Conceptual Development of a Novel Ultra-Thin and Transparent 2 T Superconducting Detector Solenoid for the Future Circular Collider

Tobias Kulenkampff, Alexey Dudarev, Veronica Ilardi, Matthias Mentink, Helder Silva, Erwin Bielert, and Herman H. J. ten Kate

Abstract—**In the frame of the ongoing Future Circular Collider (FCC) Study, a novel ultra-thin and maximum radiation transparent solenoid for next generation particle detectors is under development. Actually, two versions providing 2 T and 3 T for the FCC-ee and FCC-hh detectors, respectively, are engineered, but here we report on the 2 T version only. Essential aspects of the design are presented. The mechanical and thermal stability of the cold mass is investigated. New, very high-yield stress Al-stabilized NbTi/Cu conductors are required to allow a $0.4 * X_0$ radiation thickness. For conductor production, welding of dissimilar aluminum alloys will be necessary. Electron beam and friction stir welding techniques were tested to connect the Ni-doped pure Aluminum stabilizer to the very high-yield strength Al-7068 alloy. The welding results and their applicability are presented and discussed. The proposed conduction-based cold mass cooling scheme using heat drains, and quench protection were analyzed and results are presented.**

Index Terms—**Future Circular Collider (FCC), detector solenoid, thin, transparent.**

I. Introduction

FOR PREPARING the post-LHC era the FCC Study is focused on analysis and evaluation of different design options for a new circular collider. As a proposed first step for the FCC serves a high precision, high luminosity electron-positron collider, the FCC-ee. To reach higher collisions energies, the FCC-ee would be replaced by FCC-hh, a proton-proton machine which can make use of the already existing infrastructure.

The FCC-ee is based on a top-up booster and separate e and e+ channels. The center-of-mass energy allows precise measurements ranging from the Z-pole (90 GeV) to above the top pair threshold (400 GeV). The FCC-ee can eventually serve as a predecessor for a stronger machine, the FCC-hh used for proton-proton collisions with a center-of-mass energy up to 100 TeV.

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T. Kulenkampff is with CERN, Geneva, Switzerland, and also with TU Wien, Vienna, Austria (e-mail: Tobias.Kulenkampff@cern.ch).

A. Dudarev, M. Mentink, H. Silva, E. Bielert, and H. H. J. ten Kate are with CERN, Geneva, Switzerland (e-mail: Alexey.Dudarev@cern.ch; Matthias.Mentink@cern.ch; helder.filipe.pais.da.silva@cern.ch; Erwin.Bielert@cern.ch; Herman.TenKate@cern.ch).

V. Ilardi is with CERN, Geneva, Switzerland, and also with the University of Twente, Enschede, the Netherlands (e-mail: Veronica.Ilardi@cern.ch).

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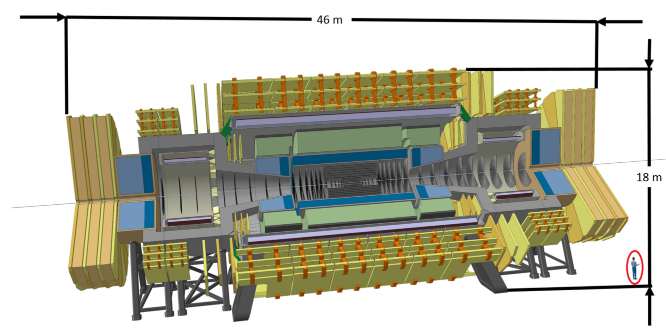

Fig. 1. Baseline FCC-hh Detector Design, featuring a Solenoid (in lilac) positioned around the calorimeters with a 10 m free bore, 20 m long, and providing 4 T centre magnetic field; with manikin for scale (bottom right).

