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EuCARD-2

Enhanced European Coordination for Accelerator Research & Development

# Journal Publication

# Accelerator Quality HTS Dipole Magnet Demonstrator designs for the EuCARD-2, 5 Tesla 40 mm Clear Aperture Magnet

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# Accelerator Quality HTS Dipole Magnet Demonstrator Designs for the EuCARD-2, 5 Tesla 40 mm Clear Aperture Magnet

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***Abstract* – Future high-energy accelerators will need very high magnetic fields in the range of 20 T. The EuCARD-2 work-package-10 is a collaborative push to take HTS materials into an accelerator quality demonstrator magnet. The demonstrator will produce 5 T standalone and between 17 T and 20 T, when inserted into the 100 mm aperture of Fresca-2 high field *out-sert* magnet. The HTS magnet will demonstrate the field strength and field quality that can be achieved. An effective quench detection and protection system will have to be developed to operate with the HTS superconducting materials. This paper presents a *ReBCO* magnet design using multi strand Roebel cable that develops a stand-alone field of 5 T in a 40 mm clear aperture and discusses the challenges associated with good field quality using this type of material. A selection of magnet designs is presented as result of a first phase of development.**

*Index Terms*—**Accelerator magnet, EuCARD-2, Superconducting Magnets, HTS magnet design, quench protection, YBCO Roebel cable, ReBCO.**

## I. Introduction

EuCARD-2 is a European, EC-FP7 supported, collaboration intending to develop a High Temperature Superconductor (HTS) accelerator quality magnet demonstrator, capable of producing a 5 T central magnetic field in standalone configuration [1]. In a second stage the field is increased further, ~17 T, when inserted in the high field aperture of Fresca-2 or similar. As a design constraint the EuCARD-2 magnets must contain all forces without relying on mechanical support from the structure of Fresca-2 [2]. Both *ReBCO* and *BSCCO* conductors are being considered, however due to the complexity of the reaction treatment for high performance *BSCCO*, this design is part of the US program, supported by the US-BSCCO collaboration, based on the Canted Cosine-Theta (CCT) geometry [3],[4].

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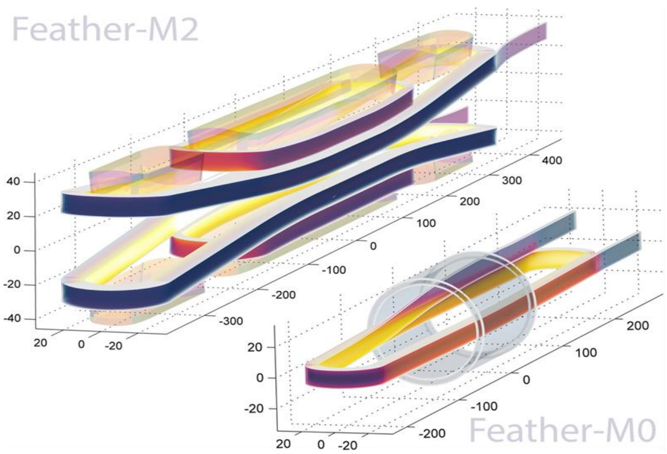



Fig. 1. Aligned block development HTS magnets, (bottom right) Feather-M0 quench detection development coil, (top left) Feather-M2 the EuCARD-2 five Tesla standalone approaching accelerator field quality insert magnet.

The EuCARD-2 dipole magnet design is therefore focused on *ReBCO* coated conductors. As part of the EuCARD-2 project [1],[5], a number of collaborating laboratories, universities, and industry are working together to achieve the above mentioned goal. CERN is specifying and procuring the ReBCO Roebel cable in collaboration with KIT and other institutes. As the result of a broad design study, two magnet designs are being developed, aligned block and cosine-theta. CERN is focusing on the design and construction of a set of novel aligned block designs, named Feather-M0/2 [6]. Feather-M0 is used to develop coil winding and quench detection. Feather-M2 is the EuCARD-2 insert-magnet (see Fig. 1). CEA Saclay is studying a *ReBCO* classical cosine-theta design [7]. A new finite element quench code for HTS coils is being developed by the Tampere University of Technology (TUT), and INFN Milan is preparing a low temperature test station for the standalone test for the final magnet. The 13 T Fresca-2 magnet has a 100 mm diameter clear aperture, which is under construction at CERN.

This paper compares the different design options for

EuCARD2 and discusses the challenges for the design and construction of an HTS accelerator quality magnet.

