Preliminary Conductor Layouts for the Detector Magnets of the Future Circular Collider

C. Berriaud, A. Dudarev, A. Gaddi, H. Gerwig, V. Klyukhin, M. Mentink, G. Rolando, H. F. Pais Da Silva, and H. H. J. ten Kate

***Abstract*—For the Future Circular Collider (FCC) presently under the conceptual design at the European Council for Nuclear Research (CERN), very large conductors are needed for the detector magnets. The requested critical current is an order of magnitude higher than that of the previous generation, corresponding to about 250 kA at 4.2 K and 5 T. Characteristic conductor layouts, particularly the type and fraction of structural materials, are reviewed in order to extrapolate to the most promising designs and adapt those to the requirements imposed for the FCC detector magnets. The nominal currents required at characteristic operating conditions of 6.5 T and 4.6 K, conductor dimensions, production unit lengths and mass are investigated for defining the design of the conductor. For comparing various conductor layout options, and as a first step in the conductor R&D, it is proposed to study the conductor sizing according to relevant material characteristics.**

***Index Terms*—Conductor layout and reinforcement, detector magnets, FCC, Future Circular Collider, superconductor.**

I. Introduction

THE future circular collider (FCC) project requires a design for 100 TeV collision energy, a value 7 times higher than in the present Large Hadron Collider presently in operation at CERN. For achieving the same momentum resolution of the particles escaping from the collision point, and assuming the same spatial resolution in the detectors, the FCC detector has to provide a seven times higher value for BL^2 (B magnetic field in the tracking area, L tracking length), for the same performance. For a solenoid this corresponds to a 6 T central magnetic field in a free bore diameter of 12 m and a coil length of about 20 m. Various detector options are investigated [1] in order to define the two best designs for further engineering and construction. The conductors used in the magnets of both detectors will probably be significantly different. Many parameters are still free for variation and there is room for standardization of the constituents and sub-cables in the conductors.

Manuscript received October 19, 2015; accepted February 29, 2016. Date of publication March 3, 2016; date of current version March 18, 2016.

C. Berriaud is with the Institute of Research into the Fundamental Laws of the Universe (IRFU), French Alternative Energies and Atomic Energy Commission (CEA), 91191 Saclay, France (e-mail: Christophe.berriaud@cea.fr).

A. Dudarev, A. Gaddi, H. Gerwig, M. Mentink, G. Rolando, H. F. Pais Da Silva, and H. H. J. ten Kate are with the Physics Department, European Council for Nuclear Research (CERN), 1211 Geneva, Switzerland.

V. Klyukhin is with the Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, 119991 Moscow, Russia.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2016.2537651

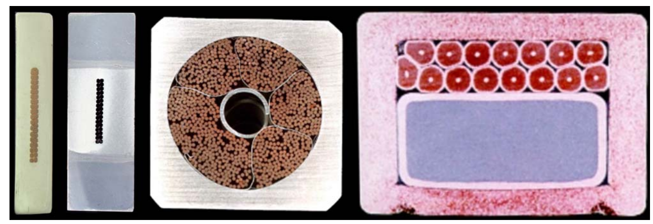

Fig. 1. Characteristic conductor layouts used in the present large-scale magnet like ATLAS and CMS detector magnets; ITER PF coils and LHD.

II. Issues of Large Superconducting Magnets

A. Conductors

Large conductors with nominal current over 10 kA for magnets with stored energy over 1 GJ are not that many and mostly designed for fusion magnets. The Cable-In-Conduit (CIC) type conductor has seen a rich development in the frame of the ITER coils construction. Fig. 1 shows a few typical cross sections of large conductors. We can distinguish:

— Block-type, NbTi Rutherford cable coextruded with pure Al as in the ATLAS Barrel Toroid [2] or with additional mechanical reinforcements as in CMS Solenoid [3], [4];
— CICC-type, NbTi or Nb3Sn are used in the ITER coils [5];
— Box-type, when assembling cable and stabilizer elements by soldering, used in the Large Helical Device (LHD) [6].

B. Comparing Conductors for Fusion and Detector Magnets

CIC conductors for fusion are developed with the main constraint of fast current ramping. The high level of AC loss requires the use of forced flow cooling with direct contact between helium and superconductor. This type of conductor is also efficient for quickly extracting the stored energy in the case of a quench, however, unavoidably with generating a high discharge voltage. The conductor show a minimal cross section used for stabilizing material. Another disadvantage is that it is hard to make low-resistive CIC cable joints.