To provide the necessary momentum resolution in the detectors at such high energies, a combination of two paths can be followed i.e., a higher resolution pixel-system and a higher field magnetic system. A higher magnetic field goes together with largely increased requirements on power, mechanics, and protection. Applying a solution which is similar to the present Compact Muon Solenoid in LHC in which the detector solenoid represents a component which covers a large fraction of the overall detector system quickly leads to a very large system with, depending on the design, multiple GJ of stored energy. Not only is such a system difficult to build, maintain, and protect, also most of the magnetic energy will go to waste in the calorimeters where magnetic field is not useful. These aspects are also cost drivers, making an alternative solution interesting. Fig. 1 shows the baseline detector for FCC-hh comprising a 4 T, 10 m free bore solenoid surrounding the calorimeter (and 2 smaller solenoids in forward direction to serve low angle particle tracking. A much more elegant and cost efficient solution would be to position the solenoid inside the calorimeter bore, thus directly around the inner tracking detector.

This solution was accepted as baseline for one of the FCC-ee detectors called IDEA (International Detector for Electron-positron Accelerator) [1], see Fig. 2, following the design of the ATLAS central solenoid. The idea is to build a radiation transparent solenoid which only covers the inner tracker. Such a system is lighter, imposes less technical constraints, and as a result is a cheaper option. The cold mass in conjunction with the cryostat need to be as thin as possible and built out of material with a high strength/density ratio. The radiation transparency imposes

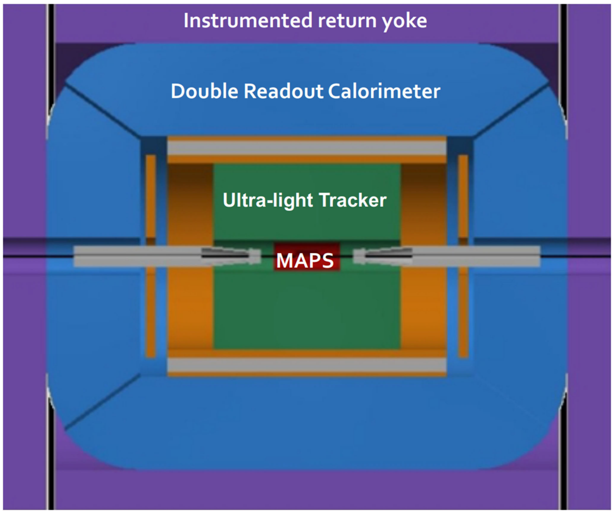

Fig. 2. Baseline concept of the FCC-ee IDEA detector, featuring a 2 T Solenoid positioned inside the calorimeters, directly surrounding the inner tracker, with a 4 m free bore, 6 m long.

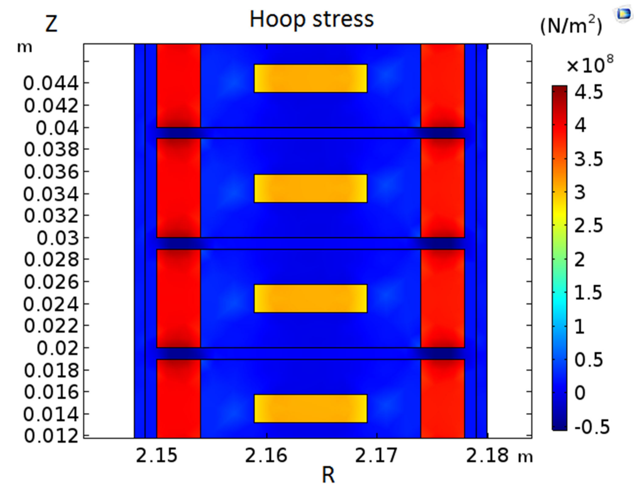

Fig. 3. Composite conductor dimensions and hoop stress on the centermost turns. Components from left to right: RRR-900 Aluminium as cooling providing heat drains, G-10 for turn-to-turn insulation, alloy Al-7068 reinforcement bars, 0.1%wt.Ni doped pure Al-stabilizer, NbTi/Cu-matrix superconducting Rutherford cable.