## II. Roebel Cable

The use of cable offers the possibility to increase the current that is transported in a single turn of the magnet winding. High current will reduce the required number of turns and therefore inductance. This leads to the possibility of faster current extraction for protecting longer magnets, a common practice in large scale applications. The Roebel cable was selected because it has the overall engineering current density to meet the field requirements. In addition, the tapes in the cable are transposed with respect to an external transverse field, which should help reduce transient time constants, and improve current sharing. However it should be noted that the individual tapes are not transposed like the filaments in a Rutherford cable. Because Roebel cable is relatively new in the field of magnet technology the following development steps are taken.

### *A. Dummy Cable Production*

For initial mechanical tests, short lengths of cable are required. Because of the high cost of such HTS cables, and because the mechanical properties of the ReBCO tape are dominated by the hard steel substrate, several lengths of dummy cable were produced from 0.1 mm thick stainless steel tapes. The precise shape is cut from a wide sheet using chemical etching at CERN, or fine blanked in a semi-automatic Roebel cable manufacturing line at KIT. The cable was assembled by hand, from short lengths of 2 m, at CERN, and up to 20 m of cable was produced at KIT, (see Fig. 2). Cable assembly was a lengthy and a delicate process. Manufacturing longer cable lengths is an issue that will require demonstration. The dummy cable was used to perform a number of tests: coil winding, cable hard way bend, cable insulation, and stacked cable compression tests.

### *B. Mechanical Winding Tests*

Previously KIT has experimentally determined the minimum easy-way-bend to be 11 mm radius [8]. For the hard-way-bend radius, needed for the layer jump, a series of tests was performed. During the tests a dummy cable was clamped underneath a glass plate while being bent over a length of ~50 cm. The cable achieved a 2 m radius hard-way-bend without buckling the individual tapes. This is a larger value than the theoretical strain limits in the tape, which predict 0.9 m. Winding the tape around a 70 mm diameter rod highlighted the problem of longitudinal slippage between tapes. This is a complex problem caused by the difference in arc-length when the cable is wound around the coil end. There is no immediate solution. Axial cable tension applied during winding must be limited to prevent damage.

### *C. Compression Test and Impregnation*

The bare cable is cut into 20 cm long sections and assembled into a stack. The stacks of conductors are then compressed up to 150 MPa. This is the calculated transverse average stress expected in a 20 T coil. The resulting severe plastic deformation to the cable (see Fig. 3) confirms the need to protect the cable by impregnation. This instigated a search for a suitable resin capable to fully impregnate the coil and support each tape from the scissoring action of the adjacent tapes.

Fig. 2. Roebel cable, 20 m, dummy stainless steel, supplied by Karlsruhe Institute of Technology Institute for Technical Physics (KIT).

A further series of pressure sensitive film tests highlighted the differences between even and odd numbers of tapes [9]. Due to the geometry of the cable, wrapping with insulation compresses the cable width significantly so is not suitable as an insulation system. We selected glass-sleeve insulation similar to $Nb_3Sn$ magnets. Testing of many resins is ongoing [10]. A promising results obtained with resin/silica mixture.

Fig. 3. Damaged dummy stainless steel Roebel cable after loading the bare cable up to 150 MPa.

### *D. Finite Element Roebel Cable Model*

As a result of the compression tests, a parametric, finite element model was built to investigate the stress history during manufacture, cool-down and powering of the impregnated Roebel cable. The model highlights the need to control the thermal contraction of the resin-cable assembly [10], [11] and the need to perform impregnation, cool-down, and load testing with real superconducting tapes.

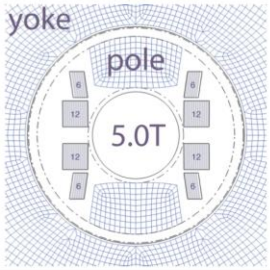
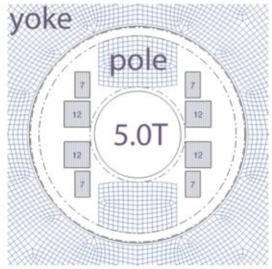
## III. Cross Section Layout Comparison

The hunt for a promising cross section that meets all the requirements has led to a comparison of many cross section layouts: cosine-theta, normal rectangular block, and ultimately aligned block designs. The most promising layout options from this study are presented in Table I.