Contrarily, for a detector magnet a very high magnetic field variation cannot be accepted because of its impact on detector structures and instrumentation. After a quench, the magnet stored energy is preferably dissipated in the coil windings without needing the high terminal voltage. Consequently the percentages of stabilizing and quench protection material is much higher in conductors for detector magnets. Therefore the classical CIC conductor applied in fusion magnets is not necessary the best layout for detector conductors.

C. NbTi and MgB_2 Superconductors

The only cost-effective superconducting material that can compete at certain operating temperatures and magnetic field with NbTi is MgB_2. Presently, MgB_2 is an interesting material for use in the 10–20 K range and magnetic field below 2 T. However, its performance shows progress and in due time it could be usable in the 5–8 T range and be available in the shape of performing round wires. As the superconductor content is rather low in a detector magnet conductor (~5%), the use of MgB_2, with possibly a lower critical current density than NbTi, will not change significantly the conductor material ratios. However, MgB_2's critical current density is significantly stress sensitive in particular for strain exceeding 0.4%. Also working MgB_2 tape conductors into cables is less straightforward and additional measures are needed to create performing conductors. Another issue is the conductor's ferromagnetism when using the usual matrix materials. Altogether, there is a long way in the development of performing MgB_2 conductors.

III. Conductor Constraints

The conductor design presented here is suitable for an FCC detector magnet design called Twin Solenoid, featuring a 6 T, 20 m long main solenoid with 12 m bore and actively shielded by a second concentric outer solenoid [1].

A. Conductor Design Criteria

The operating temperature is set to 4.6 K while the required superconductor temperature margin is 1.5 K. These values are based on present detector magnets operating successfully at the LHC. A stability criterion is not set because large conductors will have a very high minimum quench energy not allowing training except in the case of a major defect.

Given the magnet dimensions mentioned, the magnet stored energy is about 50 GJ and an appropriate conductor operating current is about 80 kA. The current level may be adjusted as its choice is the result of an optimization taking into account conductor cost, winding technology, power circuit components and protection constraints. With a self-inductance of 16 H and a 100 V power supply, the current will ramping up in about 3.5 hours. Obviously, the ramping up shall not cause a quench of the magnet due to eddy current loss.

The peak magnetic field on conductor is 6.5 T. Note that at 80 kA, the self-field for a Rutherford cable or another compact circular cable is a significant 0.7 T. The conductor self-field can be reduced to some 0.2 T by spreading the strands over 40% of the conductor section which seems mandatory.

Concerning the mechanical constraints regarding acceptable stress levels are the usual values of 2/3 of the elastic limit and of 1/3 of the ultimate stress. When applying high Residual Resistance Ratio (RRR) ductile materials in the conductor like pure aluminum, doped aluminum like $AlNi_{2\%}$ or even annealed cooper, the stress criteria are replaced by a 0.15% elongation limit (this value come from CMS results, but may be adjusted up to 0.2%), to limit among other arguments the degradation in RRR (or resistivity) due to work hardening [7]. The cool down cycle cause an increase in stress, but when back at room temperature annealing takes place partly restoring the work hardening effect, at least in pure aluminum.

A mechanically self-supporting magnet features a maximum effective enthalpy contribution when the mechanical reinforcement is distributed and integrated within the conductor. In this way the structural material will contribute in limiting the conductor hot spot temperature. Here the maximum hot spot temperature is defined at 100 K level in combination with a maximum temperature difference of 25 K within a coil winding. Active electrical heaters are applied at many positions on the winding surface. When fired they introduce multiple normal zones along the conductor within one second, which expand by normal zone propagation. Depending of the number of quench heaters and of quench back efficiency of the supporting outer cylinder, the entire volume of coil windings can be transferred to the normal conducing state within 20 s.

B. Large Detector Magnet Manufacturing Requirements

For large conductors, several manufacturing considerations have to be taking into account. The available manufacturing techniques for assembly of the conductors are: co-extrusion, twisting, rolling and crimping, soldering and welding. Transportation can be an issue because of the conductor minimum bending radius. Also it may be difficult to maintain the elongation below 0.15% when the magnet is fully charged given the 1% strain introduced during coil winding following the conductor thickness relative to the coil winding radius. Improvements may partly be achieved by:

- Specific heat treatments before and after the winding to let increase the mechanical properties (as done for CMS [8]);
- Reducing the thickness of the conductor for limiting the introduced strain by coil winding;
- Imposing solid connections between conductor constituents without allowing shearing.