TABLE I
MAIN CONDUCTOR AND COLD MASS PARAMETERS, SEE FIG. 3

Element	Value	Unit
Total height of windings	32	mm
Al-Ni0.1%w.t stabilizer height	20	mm
Al-7068 reinforcement height	8.0	mm
No. of NbTi/Cu strands in cable	16	-
Cu/NbTi-ratio in strands	1.8	-
Turn-to-turn insulation thickness (G10)	1.0	mm
Al-RRR900 heat drain plates thickness	1.0	mm

high mechanical requirements on the conductor. In addition the thermomagnetic stability and quench protection can cause issues due to the low amount of material used in the construction.

Presented here is the design of a novel ultra-thin cold mass satisfying the requirements of an FCC-ee detector magnet by providing 2 T in a free bore of 4 m across a coil length of 6 m. The current strategy is to find a hybrid solution between a Ni doped pure Al conductor stabilizer [2] (as used in the ATLAS Central Solenoid [3]), in combination with a high yield strength Al alloy reinforcement to create a sandwich structure similar to the CMS conductor [4].

Mechanical stress, quench protection, cooling, and weldability of joint materials are investigated.

II. Magnet Design

A. Conductor and Cold Mass

The FCC-ee detector magnet is a solenoid with 6 m length and a free bore of 4 m in diameter and is to provide a magnetic field of 2 T in the center. The wall thickness is to be minimized.

The hoop stress in a solenoid increases as the wall becomes thinner. For a solenoid magnet with the given dimension and field, the average hoop stress on the conductor for a radiation thickness of 0.4 X_0 (~35 mm) amounts to ~150 MPa. X_0 is a measure for the radiation length of a material. For aluminum, X_0 is 84 mm. To fulfill the systems stress requirements, the concept of reinforcement bars as used in the CMS conductor [4] in combination with the low percentage (0.1%w.t.) Ni-doped Aluminum stabilizer used in the ATLAS central solenoid conductor [3]. Due to its density/strength ratio, an aluminum alloy of the 7000 series (7068-T6511) was chosen as reinforcement material.

Fig. 3 shows 4 turns of the coil in the center of the solenoid. Mechanically, the center is the area were the hoop stress distribution has its maximum of ~490 MPa. Dimensions are chosen such that the conductor is as thin as possible whilst staying within safety limits (2/3 σ_{yield}).

The conductor is a made up of multiple materials. In the center, around the NbTi/Cu super conductor cable is an inlay made of 0.1%w.t. Nickel doped and precipitation hardened Aluminium. It serves as thermomagnetic stabilizer and adds to the overall mechanical stability of the system. On the left and right of the stabilizer, are the reinforcement bars made of Al-7068-T6511. It is one of the strongest aluminum alloys currently available with a yield strength of 680 MPa in longitudinal direction at room temperature [5]. The turn to turn insulation is modelled with a 1 mm layer of G10. The cold mass is covered in separated high purity aluminum strips. These strips serve as a component in the cooling circuit and to facilitate normal zone propagation in case of a quench. The dimensions of the components which make up the conductor seen in Fig. 3 are summarized in Table I.

The performance of a super conducting magnet is limited by local peak fields as they impose the lower boundary of the temperature margin. A method to reduce the peak fields, is to locally dilute the current density. This can be achieved by increasing the distance between the turns in the vicinity of the peak fields. To study this approach, a parameter sweep of the thickness of the windings was performed. The thickness was varied in defined areas around the peak fields in the center and edge region to locally decrease the magnetic field. The goal was to find a geometry that allows higher operational current and maintaining a temperature margin of 2 K. The performance in terms of bending power, the integral in (1) as evaluated along a 9 m long trajectory starting at the center of the magnet and propagating at an angle

