Conceptual Design of the Cryostat for a Highly Radiation Transparent 2 T Superconducting Detector Solenoid for FCC-ee$^+$

Veronica Ilardi, Alexey Dudarev, Helder Silva, Torsten Koettig, Lennard N. Busch, Patricia Borges de Sousa, and Herman H. J. Ten Kate

***Abstract*—The Future Circular Collider electron-positron version (FCC-ee$^+$) may be the next step towards a next generation of particle colliders. It may include an Experiment for probing ee$^+$ collisions using the IDEA (International Detector for Electron-positron Accelerator), or a similar detector, requiring a solenoid enclosing the inner tracking detector. An innovative 2 T superconducting solenoid with 4 m bore and 6 m long has been accepted as baseline. Positioning the solenoid in between tracker and calorimeter requires an ultra-thin and highly radiation transparent cold mass. Likewise, a thin and radiation transparent cryostat is needed. The set value for the solenoid's maximum radiation length is $1 \times X_0$. The cryostat is designed as a sandwich of thin Aluminum alloy inner and outer shells, eventually locally reinforced, for achieving vacuum tightness, and layers of innovative insulation material providing lowest thermal conductivity and sufficient mechanical resistance. Cryogel Z, a composite blanket of silica aerogel and reinforcing fibers, has a density of 160 kg/m^3 and would allow a 250 mm cryostat thickness. As an alternative, glass spheres (e.g., K1 type, manufactured by 3M, with a 65 μm diameter and a 125 kg/m^3 density), or similar material, can be dispersed between the vacuum vessel thin-walls providing structural support. Besides the cryostat conceptual design, we outline the setup developed at CERN to represent the real-case cryostat and to measure the heat load transferred through the above-mentioned materials and we present the test results for Cryogel Z.**

***Index Terms*—Cryostat, aerogel, insulation testing, solenoid, superconducting magnet.**

I. Introduction

CERN has carried out in the last five years, a design study for the Future Circular Collider (FCC), which will require a new tunnel with a circumference of about 100 km. The detector magnets foreseen aim to analyze different particle collisions: hadron-hadron (FCC-hh), electron-positron (FCC-ee$^+$) and electron-hadron (FCC-eh). The long term goal of the project is the FCC-hh with a 100 TeV center of mass energy. Its detector features a 14 GJ magnet system, composed of three superconducting solenoids: a 4 T–10 m free bore, 20 m long main solenoid, in series with two 3.2 T forward solenoids, with 5.1 m free bore and 4 m long [1], [2].

The first step towards the construction of FCC-hh is FCC-ee$^+$, comprising physics experiments with detectors magnets providing 2 T magnetic field. Two designs are proposed: the CLIC Like Detector (CLD) [3] and the International Detector for Electron-positron Accelerator (IDEA) [4]. Focus of this paper is on the technology for the latter, much more challenging and, in principle, suitable for FCC-hh detectors as well.

II. Conceptual Design of FCC-ee$^+$ Detector Solenoids

For both CLD and IDEA, the foreseen magnetic field is 2 T, but the two designs are substantially different. CLD shows a conventional superconducting solenoid surrounding the inner tracker and the calorimeter. This solution, based on the proven concept of the Compact Muon Solenoid (CMS) [5], provides a robust system with the solenoid acting as a mechanical support structure for tracker and calorimeter. Moreover, it avoids the typical problem of insufficient radiation transparency for high field detector magnets.

However, the magnetic field of a detector solenoid is only required in the inner tracker and muon chamber. About 80% of the magnetic energy is wasted in the calorimeter [6]. Evolving from the ATLAS Central Solenoid [7], in IDEA the superconducting solenoid is positioned directly around the inner tracker, thus inside the calorimeter. This requires the solenoid to be extremely thin and "radiation transparent". The maximum radiation length accepted for cold mass and cryostat is $1 \times X_0$, while the total solenoid's radial envelope should not exceed 300 mm.

The main parameters of the two designs are listed in Table I, while Fig. 1 gives an overview of the IDEA detector.