This last option can be efficient, especially when various variants of FCC detector magnet conductors are needed. Cables can be assembled using the same elementary conductor. The elementary conductor can comprise stabilizing, structural and superconducting materials. A disadvantage may be that the final conductor has to be assembled at the coil winding site.

C. Input for the Conductor Evaluation Model

According the twin solenoid design [1], 7.1 MA/m of linear current density is required to create 6 T. The active shielding coil further increases the need for ampere-turns. Using the linear current density, the conductor aspect ratio follows according to the odd number of layers. Options for combinations of conductor width and height at a certain current density are listed in Table I.

TABLE I
CONDUCTOR DIMENSIONS (IN mm): HEIGHT H AND WIDTH W AT A CERTAIN COIL WINDINGS CURRENT DENSITY J (IN A/mm^2)

Number of layers	W [mm]	J = 5.8 H [mm]	6.3 H [mm]	9.8 H [mm]	11.4 H [mm]
8	90	153	141	91	78
10	113	122	113	72	62
12	135	102	94	60	52
14	158	87	80	52	44
16	180	77	70	45	39
18	203	68	63	40	35
20	225	61	56	36	31
22	248	56	51	33	28

TABLE II
PROPERTIES OF RELEVANT MATERIALS AT 4.2 K

Material	RRR	$\sigma_{0.2\%}$" [MPa]	σ_{US} [MPa]	E [GPa]	$\Delta\ell/\ell$ 300-4K	Cost level
NbTi		600	900	82	0.20%	++
Cu	100	220	250	138	0.34%	+
Al 5N	1000	25	40	78	0.42%	0
AlNi$_{2\%}$	100	120	170	78	0.42%	0
Al-6082	3	400	600	78	0.42%	-
Al-7020	2	650	800	78	0.42%	-
SS-304L		450	1500	200	0.31%	0
SS-316L		700	1400	205	0.31%	0
G10		27	250	15	0.48%	-

TABLE III
PRESENTATION OF VARIOUS CONDUCTOR MATERIAL RATIOS

Reinforcement material:		Al alloy 6082	Al alloy 7020	SS 304	SS 316	SS 304 + Cu
NbTi	%	2	2	3	3	4
Cu	%	3	2	4	4	52
AlNi2%	%	0	2	37	38	0
Structural	%	91	90	50	48	37
Insulation	%	4	4	6	6	7
$\sigma_{meca}/\sigma_{US}$	%	22	15	18	19	18
$\sigma_{meca}/\sigma_{0.2\%}$	%	33	19	59	39	61
$\sigma_{av.}$	MPa	125	116	190	190	220
Strain ε	%	0.16	**0.15**	**0.15**	**0.15**	**0.15**
J_e	A/mm^2	6.3	5.8	9.8	9.8	11.4
Mass	kt	4.0	4.5	4.9	4.8	5.9
Material Cost		-	-	0	0	+

In order to arrive at the most efficient conductor, it has to fulfill all antagonistic specifications and to be at the high limit for both main criteria: stress limit and hot spot temperature.

To estimate the level of stress in the windings, the coil is considered self-supporting even if some structure is needed for the supports. For hoop stress evaluation, the magnetic field is supposed to fall linearly along the radius between main coil and shielding field. For the axial stress evaluation, the infinitely long solenoid case is assumed.

The hot spot is calculated assuming a classical coil discharge through a dump resistance with 1 s breaker delay, and an immediate and complete quench back acting on the entire coil windings after 20 s. The dump resistor value is set to limit at 1 kV the voltage during the discharge. The dump resistor will extract less than 30% of the magnet stored energy.

Materials properties are listed in Table II (data from Cryocomp and [9]) and they are used to study their usefulness when part of the conductor. The last column gives an indication of the impact of the material volumetric cost.

IV. SHAPE OF THE CONDUCTOR

A. *Percentages of Materials in Conductor Cross Section*

The area needed for NbTi superconductor is defined by the peak magnetic field and imposed temperature margin, leading to 270 mm^2. A regular copper to superconducting ratio of 1.25 yields a copper section of 350 mm^2. The area required for conductor insulation will depend on the conductor dimensions but, here, is set to 500 mm^2.

When optimizing, the fractions of materials in the conductor cross section are varied until encountering a mechanical constraint (indicated in bold in Table III), by adjusting the section used for structural material while keeping the hot spot at 100 K by changing the section for stabilizing material.

The first option using Al alloy 6082 material (Table III) was expected as a good solution, similar to the CMS magnet where pure aluminum stabilizer and aluminum alloy as structural material was used. Here the hot spot criterion is fulfilled even without using pure aluminum. The E-modules of 6082 alloy does not allow reducing the elongation to below 0.15% needed for using ductile material. Note that the copper in the strand is not considered as stabilizing material as it has a small section.