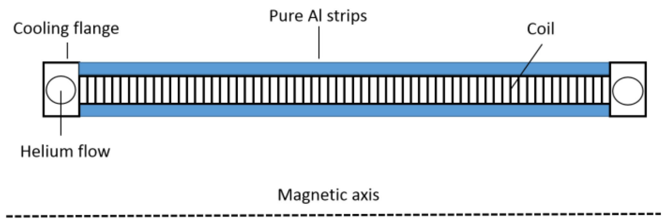

Fig. 4. A schematic representation of the conduction based cooling system. RRR 900 aluminum strips (in blue) are covering the surface of the coil windings.

of $\vartheta = 50°$.

$$\int_0^{9m} (B_r \sin\vartheta + B_z \cos\vartheta) ds \quad (1)$$

A geometry which allows an increase in bending power and temperature margin was identified. Comparing both geometries at a temperature margin of 2 K, an increase of ~3% (compared to a constant winding thickness) in bending power could be achieved.

III. Cold Mass Cooling

The cooling system is an evolution of previous design of thin solenoids [6] in which the inner and outer wall of the coil-windings are covered with high purity aluminum strips. The cooling is provided by liquid helium flowing in a cooling pipe at the end turns of the solenoid. Fig. 4 shows this model. The heat drains are made of high purity aluminum providing the indirect cooling.

For the calculation a RRR-value of 900 was chosen to take the magnetic resistive effect and the decrease of transport properties due to cycling cold work of radiation damage into account [4]. For simplicity in the model, the cooling power is assumed to be infinite as the cooling will be provided by a cryo-plant. Assuming a homogeneously distributed heat load of 3 W/m^2 over the inner and outer wall surface of the cold mass [7]. This cooling scheme warrants the required temperature gradient <0.5 K over the entire cold mass. The aluminum heat drain will also facilitate normal zone propagation in case of a quench similar to the protection scheme used for the ATLAS central solenoid [3].

IV. Quench Protection

The material composition of the conductor yields a load integral of $2.4 * 10^{16}$ A^{2}sec/m^4/J^2. At the operational current of 15 kA this corresponds to a hot-spot of 110 K within 3 seconds at constant current or 6 seconds at exponentially decaying current, respectively. With an E/M value (Energy to Mass ratio) of ~21 kJ/kg and assuming homogeneous heat dissipation throughout the cold mass, the temperature would rise up to 110 K. As a quench occurs locally, the dissipation initially occurs in a very limited area, leading to much higher temperatures and thermal stress which will damage the resin and endanger the winding.

Using an internally developed quench-code a manifold of quench protection schemes (number of heaters, dimensioning of external dump resistor) was investigated. It was found that to protect the magnet an active protection scheme with external energy extraction and quench heaters may be necessary. For radiation transparency the use of a quench back cylinder is waived. Assuming a voltage drop over the external dump resistor of 1000 V and the use of 24 evenly distributed quench heaters on the coil windings, the hot spot temperature can most likely be kept below 150 K. Without heaters the hotspot temperature was estimated to be around 700 K. For the calculation the quench is initiated at the edge of the coil to represent the worst quench scenario. The code averages over all material properties of the composite conductor, including the pure Aluminum strips. This is a clear deficit as those strips would serve as thermal shunts between all turns triggering quenches throughout the coil. Also, the quench heaters are implemented as initial conditions rather than elements providing heating power. An extension of the code is currently under development and a more detailed analysis is too follow. Fig. 5 shows the equivalent circuit used for quench calculations.

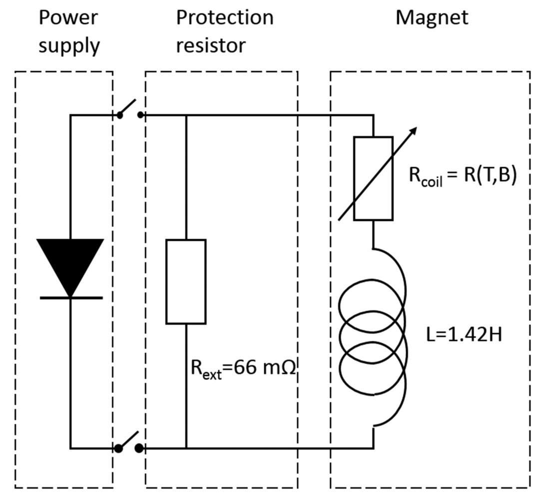

Fig. 5. Equivalent circuit for winding protection.