Placing the solenoid inside the calorimeter allows to save about a factor 4 in stored magnetic energy and about a factor 2 in cost [6]. Intensive R&D and innovative solutions are required

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TABLE I
DESIGN PARAMETERS OF CLD AND IDEA DETECTOR SOLENOIDS [8]

Parameter	CLD	IDEA
Cryostat length (m)	7.4	6.0
Cryostat inner radius (m)	2.7	2.1
Cryostat outer radius (m)	4.4	2.4
Cryostat mass (t)	71 (Al) / 114 (ss)	7.4
Cold mass length (m)	7.0	5.7
Cold mass inner radius (m)	4.02	2.24
Cold mass thickness (m)	0.09	0.03
Cold mass (t)	44.1 / 43.8	7.0
Stored energy (MJ)	600	160
Magnetic field at IP (T)	2.0	2.0

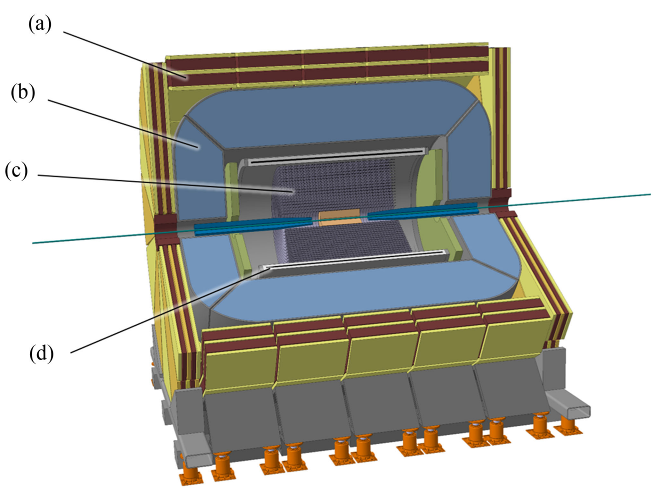

Fig. 1. Baseline design of the IDEA detector for FCC-ee$^+$: (a) instrumented return yoke, (b) calorimeter, (c) inner tracker, (d) detector solenoid.

for this challenging concept that presents remarkable technical changes from the standard design.

A. Layout of the Cryostat for the IDEA Solenoid

In order to follow the demanding design requirements of an ultra-thin, light and "radiation transparent" cryostat, the research started by looking into innovative insulation materials that would provide lowest possible thermal conductivity paired with sufficient mechanical resistance. The first investigated material is Cryogel Z, manufactured by Aspen Aerogels. It consists of a flexible composite that combines silica aerogel with reinforcing fibers and it comes as a blanket of 10 mm thickness. The density value provided by the company is 160 kg/m^3. The material is designed as insulation for temperatures ranging from cryogenic to ambient. Inside the cryostat, layers of Cryogel Z fill the spaces between vacuum vessel walls, thermal shield and cold mass. The external shells of the vessel are designed to be extremely thin, therefore they do not act as a support structure against vacuum. They are expected to mechanically collapse on Cryogel Z, which is therefore required to withstand atmospheric pressure. At both sides of the vessel, end flanges are connected to the cold mass

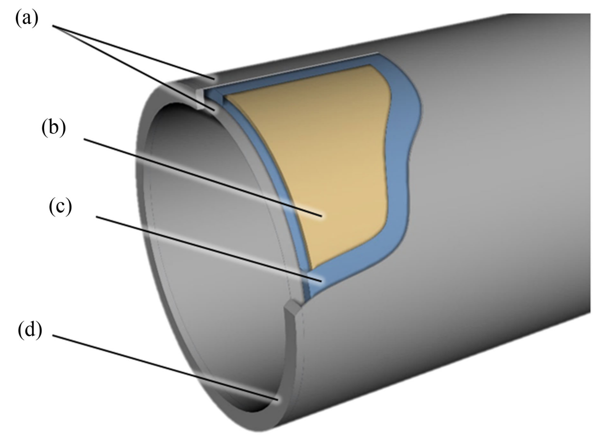

Fig. 2. Conceptual layout of the IDEA magnet's cryostat: (a) inner and outer vacuum vessel walls, (b) cold mass, (c) thermal shield, (d) side flange.

through a support structure. Fig. 2 shows the cryostat comprising vessel walls, thermal shield, cold mass and side flange.

Since the maximum radiation length accepted for the superconducting coils and the cryostat is $1 \times X_0$, Cryogel Z is required to be highly radiation transparent and a test to measure its radiation length is currently being carried out.

The relevant mechanical and thermal properties of Cryogel Z, under different conditions of pressure and temperature, were measured at CERN. At room temperature and atmospheric pressure of 1 bar mechanical load, corresponding to the pressure applied to the real case cryostat, Cryogel Z's compression is about 30% of the initial thickness, over 10 cycles. The material shows hysteresis, as it recovers of about 20% of the initial thickness at each cycle [9]. Using a different test setup, the compression of Cryogel Z was measured under vacuum. It remained equal to roughly the 30% under the differential pressure of 1 bar [9].