Considering the elastic limit, both aluminum alloys, having the same elastic modulus, give the same weight. But, while both alloys have significantly worse electrical properties compared to a typical stabilizer, 6082 is favorable in terms of electrical properties. Using a more rigid material like SS 304L allows increasing the stress level and current density but unfortunately the gain due to mechanic is not sufficient to compensate the weight increasing due to the higher density. Such cold worked material will be magnetic with a magnetic permeability of some 1.1, though 316 is less magnetic. When applying a 304 L/Cu mixture as reinforcement material, current density and stress level increase but again accompanied by mass and cost increase as well. This mix of reinforcement material is about twice expensive than 6082 alloy material.

B. *Strand and Elementary Cable Geometry*

A robust cost effective strand diameter of 1.5 mm is taken here leading to 342 strands required to meet the NbTi section. With such a high number, it can be interesting to develop a standard sub-cable with 18 superconducting strands. The full conductor can then be composed of 19 sub-cables to arrive at 80 kA (and another number of sub-cable to adjust for a

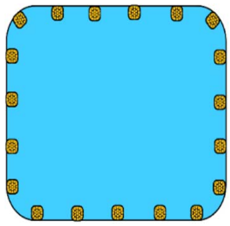

Fig. 2. Monolith conductor layout, size 113 mm × 113 mm, for an 80-kA nominal current in a 50-GJ solenoid, 20 m long, and providing 6 T in a 12-m bore.

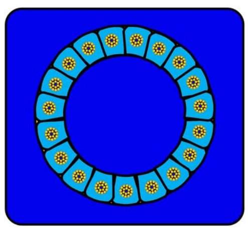

Fig. 3. CIC conductor layout 80-kA nominal current in a 50-GJ solenoid. Subcables included in an SS304 structure, outer size 90 mm × 91 mm.

different field). The configuration of the standard sub-cable can for example be:

— $8 + 6 + 1$ strands in coaxial configuration, the most compact solution but not fully transposed;
— 3 triplets of $(6 + 1)$ strands;
— 18 strands around a 6 mm core representing 45% of the overall section.

C. Conductor Layouts

Several conductor variants are needed depending on the detector magnet diameter and peak magnetic field. In the twin solenoid, the conductors for the main and the shielding coils are different. Various generic layouts can be considered.

Block Layout: The 6082 alloy can be used in a monolith solution with large cold work hardened. The conductor aspect ratio can be square $113 \times 113\ \text{mm}^2$ with 10 layers (Table I with 6.3 A/mm^2) (Fig. 2).

In order to transpose the sub-cable around the monolith, the conductor initial section may be cylindrical with grooves and twisted with the sub-cable in place. The large deformation of the 6082 alloy when rolling into final shape could be used to strengthen the material and performing adequate cold work. The sub-cables can be protected against high local stress during the rolling process by a soft copper or aluminum barrier sheet.

"CICC" Layout: The "CICC" manufacturing technique can be used with 304 structural material as in ITER [10]. Again the square solution is preferred and corresponds to 8 layers (Table I, 9.8 A/mm^2), with conductor dimensions of $90 \times 91\ \text{mm}^2$ (Fig. 3).

The sub-cable conductor can be co-extruded for example with doped aluminum and then twisted around the inner cylinder of the structural material. Next the inner core cable can be compacted and introduced into the outer jacket where after the entire conductor is compacted by rolling to lock the sub-cable conductor in between the structural core and jacket.

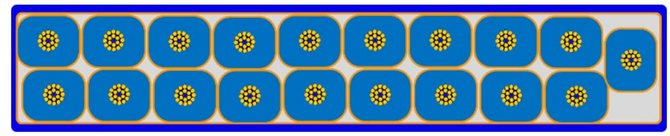

Fig. 4. Box-type Rutherford conductor layout for an 80-kA conductor.

Box Layout: A more flexible configuration is an assembled Rutherford type of conductor built up with sub-elementary conductor composed of sub-cables including structural material and stabilizer. This sub-elementary conductor can be blocked by impregnation or by soldering with the beneficial effect of enhanced stability, improved current distribution and thermal homogeneity. A box can be applied around the Rutherford cable to limit the soldering zone and yield a smooth surface. The box can be in copper or in stainless steel (Fig. 4). This configuration is also flexible for incorporating various fractions of stabilizing material and structural material.

