Superconducting Detector Magnets Baseline Designs for Particle Physics Experiments at the Future Circular Collider

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***Abstract*—In early 2014 a design study started at CERN for a Future Circular Collider. A new tunnel with a circumference of about 100 km for the collider magnets is foreseen as well as new general-purpose particle detectors to probe electron–positron (e^-e^+), electron–hadron (eh), and hadron–hadron (hh) collisions, housed in large underground caverns. In the last four years baseline designs for the various detector magnets were developed. For the FCC-ee detector two magnet variants were defined: a 7.6-m bore and 7.9-m-long classical 2 T solenoid with 600 MJ stored energy, surrounding the calorimeters, and also a very challenging 4-m bore, 6-m-long, some 100-mm-thick ultrathin and radiation transparent 2 T solenoid with a stored energy of some 170 MJ, that surrounds only the inner tracker of the detectors. For the FCC-eh detector, the detector solenoid is combined with forward and backward dipole magnets required to guide the electron beam in and out of the collision point. This detector requires a 3.5 T solenoid, 2.6-m free bore and 9.2-m length with about 230 MJ of stored energy. Most demanding is the FCC-hh detector with a 14 GJ stored energy magnet system comprising three series connected solenoids, requiring 4 T in the main solenoid with 10-m free bore and a length of 20 m, in line with two 3.2 T forward solenoids with 5.1-m free bore and 4-m length. A quite challenging series of detector magnets is proposed, that needs to be further engineered in the coming years. The superconductor technology though is essentially the same in all the solenoids proposed: conductors comprising Rutherford type cables made of NbTi/Cu strands, stabilized by nickel doped pure aluminum and structurally reinforced with a high yield strength aluminum alloy. The cold masses are conduction cooled through helium cooling pipes welded to their outer support cylinder. The designs of the various baseline magnets as well as their engineering are presented.**

***Index Terms*—Detector magnet, solenoid, FCC, forward dipole magnets, forward solenoids.**

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I. Introduction

THE European Strategy Update for particle physics from 2013 foresees a Conceptual Design Report (CDR) for the Future Circular Collider (FCC) in 2019. Conceptual designs for both viable accelerators and new high-tech detectors are investigated [1]. The proposed center of mass energy of proton-proton collisions at the FCC-hh machine of 100 TeV is up to 7 times the nominal collision energy of the world's presently largest accelerator, the LHC at CERN. A staged approach may be followed, by which first an electron-positron (e^-e^+) machine is used for precision measurements, which may then later be replaced by a proton-proton (hh) machine, to be installed in the same 100 km long circular tunnel, similarly to the LEP-LHC approach, successfully followed at CERN. A dominating part of detector designs and performances are their magnet systems, required for precise momentum measurements. Proven superconducting magnet concepts for collider experiments are mostly based on solenoids or toroids, like in the CMS [2] and ATLAS [3]–[7] experiments at CERN, respectively. At higher collision energy, precise momentum measurements become more difficult, since the newly created particles emerging from the collision point are more difficult to bend. With new generation detectors a better tracker resolution is assumed, but this still needs to be combined with an as-high-as-possible magnetic field over a longer tracking length leading to ever increasing detector volumes. This follows directly from equation 1 [8], where the relative transverse momentum resolution is given. It shows that the error of the transverse momentum can be reduced by either measuring more precisely (resolution of used detectors) or by increasing the double field integral BL^2, which is a direct measure of the sagitta of a particle track [9]:

$$\frac{\sigma\left(p_T\right)}{p_T} = \frac{\sigma\left(\kappa\right)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}} \quad (1)$$

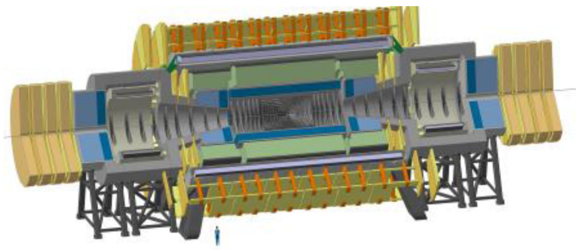

Fig. 1. Baseline FCC-hh detector. From the center in radial direction, several distinct layers can be distinguished: inner tracker, electromagnetic calorimeter, hadronic calorimeter, main solenoid, muon chambers. In the forward direction a similar scheme is applied.