The material shrinkage was checked by placing it in a bath of liquid N_2. The average minimum temperature of Cryogel Z was kept between 80 and 180 K. No relevant shrinkage was observed, so Cryogel Z may have contracted within our measurement accuracy, which corresponds to a maximum of 0.5% of Cryogel Z's thickness [9]. New tests will be conducted in order to further analyze this effect.

The thermal conductivity of bulk samples of Cryogel Z was measured in a small scale test setup. The results show a particularly low thermal conductivity that ranges from 0.2 mW/mK at 10 K to 50 mW/mK at 275 K [10]. The test was conducted according to the so-called integral and differential thermal conductivity methods [9], [11], which gave consistent results, compared in Fig. 3.

The FCC-ee$^+$ cryostat will be filled with blankets of 10 mm thickness. This introduces a substantial number of interfaces between the layers that may affect the heat load. A large-scale test setup was designed and manufactured at CERN. It represents the real case cryostat and enables to measure the heat load transferred, through Cryogel Z, between vessel walls, thermal

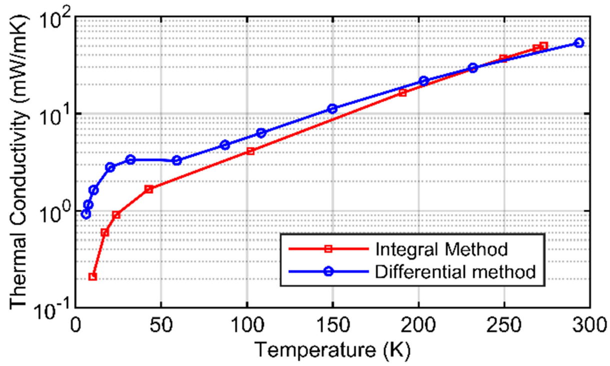

Fig. 3. Cryogel Z thermal conductivity measurements on a small-scale setup: thermal conductivity versus temperature. In red are the results obtained using the integral approach, while in blue the results for the differential one [10].

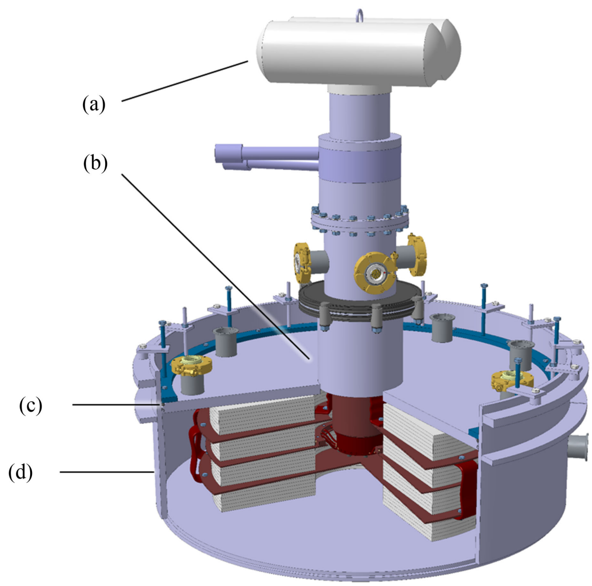

Fig. 4. Schematic of the setup for the heat transfer test, filled with four stacks of Cryogel Z, seven layers each: (a) cryocooler cold head, (b) cryostat top panel, (c) sliding vacuum interface, (d) cryostat wall.

shield and cold mass. In principle, the setup can be filled with other insulation materials as well.

III. Test Setup

Aim of the test is to determine the heat load that can be expected in a large cryostat when using Cryogel Z as thermal insulation. The setup developed allows to conduct heat load measurements at different temperatures while, at the same time, compressing the Cryogel Z blankets by 1 bar, corresponding to the differential pressure acting on the cryostat under vacuum.

