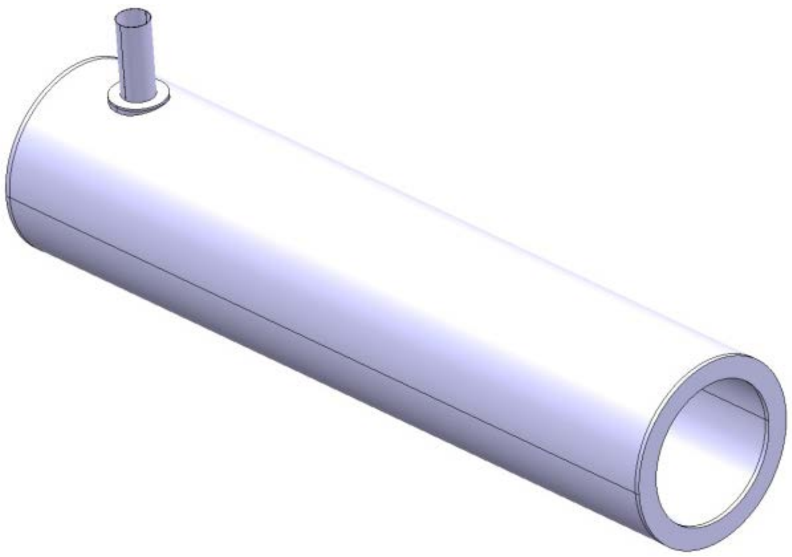
Worst point with peak magnetic field 3.9 T



- LHeC detector for the Linac-Ring option, the positions of the 3.5 T solenoid and the 0.3 T inner superconducting dipole sections.
- 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.