### *A. Attainable Magnetic Field*

The current densities of most layouts are set to 70% on the load line, for both 5 T standalone mode and when operated as an insert in a 13 T background field. During the studies it was found that the critical current of the coil blocks could be increased by aligning the tapes with the magnetic field lines. This aligned block layout is an improvement over the normal block, especially when operated in a background field. It can be seen that a higher magnetic field can be reached with less conductor. In a standard low temperature superconductor the short sample limit would be in the high field position, but here the position moves to the upper and lower edges of the coil blocks where the field angle is less well aligned with the tape. For the cosine-theta design achievable current density is much lower due to the perpendicular magnetic field located on the mid-plane. This means that this layout requires the use of more conductors to attain the 5 T in standalone. In addition a lower field is attained when operated in a background field. However due to the lower current density the cosine-theta is a viable option for the final design, as it may be easier to protect against quenches.

TABLE I
COMPARISON BETWEEN THE THREE MOST PROMISING MAGNET CROSS SECTIONS DESIGNS.

| **parameter name** | **1 - Aligned block** | **2 - Normal block** | **3 - Cosine Theta** |
|---|---|---|---|
| coil layout |   |   |   |
| **general** | | | |
| cable width / thickness | 12 mm / 0.8 mm | 12 mm / 0.8 mm | 10 mm / 1.2 mm |
| required bend radius | 16 mm | 16 mm | 7.5 mm |
| number of turns | 12/6 (18) | 12/7 (19) | 4/5/3 – 6/10/4 (32) |
| block area (all quadrants) | 790 $\mathrm{mm}^2$ | 909 $\mathrm{mm}^2$ | 1827 $\mathrm{mm}^2$ |
| inductance (w.o. iron) | 0.29 mH/m | 0.31 mH/m | 0.80 mH/m |
| **standalone (in yoke)** | | | |
| percentage on loadline | 70% | 70% | 60 % |
| current density (block) | 648 $\mathrm{A/mm}^2$ | 635 $\mathrm{A/mm}^2$ | 387 $\mathrm{A/mm}^2$ |
| critical current density | 1216 $\mathrm{A/mm}^2$ | 1164 $\mathrm{A/mm}^2$ | 915 $\mathrm{A/mm}^2$ |
| cable operating current | 7905 A | 7747 A | 5526 A |
| dipole field B1 | 5.0 T | 5.0 T | 5.0 T |
| harmonics b3 / b5 / b7 | 8 / 5 / 2 units | 16 / 1 / 0 units | 0 / 0 / 0 units |
| estimated coil pressure $\perp$ | 17 MPa | 17 MPa | 20 MPa |
| **in 13 T background field** | | | |
| percentage on loadline | 70 % | 70 % | 70 % |
| current density (block) | 667 $\mathrm{A/mm}^2$ | 530 $\mathrm{A/mm}^2$ | 283 $\mathrm{A/mm}^2$ |
| critical current density | 1282 $\mathrm{A/mm}^2$ | 1068 $\mathrm{A/mm}^2$ | 477 $\mathrm{A/mm}^2$ |
| cable operating current | 8137 A | 6466 A | 4041 A |
| dipole field B1 | 16.9 T | 16.2 T | 15.8 T |
| harmonics b3 / b5 / b7 | 13 / 3 / 0 units | 4 / 0 / 0 units | 6 / 0.4 / 0.1 units (in Fresca2) |
| estimated coil pressure $\perp$ | 110 MPa | 87 MPa | 51 MPa |

## *B. Field Quality*

Due to the aperture restrictions of Fresca-2 and the width of the cable, it is not possible to position three blocks above the mid-plane. This means that the (aligned) block layouts are limited to two decks, which when optimized for $b_3$ field quality leads to an open mid-plane design. To be able to fit in the layer jump it is necessary to align the inner turns of the wing and central decks. In order to attain $b_3$ field quality it is necessary to add a set of magnetic poles inside the wing coil. This also helps to achieve the stringent field strength requirement. However, due to saturation, a non-linear term in the harmonics is introduced. The bend radius required for the coil ends of the classical cosine-theta layout, with good field quality, is currently smaller than the value at which significant degradation occurs. A solution for this problem could be the inclusion of an iron pole again at the cost of non-linearity. However for future *ReBCO* magnets it is expected that dynamic field quality, caused by shielding currents in the wide tapes [6], could be the real issue. Measurement of harmonics during cold testing of Feather-M2 should clarify achievable dynamic field quality.