The test setup, shown in Fig. 4, comprises a cylindrical stainless steel vacuum vessel of 800 mm diameter and 290 mm height. Two copper discs with an external diameter of 660 mm, placed inside the vessel, are thermally linked by copper braids. They are connected to the first stage of a pulse tube cryocooler type PT420 of Cryomech Inc. and represent the thermal shield

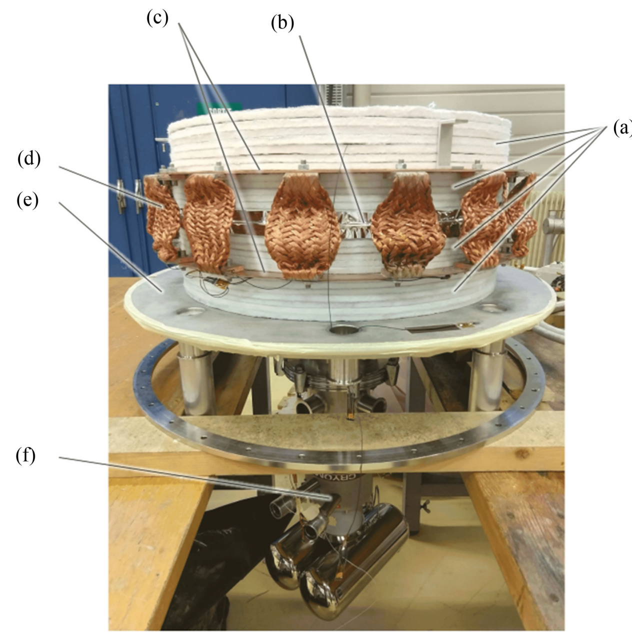

Fig. 5. Interior of the vessel with mounted PT420 during the assembly: (a) Cryogel Z stacks of seven layers each, (b) cold mass, covered with aluminium tape, (c) thermal shield, (d) flexible copper braids, (e) vessel top flange, (f) Cryomech PT420.

of the real case cryostat. Between them, a third copper plate of 620 mm external diameter is connected to the second stage of the cryocooler, recreating the cold mass of the system. Cryogel Z blankets separate the three copper discs from each other and from the top and bottom walls of the vessel, so that the test setup shows a thermally symmetrical sandwich. Four stacks of seven insulation layers each are interposed between the discs, for a total of 28 blankets. Each blanket is 10 mm thick and has a 600 mm diameter. The maximum cross area possible for Cryogel Z blankets is driven by the cooling capacity of both stages of the cryocooler. A detailed and widely-ranged capacity map of the Cryomech PT420 used during the test was experimentally determined by the Cryogenics Laboratory at CERN. Fig. 5 gives an overview of the inner parts of the setup. It is positioned upside down to facilitate assembly.

To minimize radiation from the vessel, two MLI blankets of 30 layers each are wrapped around the outer circumferences of the copper discs. The first one is placed around the thermal shield, while the second one goes from the top flange of the vessel to the bottom one. The central part of the thermal shield's bottom plate is also exposed to the vessel over 200 mm and therefore covered with a 10 layers MLI blanket.

Two areas of the cold mass, one around the inner diameter and another on the outer diameter, are not covered by Cryogel Z and facing the thermal shield. Aluminium tape covers the external area, so that it is not exposed to radiation from the thermal shield. Since it was not possible to cover the inner part as well, the values of heat load on the cold mass are corrected for the radiation between it and the thermal shield, with a mathematical estimation.

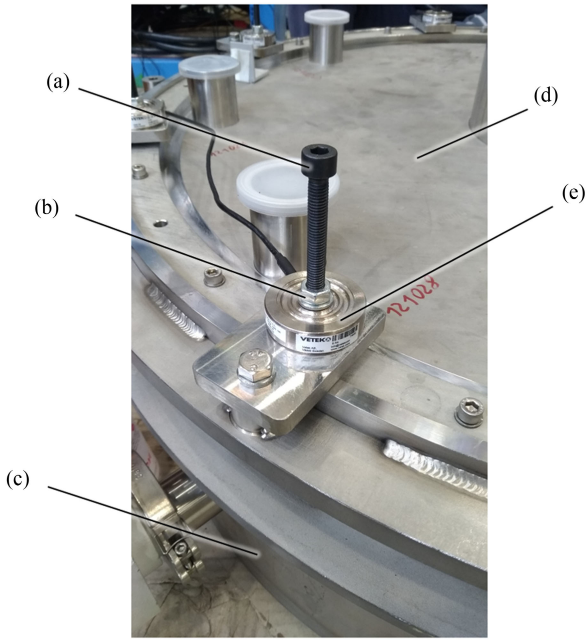

Fig. 6. Position of one load cell in the test setup for the heat transfer measurements of Cryogel Z. Some parts can be distinguished: (a) sliding screw, (b) locking bolt, (c) side wall of the vessel, (d) top flange of the vessel, (e) load cell.