Solenoid and Dipoles in single Cryostat

Turret for services connections

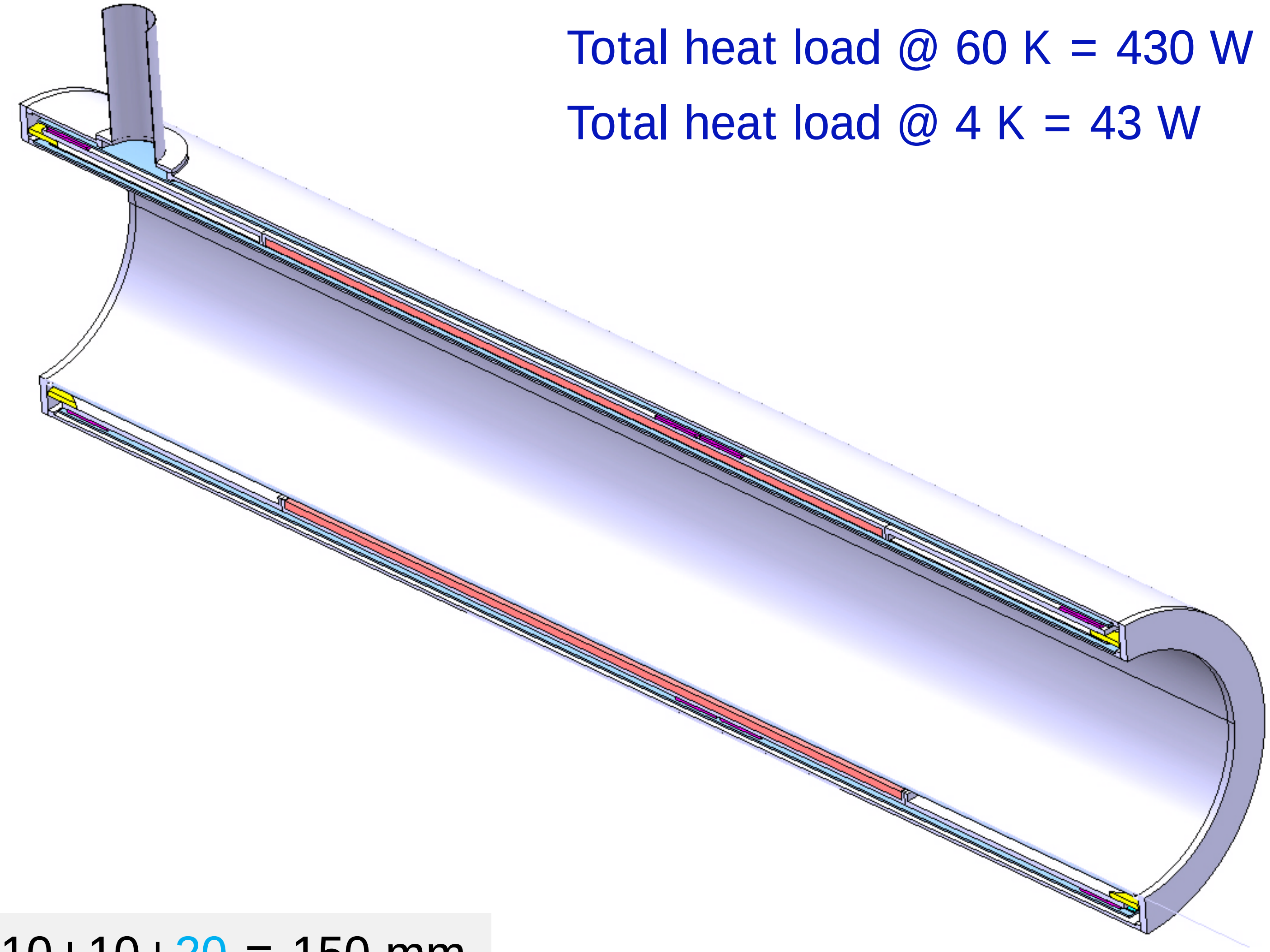


Length 10.2 m

Free bore 1.8 m

Outer diameter 2.35 m

Mass 24 t



Total heat load @ 60 K = 430 W

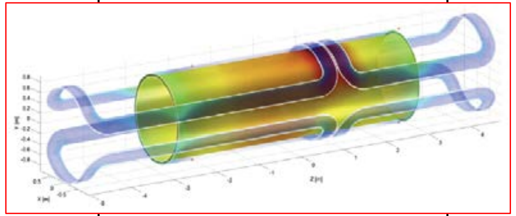
Total heat load @ 4 K = 43 W

Total Aluminum thickness: 10+10+60+30+10+10+20 = 150 mm

May be reduced to 135-140 mm with some effort

Solenoid parameters

Property	Parameter	value	unit
Dimensions	Cryostat inner radius	0.900	m
	Length	10.000	m
	Outer radius	1.140	m
	Coil windings inner radius	0.960	m
	Length	5.700	m
	Thickness	60.0	mm
	Support cylinder thickness	0.030	m
	Conductor section, Al-stabilized NbTi/Cu + insulation	30.0×6.8	mm^2
	Length	10.8	km
	Superconducting cable section, 20 strands	12.4×2.4	mm^2
	Superconducting strand diameter Cu/NbTi ratio = 1.25	1.24	mm
Masses	Conductor windings	5.7	t
	Support cylinder, solenoid section + dipole sections	5.6	t
	Total cold mass	12.8	t
	Cryostat including thermal shield	11.2	t
	Total mass of cryostat, solenoid and small parts	24	t
Electro-magnetics	Central magnetic field	3.50	T
	Peak magnetic field in windings (dipoles off)	3.53	T
	Peak magnetic field in solenoid windings (dipoles on)	3.9	T



- Coil technology is based on Al-stabilized NbTi conductors, conduction cooled at around 4.6 K, as the ATLAS Solenoid.

Solenoid parameters

	Nominal current	10.0	kA
	Number of turns, 2 layers	1683	
	Self-inductance	1.7	H
	Stored energy	82	MJ
	E/m, energy-to-mass ratio of windings	14.2	kJ/kg
	E/m, energy-to-mass ratio of cold mass	9.2	kJ/kg
	Charging time	1.0	hour
	Current rate	2.8	A/s
	Inductive charging voltage	2.3	V
Margins	Coil operating point, nominal / critical current	0.3	
	Temperature margin at 4.6 K operating temperature	2.0	K
	Cold mass temperature at quench (no extraction)	~ 80	K
Mechanics	Mean hoop stress	~ 55	MPa
	Peak stress	~ 85	MPa
Cryogenics	Thermal load at 4.6 K, coil with 50% margin	~ 110	W
	Radiation shield load width 50% margin	~ 650	W
	Cooling down time / quench recovery time	4 and 1	day
	Use of liquid helium	~ 1.5	g/s

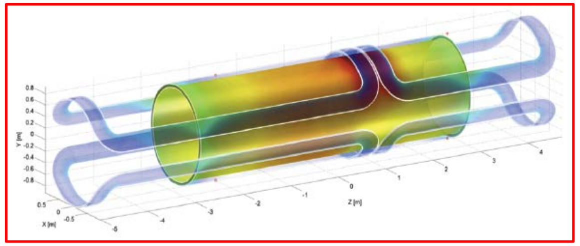
- Numbers are conservative!
- No critical issues are envisaged with the construction of this solenoid.

Twin-dipoles specification

Table 4.2 Main design parameters of the set of superconducting electron beam bending dipoles

	Long dipole coil	Short dipole coil	
Magnetic field on axis	0.3		T
Peak magnetic field in windings (solenoid off)	0.7		T
Peak magnetic field in windings (solenoid on)	2.6		T
Dipole length (including external sections)	9.0		m
Field integral internal section (sc dipole)	1.6	1.0	Tm
Field integral external section (iron magnet)	1.1	1.7	Tm
Operating current	2.0		kA
Stored Energy	1.9	1.2	MJ
Coil inductance	0.95	0.61	H
Windings engineering current density	55	55	A/mm^2
Coil inner / outer radius	1.042 / 1052		m
Coil length	6.00	3.70	m
NbTi/Cu cable (12 strands Rutherford cable)	1.44 x 4.31		mm^2
Conductor length	5.4	3.6	km

- Dipoles have classical NbTi windings, 2 kA cable.
- Force by solenoid on dipole windings look doable with proper support and qualification test.



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, an efficient coil

- 1.8 m free bore, 7.1 m long (~ 8 m external size)
- ~ 11 km Al stabilized NbTi/Cu superconductor for 10 kA
- ~ 80 MJ stored energy
- ~ 24 t mass including cryostat.