V. Conductor Sample Trials

A challenge in the production of the conductor is the required continuous and affordable welding of the Al-7068 reinforcement bars to the Nickel doped Aluminum stabilizer. The weldability in most of the high strength alloys of the 7000 series, including 7068, is not good as the welds are prone to liquation and solidification cracking.

On the other hand the mechanical requirements on the weld are relatively low as it aligns with the direction of the hoop stress. The welds mainly serve as thermal and electrical contact between the stabilizer and the reinforcement bars to increase the cross-section in the case of a quench.

Two methods of welding have been investigated: Electron beam welding and friction stir welding.

In electron beam welding a high amount of energy is deposited in a localized area within a short time, thus enabling thin welds. In addition the heat dissipation through the conductor is low enough to avoid the reduction of the current carrying capacity of the NbTi strands [4]. A technique used with the conductor of CMS.

Fig. 6 shows a cross-section of an EB-weld made at the CERN workshop between AlNi and Al-7068 taken with an optical microscope. At a first glance, the weld looks acceptable and without cracks at the heat affected zone. Looking closer however, Fig. 7

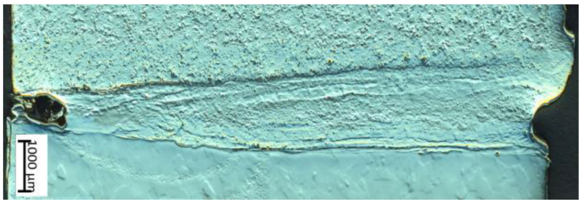

Fig. 6. Cross-section of EB weld sample between Al-7068-T6511 (top) and AlNi 0.1%w.t. under the optical microscope. Full penetration was not achieved.

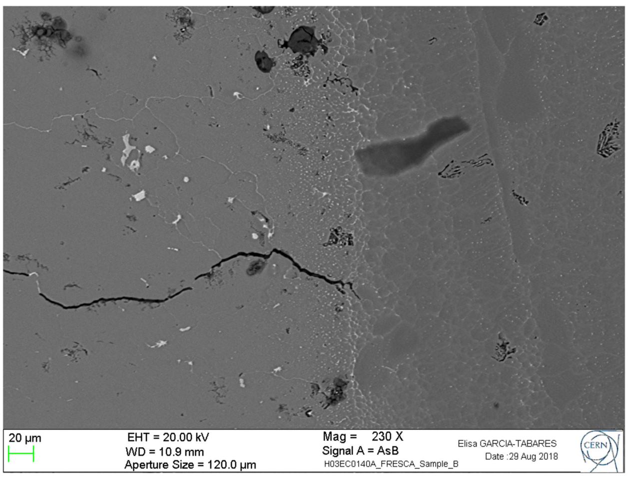

Fig. 7. Small liquation cracks in the Al-7068 reinforcement material caused by the CuZn phase generated during the welding.