The vessel's lid is allowed to slide and its position can be adjusted through the bolts placed on top of it. They allow to apply different pressures on the stacks of Cryogel Z. For this first test, it was decided to compress the material by 30%, which corresponds to 1 bar pressure difference as is the case in the real cryostat. To obtain this compression, a pressure of 490 mbar is needed inside the vessel, due to the different cross sections of the Cryogel Z stacks and of the vessel. The load sustained by Cryogel Z is measured, during the whole test, by a set of load cells. They are positioned under the locking bolts, as shown in Fig. 6. When the mechanical load on Cryogel Z does not correspond to 1 bar pressure, the position of the vessel's top flange can be adjusted accordingly.

Cold mass and thermal shield are connected to the cryocooler heads through copper braids to ensure the flexibility required by the system under compression. Once the vessel lid is in position, the setup is vacuum pumped and cooled down. Leak tightness of the system is insured by two O-rings between the top flange edge and the vessel side walls.

The instrumentation for the test comprises nine Pt100 sensors and two electrical heaters on the cryocooler's first stage and thermal shield, and four TVO sensors and two heaters on the second stage and cold mass.

IV. Heat Load Measurements

The first test run is to measure the heat load between the cold mass and the thermal shield. A heat load is applied to the thermal shield by the heaters and its temperature is then allowed to stabilize. Once reached equilibrium, the temperature of the cold mass is incrementally increased and five measurement points are taken. A linear fit to the experimental data is used to extrapolate

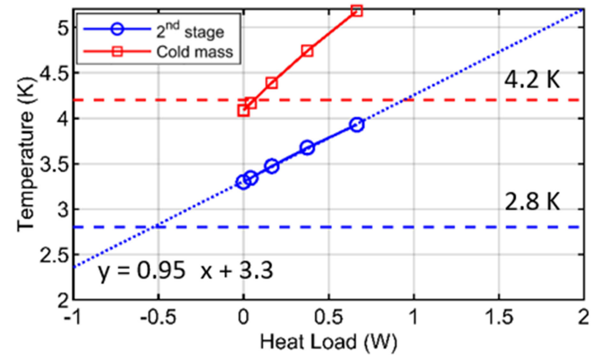

Fig. 7. Temperature of cold mass and second stage of the cryocooler for a thermal shield temperature of 65 K. The fitting curve for the second stage is also shown.

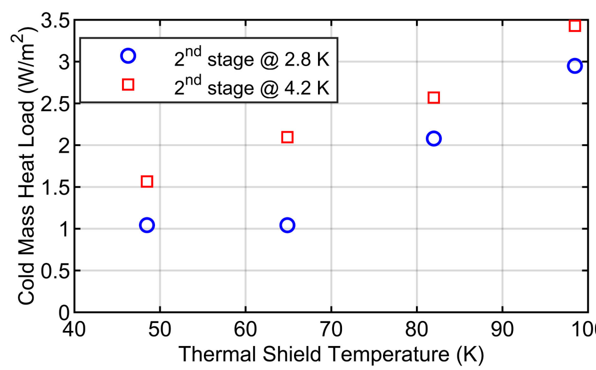

Fig. 8. Heat load through Cryogel Z on the cold mass for different temperatures of the thermal shield. The heat load values are compared for a second stage temperature of 2.8 and 4.2 K.

the heat loads at 2.8 K and 4.2 K, which correspond to the known cryocooler's cooling capacity of 0 and 2 W, respectively. The procedure is repeated for different temperatures of the shield between 40 and 100 K. An example of the typical fitting curve is shown in Fig. 7 for a thermal shield temperature of 65 K. The losses in heating power through both radiation and solid conduction are negligible, while a correction is applied for the radiation between thermal shield and cold mass.

Fig. 8 shows the values of heat load on the cold mass for different thermal shield temperatures with a second stage at 2.8 and 4.2 K. The applied pressure on Cryogel Z, detected through the load cells during the test, varied from the set value of 1 to 0.94 bar. A reduction of the material height is assumed, due to thermal shrinkage.

V. Conclusion

Cryostat and cold mass of the IDEA Solenoid are required to be highly radiation transparent and thin. A study of the heat load transferred through Cryogel Z inside a small-scale cryostat was conducted and the first results of the heat load on the cold mass presented. For a typical thermal shield temperature of 65 K the heat load is 1 W/m^2. Given these preliminary results, Cryogel Z can be considered a promising material for the project.

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