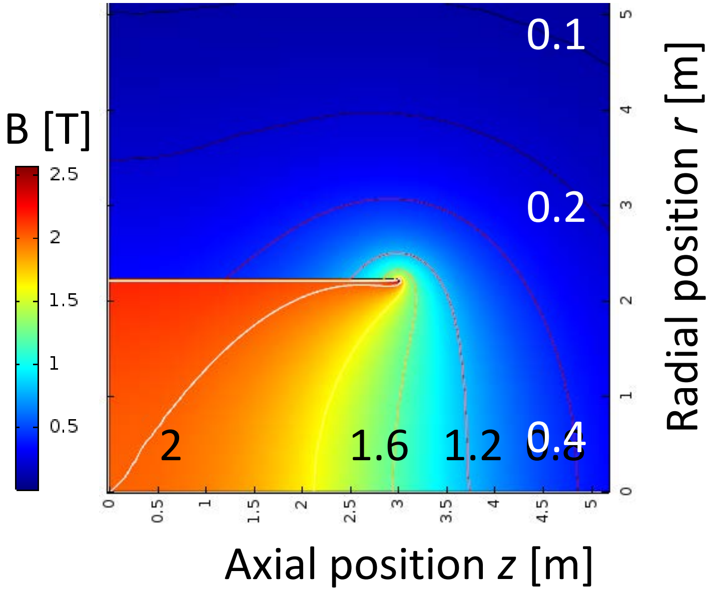
Specs for LHeC, LHeC+, HL-LHC, FCC-eh

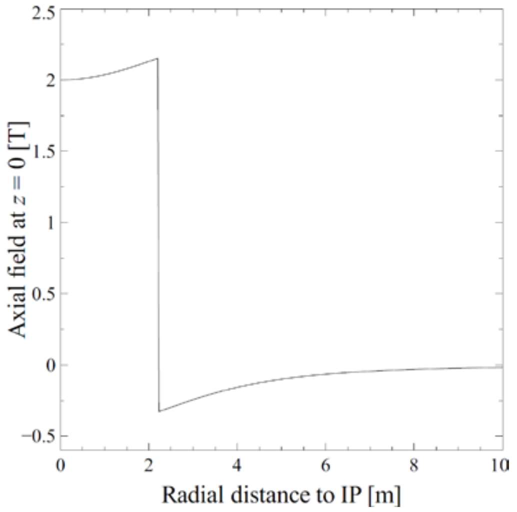
- Main parameters of the coils in the 4 he detectors (A.Polini, Sep 6, 2017 2017)

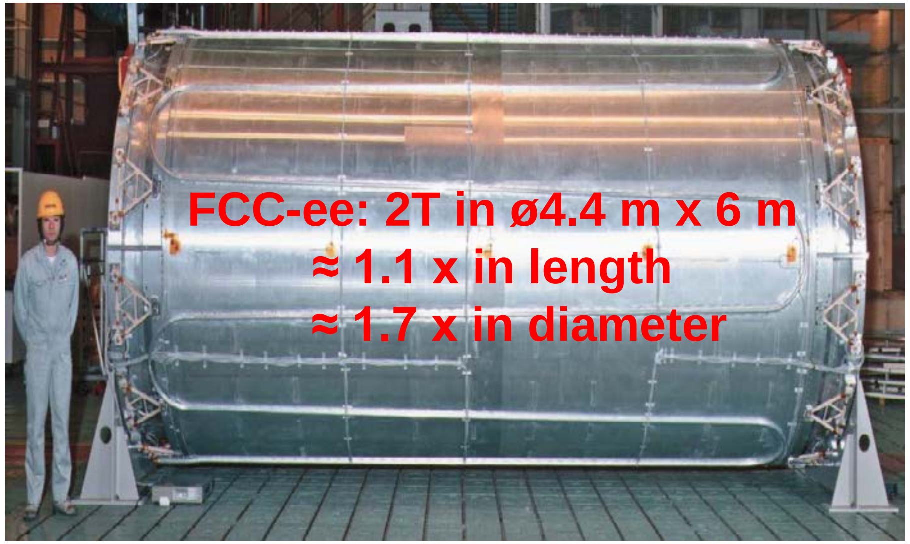
	LHeC(2014)	LHeC+	HE-LHeC	FCC he
Function	CDR design	For comparison	For HE-LHC	For FCC
Location	P2	P2 with L3 magnet	P2 with L3 magnet	Point L
B_solenoid [T]	3.5	3.5	3.5	3.5
B_dipole [T]	0.3	0.3	0.3	*0.15*
Dipole layout	along entire detectors	along entire detectors	along entire detectors	along entire 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

- *Increasing system bore and length*
- For 2028 HE-LHC/FCCeh CDR we need to adjust the designs to these new specs
- Looks all doable!