When choosing the 6082 alloy solution, a ribbon like geometry is preferable: 19 elementary conductors (Table I, 6.3 A/mm^2) in 22 layers with conductor dimensions of 248 mm × 51 mm (Fig. 4). To increase the mechanical characteristics of the solution, the box material chosen is SS 304, also increasing the insulation shear stress limit. The elementary conductor can be made with a cable of 18 superconducting strands around a core of SS 304. Around this cable, a soft aluminum foil will limit the deformation during the rolling down of the 6082 alloy jacket.

D. Comparison of Layouts

The block layout requires development to achieve good material properties allowing large deformation without damaging the cables and obtaining the high ultimate stress required. It is very robust but not as modifiable as the others.

The "CICC" layout is also very strong and uses available techniques A possible issue is that we need a good thermal conductivity between the core and the jacket. The unit length is not so much limited for practical reasons to 1 km (as for ITER) but by the spool mass (∼40 t/km).

The box layout using Rutherford cable requires a special cabling machine at the coil winding site in order to perform the final assembly in line or at least on site. Junctions of elementary conductors can be made allowing very long conductor unit lengths with efficient use of all materials. A copper electrodeposition must be done on each aluminum material to allow soft soldering that can be done during coil winding after the conductor pre-bending stage in order to limit the solder plastic deformation.

V. Conclusion

For 20 m long detector magnets providing 6 T in a 12 m bore with 50 GJ stored energy, large scale conductors with typically some 1200 mm2 cross section are required with low current density (~10 A/mm^2). Options for selecting structural and stabilizing materials like various Al alloys, stainless steels and copper as constituents in the conductor were studied. With the sever constraint of elongation limit for high RRR stabilizer under 0.15%, the most materials cost efficient way is using a strong aluminum alloy as 6082 to satisfy both structural and thermal requirements without using high purity aluminum around the NbTi which is more expensive. Material ratios in the conductor section may be tuned to fulfill additional constraints as fault scenarios. A cost effective may be to use a standard sub-conductor for use in a few variants of Rutherford cable based conductors to facilitate conductor grading across the coil windings and tune the conductor for low and high field sections in the coils. Depending on detector physics requirements concerning particle transparency and magnetic field map modeling, the use of magnetic material as high strength magnetic steel, may lead to a cost reduction. As the design of the detector is still evolving and so the conductor configuration, but elementary conductor manufacturing and short trial units of full conductors can be developed to make steps forward in preparing the manufacturing process.

REFERENCES

[1] M. Mentink *et al.*, "Design of a 56 GJ twin solenoid & dipoles detector magnet system for the Future Circular Collider," in *Proc. EUCAS Conf. Lyon*, 2015.

[2] L. Rossi *et al.*, "Progress on the conductor for the superconducting toroid of ATLAS experiment," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 369–372, Mar. 2000.

[3] B. Blau *et al.*, "The CMS conductor," in *Proc. IEEE 17th Int. Conf. MT*, Geneva, Switzerland, Mar. 2002, pp. 345–348.

[4] B. Blau *et al.*, "The CMS conductor," *IEEE Trans. Appl. Supercond.*, vol. 12, no. 1, pp. 345–348, Mar. 2002.

[5] J.-L. Duchateau *et al.*, "Development of high current high field conductors in Europe for fusion application," *Supercond. Sci. Technol.*, vol. 15, no. 6, pp. 817–829, 2002.

[6] Y. Shirai *et al.*, "Transient stability analysis of large scale aluminum stabilized superconductor cooled by He II," *IEEE Trans. Appl. Supercond.*, vol. 18, no. 2, pp. 1275–1279, Jun. 2008.

[7] K. T. Hartwig and G. S. Yuan, "Energy loss, anisotropy, magnetoresistivity in aluminum strained at 4.2 K," *IEEE Trans. Appl. Supercond.*, vol. ASC-23, no. 2, pp. 1409–1412, Mar. 1987.

[8] S. Sequcira Tavares, A. Calvo, A. Desirelli, and S. Sgobba, "Mechanical characterization and assessment of the CMS conductor," *IEEE Trans. Appl. Supercond.*, vol. 10, no. 1, pp. 399–402, Mar. 2000.

[9] I. Horvath *et al.*, "Toward an improved high strength, high RRR CMS conductor," *IEEE Trans. Appl. Supercond.*, vol. 16, no. 2, pp. 530–533, Jun. 2006.

[10] A. Devred *et al.*, "Challenges and status of ITER conductor production," *Supercond. Sci. Technol.*, vol. 27, no. 4, 2014, Art. no. 044001.