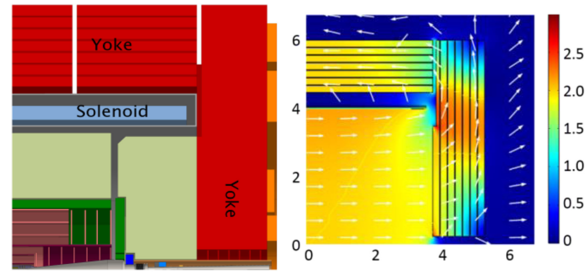

Fig. 2. (left) Schematic top-right-quarter-longitudinal-section of the CLD detector elements with the interaction point (IP) at the bottom left. (right) Corresponding magnetic field map for the CLD detector; arrows indicate the direction of the magnetic induction.

with B the magnetic field in T, L the length of the particle track in the field in m, p_T the transverse momentum in kg.m/s and N the number of measurement points. Evidently, a high magnetic field covering a large volume is required, hence the large size of particle detectors for high energy physics. To have an effective magnet, delivering perpendicular magnetic field, a solenoid or toroid is most efficient, see Fig. 1.

II. FCC-ee Baseline Designs

A. CLD Magnet System

Two detector concepts are proposed for the FCC-ee machine: CLD (CLIC Like Detector) and IDEA (International Detector for Electro-positron Accelerator) [10]–[12]. For both detector concepts, a 2 T solenoidal magnetic field is foreseen. The magnet systems are however very different in nature [13]. The proposed magnet system for CLD is a conventional solenoid, installed around the calorimeters and therefore it mechanically acts as a support structure for the calorimeters as well as for the inner tracker. Besides delivering the required magnetic field inside the inner tracker volume, it also generates magnetic field inside the calorimeter volume, where it is actually not required, nor useful. An iron return yoke is present to concentrate the magnetic field lines at the position of the muon detectors on the outside of the experiment and to reduce the stray magnetic field. Since this is a conventional superconducting solenoid, no extraordinary technical challenges or innovative solutions are necessary to obtain a robust design. The magnet system is strongly based on the ILC/CLIC systems, which are in turn based on proven concepts, like the CMS experiment at CERN's LHC.

Fig. 2 gives an overview of the detector geometry and is accompanied by the magnetic field map. In Table I the magnet's most important design parameters are summarized. Note that **the large difference in current density between Rutherford cable** and conductor is caused by the relatively large fraction of Al stabilizer coextruded with the cable (see Table I and II).

TABLE I
Design Parameters of the FCC-ee CLD Detector. Two Versions Shown Following Two Different Operating Currents

Cryostat length, IR, OR (m)	7.4, 2.7, 4.4
Cryostat mass (t)	71 (Al) / 114 (ss)
Cold mass length, IR, d (m)	7.0, 4.02, 0.09
Cold mass (t)	44.1/43.8
Support cylinder thickness (mm)	40
Conductor dimensions (mm)	17.0 / 11.3 × 50.0
Conductor length (km)	10.5 / 15.8
# layers, # turns	1, 412 / 618
Magnetic field at IP, the interaction point (T)	2.0 *
Operating current (kA)	20.0 or 30.0
Stored energy (MJ)	470 + 130 in M **
Self-inductance (H)	2.36 or 1.05
Strand diameter (mm), # strands	1.00 or 1.20, 24
Current density (A/mm^2) in cable / conductor	2280 / 35.3
Peak magnetic field on conductor (T)	2.15
Operating temperature / margin (K)	4.5 / 2.0

*The number of ampere-turns are chosen such that in combination with the magnetic material of the yoke, the 2.0 T design magnetic field at the IP is reached. The contribution of the magnetization M of the yoke of 0.55 is included in the 2.0. The field purely due to the current carrying conductors is 1.45 T.
**130 MJ is the contribution of the iron magnetization M to the stored energy.

TABLE II
Design Parameters FCC-ee IDEA

Cryostat length, IR, OR (m)	6.0, 2.1, 2.4
Cryostat mass (t)	7.4
Cold mass length, IR, d (m)	5.7, 2.235, **0.03**
Cold mass (t)	7.0
Support cylinder thickness (mm) *	-
Conductor dimensions (mm)	10.4 × 30.0
Conductor length (km)	7.8
# layers, # turns	1, 550
Magnetic field at IP (T)	2.0 **
Operating current (kA)	20.0
Stored energy (MJ)	160 + 4 in M ***
Self-inductance (H)	0.8
Strand diameter (mm), # strands	1.00, 26
Current density (A/mm^2) in cable / conductor	2020 / 64.3
Peak field on conductor (T)	2.45
Operating temperature / margin (K)	4.6 / 2.0

*The ultra-thin concept avoids the use of a support cylinder, the conductor itself is designed such that it is mechanically robust and self-supporting.
**This includes a 0.1 contribution from the iron yoke magnetization M.
***4 MJ is the contribution of the iron magnetization M to the stored energy.