2. FCCee 2T "thin" solenoid inside HCAL







- 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.%) + G10 (13 vol.%)

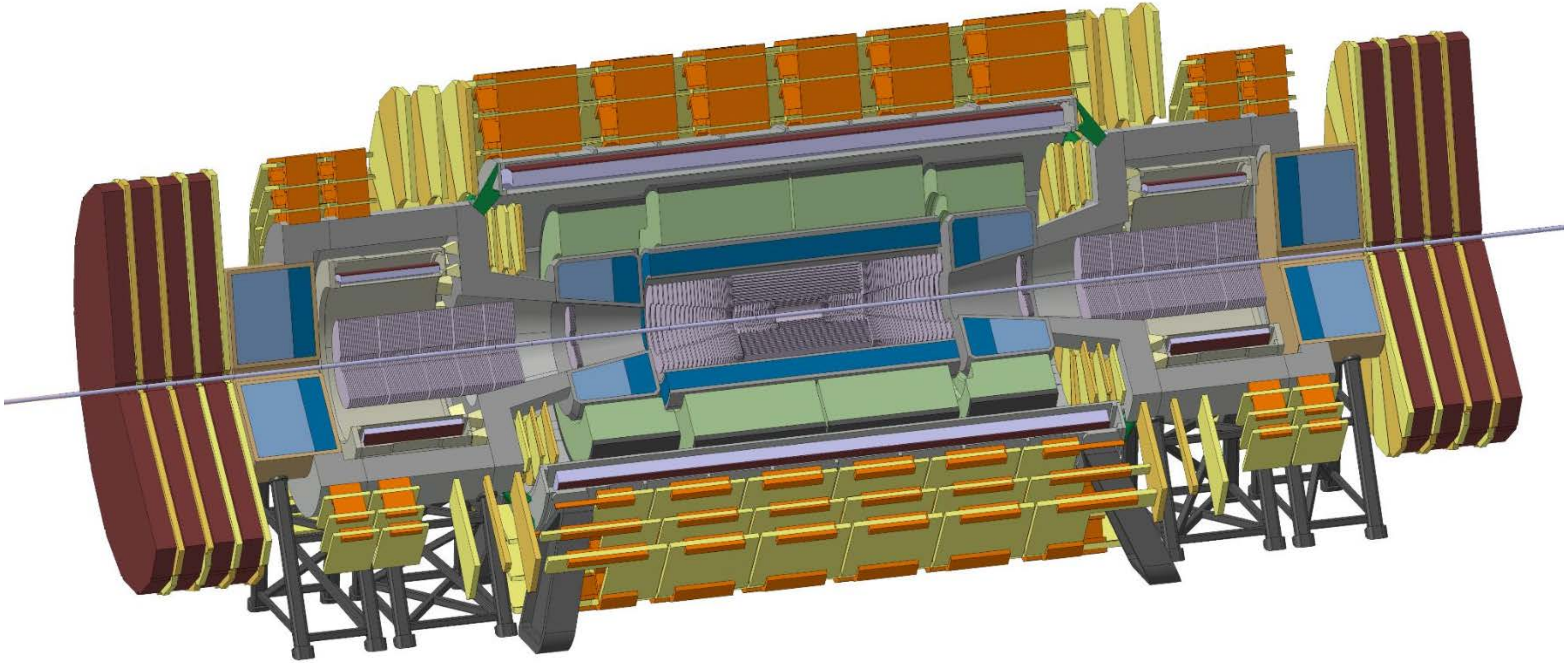
Radiation thickness:

- Cold mass: X_0 = 0.46, λ = 0.09
- Vacuum vessel (25 mm Al): X_0 = 0.28, λ = 0.07
- **Total: X_0 = 0.74, λ = 0.16 (at η = 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. Detector Magnets for 100 TeV FCC hh

- **Evolution and Baseline Design -**



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:

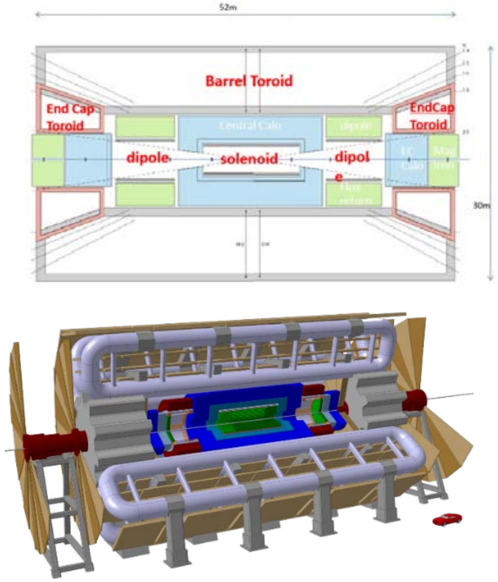
- Define CMS+ and ATLAS+ designs, but for 100 TeV
- And add magnets in forward directions for 10 Tm (dipoles, solenoids)
- For same tracking resolution, same σ, BL^2 has to go up by factor 7, in combination with thicker calorimeter, this leads to a 6T/12m bore solenoid
- Similar arguments for a toroid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

Cure:

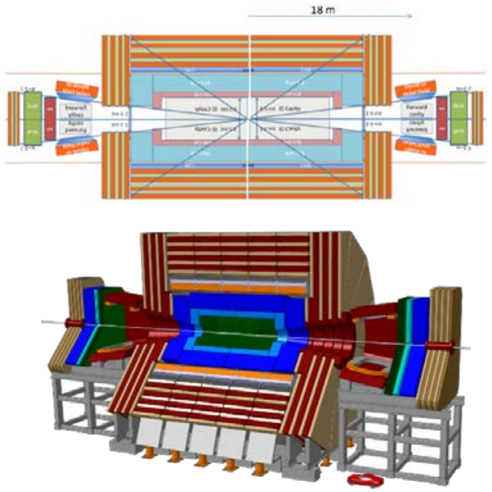
- Standalone muon tracker not needed **--> drop toroid design, define 1 detector**
- Assume higher tracker resolution, expected well possible (factor ≈3) **--> less BL^2**
- Limit calorimeter depth, not 12 but 11λ **--> less radial thickness**
- Accept no magnetic shielding (cavern at -300 m) **--> no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