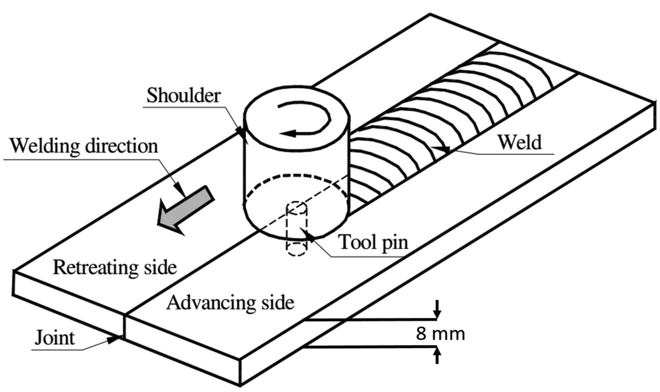

Fig. 8. Illustration of a butt weld using friction stir welding [9].

shows an image taken via electron microscopy of the heat affected zone, reveals that the heat affected zone contains many liquation cracks with lengths ranging between 2 and 200 μm. Their growth behavior during thermal and mechanical cycling is yet to be investigated.

In friction stir welding [8], the energy required to combine the two materials is introduced via a spinning tool which moves along the boundary of the two materials. The thermal energy is of mechanical origin. The shoulder (see Fig. 8) of the tool is used to stop the material from escaping whilst the tool pin mixes the materials.

Friction stir welding has the advantage of not introducing high temperature and therefor avoiding phase transitions in the first place. This way, liquation cracks or degradation of current density do not pose a risk in the production process of the conductor. In addition, welding of dissimilar alloys is known to be very successful. In cooperation with RIFTEC GmbH [10] a feasibility study of joining the comparatively soft material AlNi 0.1%w.t. with the very strong alloy Al7068-T6511 was undertaken.

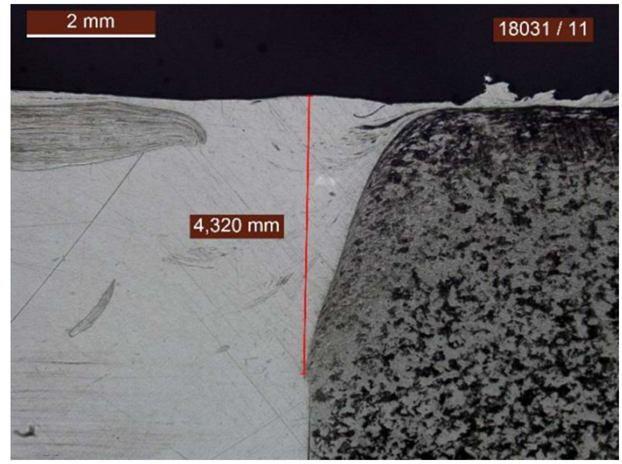

Fig. 9. Cross section of the FSW weld. The right hand side is the strong alloy. The red line indicates the full penetration depth of the weld.

The different mechanical properties of the joining materials only allowed for a small range of parameters rotation speed, welding speed, and applied pressure. For a successful weld, both materials need to be plasticized.

The maximum penetration depth with acceptable flaws in the weld is around 4.3 mm which can be seen in Fig. 9. With a conductor thickness of 8 mm, a full penetration when welding from both sides is possible. All samples produced during the study indicate the post welding machining will be necessary.

Like eb-welding, fs-welding is a continuous process thus allowing the production of very long welds. Both options seem to be feasible for producing the conductor. Important decisive factors are welding speed and associated throughput cost to produce multi-km quasi continuous welds.

VI. Conclusion

An ultra-thin cold-mass for a detector magnet for FCC-ee aiming at positioning the 2 T solenoid directly around the inner tracker was conceptualized. From a mechanical and thermal point of view, the solenoid can be operated in stable conditions. The requirement of a radiation length below $1 * X_0$ can be easily achieved for FCC-ee. The current radiation thickness of the cold-mass including cooling provisions is $0.4 * X_0$.

A quench protection concept could be established. The details of the protection scheme still need to be evaluated.

A cold mass cooling system only comprised of two helium carrying pipes (and their connection) connected to a web of 1 mm thick heat draining strips is sufficient to provide less than 0.5 K gradient under the assumed heat load of 3 W/m^2.

The result of the conductor welding study have shown that a good thermal connection between the Nickel doped Aluminum stabilizer and the Al-7068-T6511 reinforcement bars can be established.

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