B. IDEA Magnet System

The proposed magnet system for IDEA is a challenging ultra-thin, light and therefore "radiation transparent" solenoid, installed around the inner tracker and located inside the calorimeters [14]. Besides delivering the required magnetic field

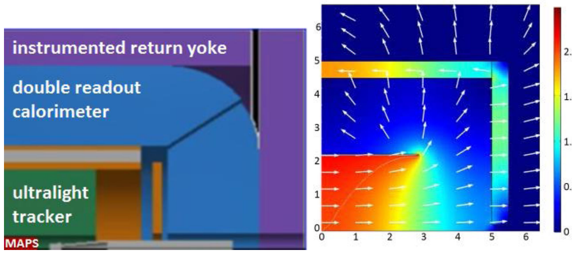

Fig. 3. (left) Schematic top-right-quarter-longitudinal-section of the IDEA detector elements with the interaction point IP at the bottom left. (right) Corresponding magnetic field map for the IDEA detector; arrows indicate the direction of the magnetic induction.

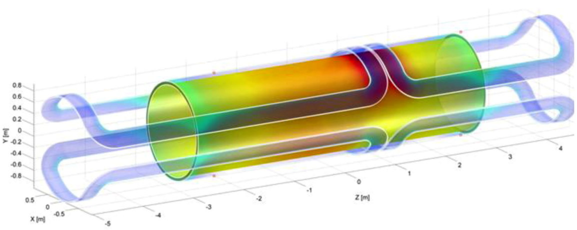

Fig. 4. Configuration of a main detector solenoid, in combination with a forward dipole magnet and a backward dipole magnet for e-beam guiding in the FCC-eh detector; magnetic field values are indicated in Fig. 5.

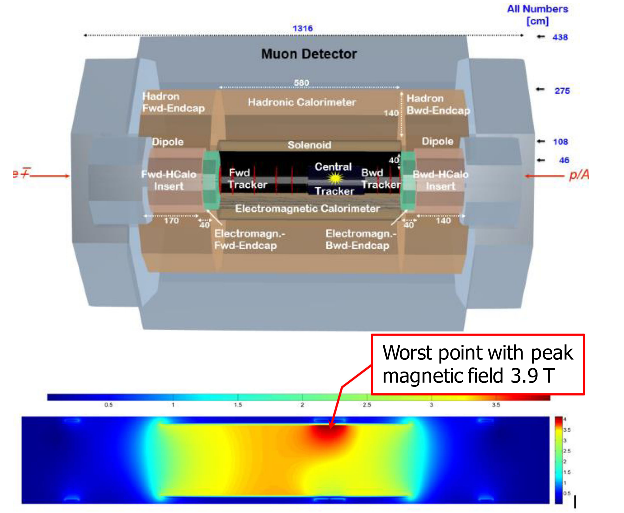

Fig. 5. (top) Schematic longitudinal section of the FCC-eh detector elements. (bottom) Corresponding magnetic field map with the location of the peak magnetic field on the conductor indicated.

TABLE III
DESIGN PARAMETERS LHEC/FCC-EH

	Solenoid	Dipoles short/long
Cryostat length, IR, OR (m)	10.0, 0.9, 1.14	idem
Cryostat mass (t)	24	idem
Cold mass length, IR, d (m)	5.7, 0.96, 0.06	6.00 / 3.70, 1.042, 1.052
Cold mass (t)	12.8	idem
Support cylinder thickness (mm)	30	idem
Conductor dimensions (mm)	6.8 × 30.0	1.44 × 4.31
Conductor length (km)	10.8	5.4 / 3.6
# layers, # turns	2, 841	
Magnetic field at IP (T)	3.5	0.3
Operating current (kA)	10.0	2.0
Stored energy (MJ)	82	1.9 / 1.2
Self-inductance (H)	1.7	0.95 / 0.61
Strand diameter (mm), # strands	1.24, 20	0.72
Current density (A/mm^2) cond./cable	49 / 336	55
Peak magn. field on conductor (T)	3.9	2.6
Operating temperature / margin (K)	4.6 / 2.0	4.6 /2.0