Result:

✓ **New baseline design for CDR 2018**

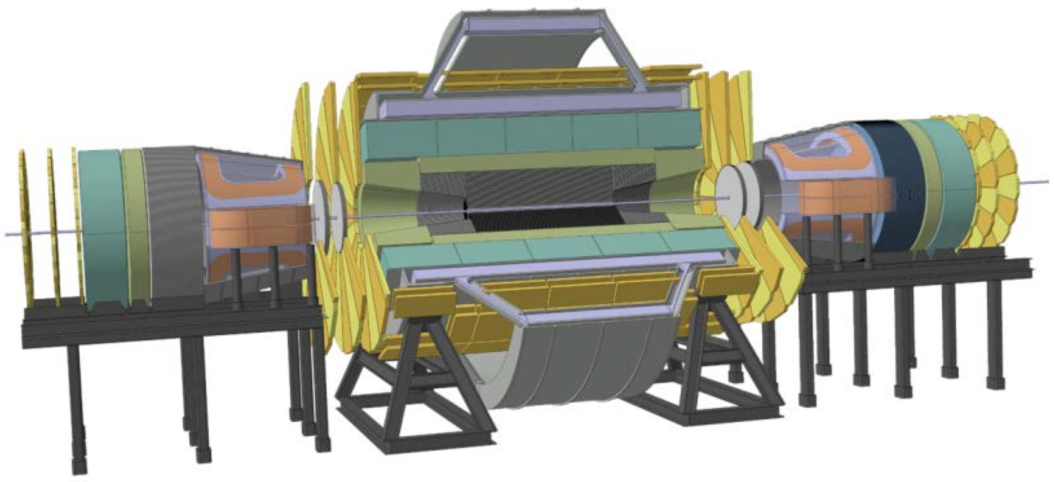


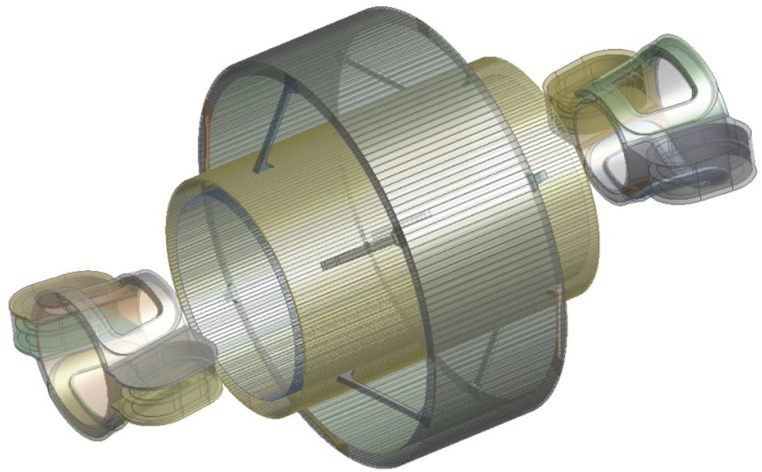
1st ATLAS+ sketch and design



1st CMS+ sketch & design

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





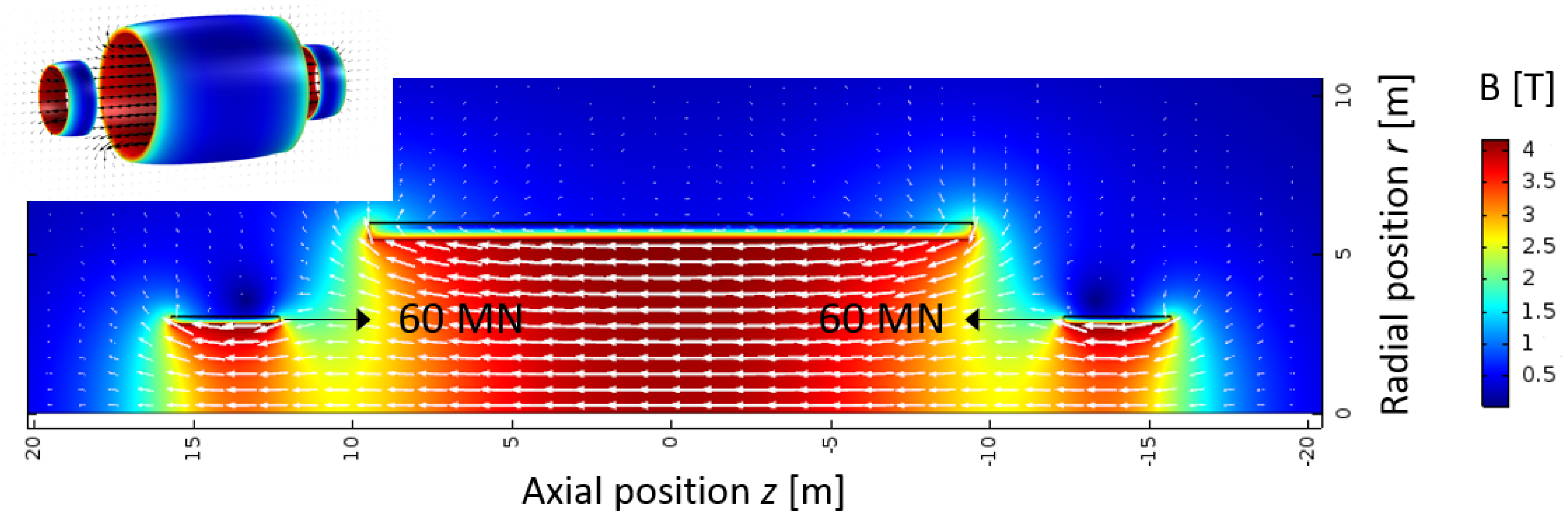
Concept:

- 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

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

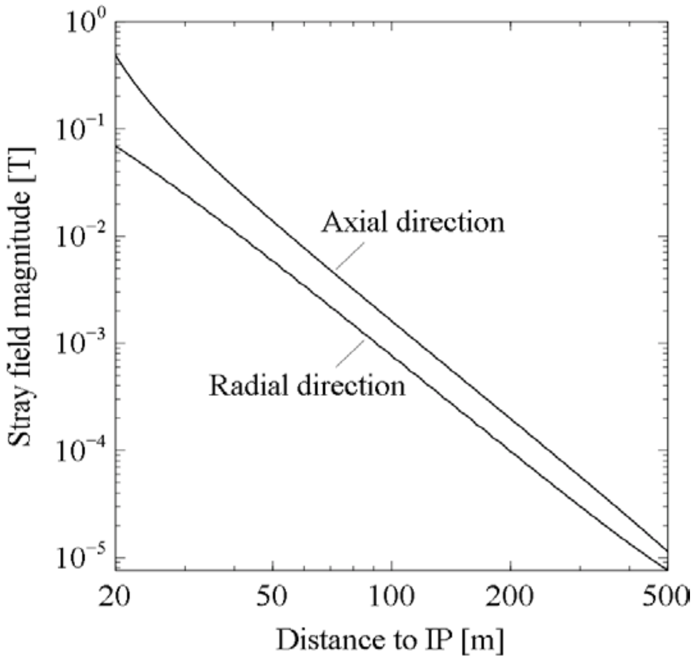


Concept:

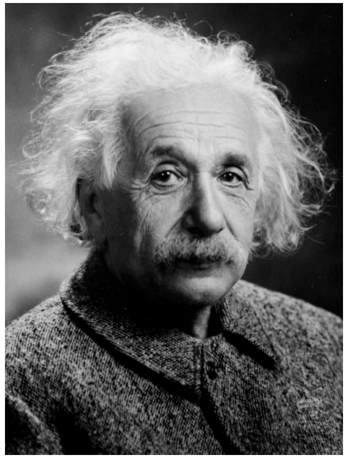
- 4 T in 10 m free bore
- Removal of outer forward solenoids, magnetic shielding not required
- 60 MN net force on forward solenoids handled by axial tie rods

Result:

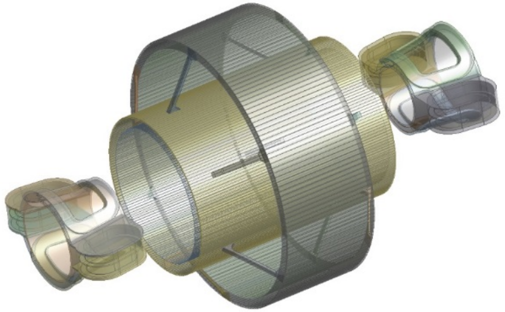
- **Stored energy: 13.8 GJ**
- Lowest degree of complexity from a cold-mass perspective
- But: with significant stray field



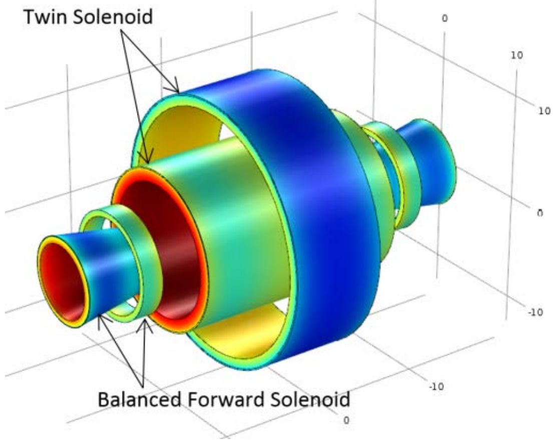
Design evolution of the FCChh detector magnet baseline



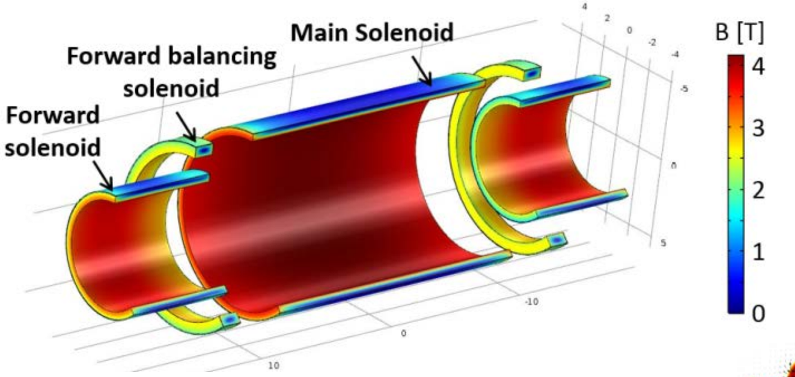
Everything should be made as simple as possible, but not simpler (Quote attributed to Einstein)