inside the tracker region, it functions as the first absorber layer of the pre-shower detector. Due to its smaller size and stored energy, the cost of the system can be strongly reduced, however, intensive R&D is needed to deliver a magnet following the more restrictive design requirements. From a particle physics perspective, the constraints are strict concerning the material budget at perpendicular incidence. The material budget for the complete magnet, including cold mass and cryostat, should not exceed one radiation length X_0. In contrast to the conventional solenoid, like the one proposed for CLD, where about 80% of the stored magnetic energy is present in the volume occupied by the calorimeters, only the tracker region is effectively foreseen with magnetic field. Large savings are thus expected, namely about a factor of 4.2 in stored energy and about 2 in cost [14]. An overview of the detector geometry and its magnetic field map are given in Fig. 3. In Table II, the IDEA magnet's key design parameters are summarized.

III. FCC-EH BASELINE DESIGN

For the LHC, upgrade plans were developed to have the possibility to generate electron-proton collisions, by introducing an additional linear electron accelerator to the existing LHC accelerator complex [15]. These conceptual studies have been extended in view of FCC-eh, a future electron-hadron collider [16], [17]. Since different particles are now used, an asymmetric design for the detector is proposed. Also the magnet system is asymmetric relative to the interaction point (IP).

Besides a main solenoidal magnetic field, additional magnetic dipole fields are required to guarantee proper beam behavior in the detector region: guiding the e-beam into and out of the collision point, making the e-beam collide head-on with one of the proton beams and to safely extract the distorted electron beam. The conceptual design therefore foresees a combination of a main detector solenoid with a forward dipole magnet and a backward dipole magnet. The configuration of the coils is shown in Fig. 4.

Like for all other systems presented here, several aspects play important roles in the final designs: minimum cost, R&D and risk. These are addressed by relying on existing and proven technology, as presently used in operating detector magnet systems. The interesting part of the concept of this specific magnet, is the use of a single cryostat and a common support cylinder for the main solenoid and both dipole magnets.

An overview of the detector geometry is given in Fig. 5, as well as the corresponding magnetic field map. In Table III the FCC-eh magnets' main parameters are summarized [18].

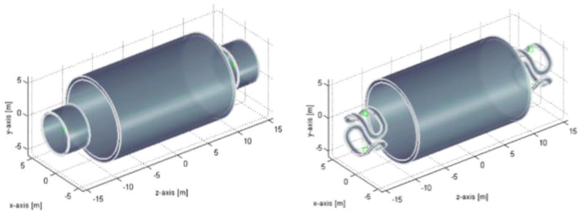

Fig. 6. (left) Coil windings of the main solenoid and the forward solenoids. (right) Coil windings of the main solenoid and the forward dipole magnets.

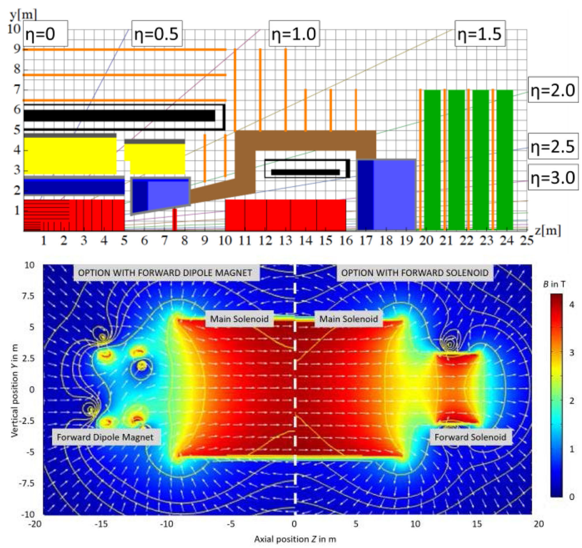

Fig. 7. (top) Schematic top-right-quarter-longitudinal-section of the FCC-hh detector elements with at the bottom left the IP; η is pseudo-rapidity. (bottom) Corresponding magnetic field map with showing on the left side the magnetic field generated by the forward dipole magnets and on the right side, the magnetic field generated when using forward solenoids.

IV. FCC-hh Baseline Designs

A. Main Solenoid

The current baseline design for the magnet system for the FCC-hh detector comprises three superconducting coils. The main solenoid produces a 4 T magnetic field over a free bore of 10 m in diameter and over a length of 20 m. The forward solenoids, on either side of the main solenoid, augment the magnetic field in the forward region to 3.2 T, required for momentum measurement of particles flying almost parallel along the beam pipe. The combined stored magnetic energy of this assembly is 13.8 GJ. The total mass of the solenoid, including cold mass and vacuum vessel add up to just under 2 kt, while the forward cold masses and vacuum vessels add up to 80 t per forward magnet. An alternative option is to use forward dipole magnets instead of forward solenoids. In Fig. 6 the bare coil windings are shown without support cylinder, vacuum vessel, or any detectors for both versions.

The FCC-hh detector magnet system is the most demanding and challenging of the several systems presented here, mainly due to its mere size and the large forces between the main and forward magnets. In several works, preliminary designs and several options were presented [19]–[35], and a comprehensive review paper was published recently [36]. Besides the baseline designs, some alternative designs are presented in the FCC CDR, including a large twin solenoid with force balanced forward dipole magnets [37], [38], a magnet with an iron return yoke [39]–[41] and a large ultra-thin solenoid [42], [43]. Fig. 7 gives an overview of the FCC-hh detector geometry, and a magnetic field map is shown as well for the two cases of using either forward solenoids or forward dipole magnets. In Table IV the FCC-hh main solenoid's key parameters are summarized.

TABLE IV
Design Parameters FCC-hh Main Solenoid

Cryostat length, IR, OR (m)	20, 5, 6.4
Cryostat mass (t)	875k
Cold mass length, IR, d (m)	18.937, 5.45, 0.55
Cold mass (t)	1067
Support cylinder thickness (mm)	50
Conductor dimensions (mm)	65.3 × 62.5
Conductor length (km)	83.1
# layers, # turns	8, 290
Magnetic field at IP (T)	4.0
Operating current (kA)	30.0
Stored energy (MJ)	12500
Self-inductance (H)	27.7
Strand diameter (mm), # strands	1.50, 40
Current density (A/mm^2) conductor / cable	7.35 / 424
Peak magnetic field on conductor (T)	4.48
Operating temperature / margin (K)	4.5 / 2.0

TABLE V
Design Parameters FCC-hh Forward Magnets

	Solenoids	Dipole Magnets
Cryostat length, IR, OR (m)	4, 2.65, 3.56	4, 2.65, 3.56
Cryostat mass (t)	2 × 32k	2 × 32k
Cold mass length, IR, d (m)	3.4, 2.8, 0.27	3.4, 2.75, 0.275
Cold mass (t)	2 × 49.2	2 × 69.0
Support cylinder thickness (mm)	40 (Al)	50 (ss)
Conductor dimensions (mm)	48.6 × 38.3	25.0 × 25.0
Conductor length (km)	2 × 7.7	2 × 23
# layers, # turns	6, 70	11, 28
Magnetic field at IP (T)	3.2 (on axis)	1.0 (transverse)
Operating current (kA)	30.0	16.0
Stored energy (MJ)	2 × 420	2 × 213
Self-inductance (H)	2 × 0.93	2 × 1.66
Strand diameter (mm), # strands	1.50, 40	1.50, 36
Current density (A/mm^2) cond./cable	16.1 / 424	25.6 / 503
Peak magn. field on conductor (T)	4.45	5.9
Operating temperature / margin (K)	4.5 / 2.0	4.5 / 1.7

B. Forward Solenoids and Forward Dipole Magnets

The role of the forward magnets is to extend the region with magnetic field, such that bending power is guaranteed also for particles moving almost parallel to the beam pipe. Since the free bore is mostly occupied with trackers, rather than also with calorimeters, the structure of the cryostat can be much lighter. Large forces between the main solenoid and the forward magnets need to be taken care of by using reinforced flanges and strong connection bars [36].

V. Conclusion

Detector magnets for the FCC project, for the proton-proton, proton electron, and electron-positron accelerator versions were conceptually designed and presented. Each concept has to fulfill specific requirements, shows different features accordingly, and comprises combinations of several magnets when necessary. For electron-positron collisions, relatively simple solenoids are sufficient, while for electron-hadron and hadron-hadron collisions, more complicated systems are required.

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