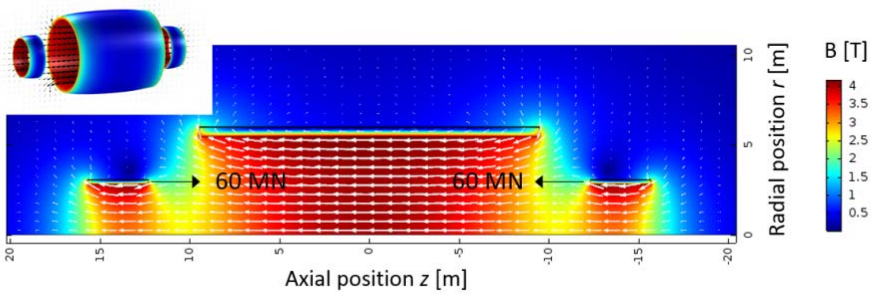
Twin Solenoid + Balanced Forward Dipoles



Twin Solenoid + Balanced Forward Solenoids



Solenoid + Balanced Forward Solenoids

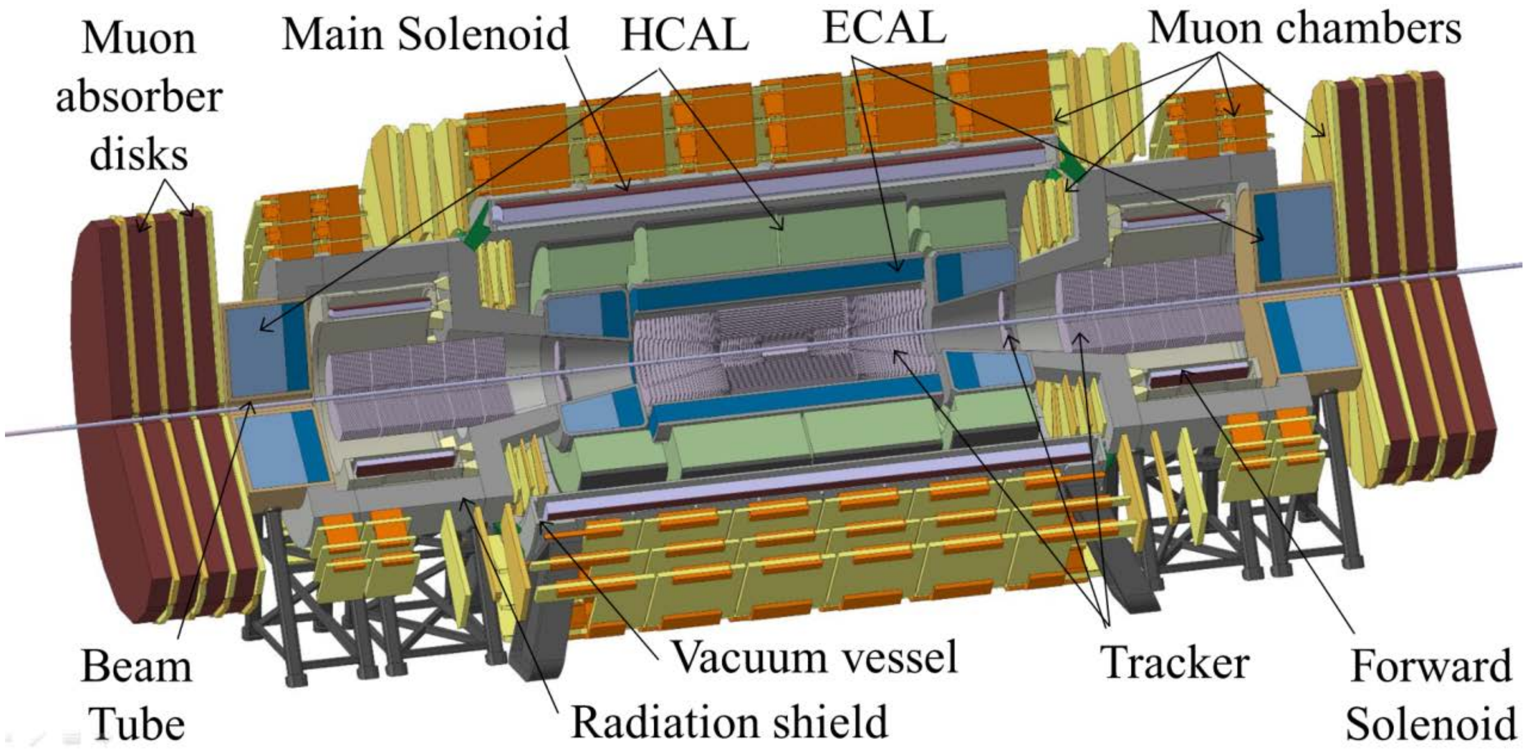


Solenoid + Forward Solenoids

Design evolution towards:

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

2017: New FCC-hh Detector Baseline for 100 TeV collisions



Main solenoid:

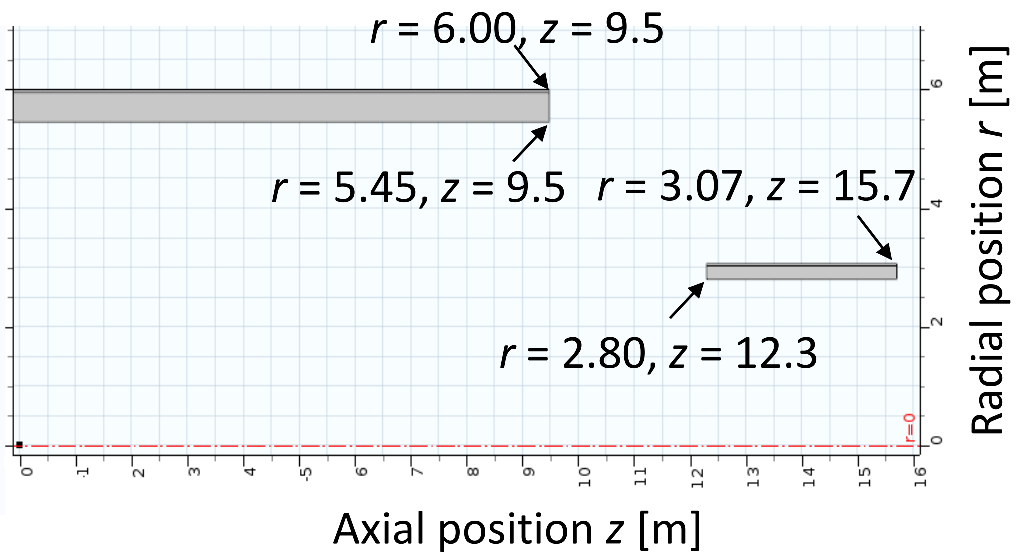
- Trackers and calorimeters inside bore, supported by the bore tube
- Muon chambers (for tagging) on outside of main and forward solenoids
- Assembly and Services see next talk

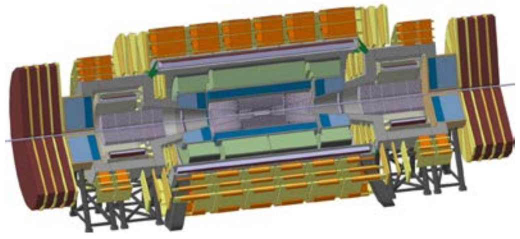
Forward solenoid:

- 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 m³ cold mass [kg/m³]	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

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**

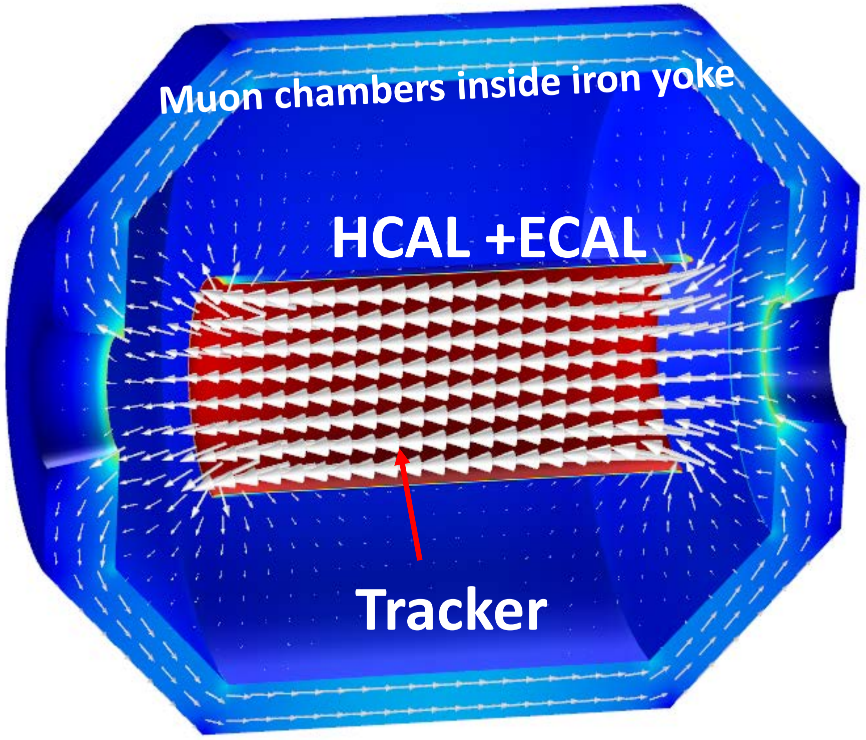
Use an iron yoke (6 kt) for returning flux

- 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

- Conceptual design of the magnet system for 2014-CDR-LHeC completed aiming at lowest cost, low risk, relatively fast production allowing fast readiness.
- A 3.5 T Solenoid, 1.8 m bore, 10 m long, is combined with the necessary 0.3 T, 2x9 m long dipoles to guide the electron beam.
- For LHeC, next, this CDR design will be adjusted to meet the HE-LHeC and FCCeh parameters.
- For FCC-ee, the design of the 2T, 4.4m bore and 6m long FCCee Solenoid was presented.
- Most advanced: the FCC-hh the design evolution was presented, after 3 years resulting in the accepted baseline design of a 4T, 10m bore, 19m long Main Solenoid with 4T forward Solenoids.