## *C. Mechanical Considerations*

In the background field the stresses in the coil blocks are significantly higher than for standalone. In the aligned block layout, these forces are directed perpendicular to the broad side of the cables. For the cosine-theta it varies from perpendicular to parallel. Large forces will be applied at the sharp edges of the Roebel cable, creating insulation challenges. On the broad face, line stresses due to scissoring between tapes are the challenge. The stresses presented in Table I, are the “perpendicular magnetic force” divided by the width of the Roebel cable. Detailed finite element modelling will follow with the final mechanical magnet designs.

# IV. QUENCH STUDIES

Due to the low normal zone propagation velocity [12] it may prove difficult to protect magnets constructed using *ReBCO* coated conductors. This section presents the development work and proposed tests.

### A. Time, Temperature, Voltage Estimates

Tampere University of Technology Finland is developing a general quench model for the analysis of HTS magnets [13]. Fig. 4 shows results from simulations. The temperature rises quickly. Therefore it is important to detect the quench during the very early stages. During this phase the voltages are very small, predicted in the order of 1 or 2 mV. If we limit the hot spot temperature to 400 K, the total time to detect and extract the current is ~60 ms at 8.2 kA and ~130 ms at 6 kA.

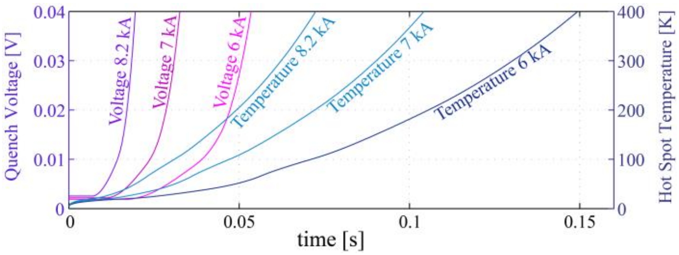



Fig. 4. Hot spot temperatures and quench voltages calculated at constant current in the Feather-M0 coil using the TUT finite element model.

### B. Quench Detection

A multi-detection system incorporating voltage taps, pickup coils, magnetic probes, fiber optics, and acoustic sensors is foreseen [14-18]. During cold testing a fast data acquisition system featuring a *field-programmable gate array* (*FPGA*) [19] will be used to simultaneously acquire signals to compare the performance of the different detection methods. Testing will prove if the multi-tape Roebel cable structure will obscure the quench signals, preventing timely quench detection.

### C. Quench protection

Standard quench protection strategies can be employed for the standalone, low inductance coils of Feather-M0 and Feather–M2 namely, using an external dump resistor and negative power supply voltage to rapidly extract the magnet energy. The situation becomes more difficult when the magnet is inserted into the high field $Nb_3Sn$ aperture of Fresca-2 [20]. For this case, fast current extraction of the insert followed by opening of a semiconducting switch is studied. This is followed by dump of the Fresca-2 magnet. In addition it is possible to use copper loops, which form part of the Feather-M2 magnet structure (see Fig. 5). When the dump resistor is switched in the circuit, the current inside the coil is inductively transferred to the loops within milliseconds, protecting the magnet in standalone mode as well as in Fresca-2 configuration. The relatively slow current decay of Fresca-2 limits the induced current in the loops, avoiding significant heating (maximum temperature is ~100 K). The resulting Lorentz forces are supported by the magnet structure. The estimated field error developed during operational ramping, due to the loops, is estimated to be less than one unit of the principal dipole field. The loops also provide conduction cooling close to the coil outer surfaces.

## V. Magnet Assembly

The layer jump section of the coil is first placed in a mold that forms the 'S' shape of the layer jump. The layer jump is impregnated to fix the cable in position. It is then fitted into the coil winding/impregnation tool. The coil will then be wound with low actual cable tension to prevent damaging individual tape. A moderate cable transverse pressure is applied to produce a relatively low contact resistance between tapes after which the coil is impregnated. The finished coil is then mounted onto the titanium former. Fig. 5 presents Feather-M2 cross-section with copper loops (ICEE) that fill the space between the coil and high-strength external support. The full assembly is then impregnated. On cooling to 77 K or 4 K, the external high strength super-alloy support cylinder contracts more than the titanium former and coil. This places the coils under a small compressive stress. We expect to unload the coil on the inner coil surface during magnetic powering at high fields. Any resulting movement of the coil should not pose a problem as at 6 kA the temperature margin is ~28.6 K.

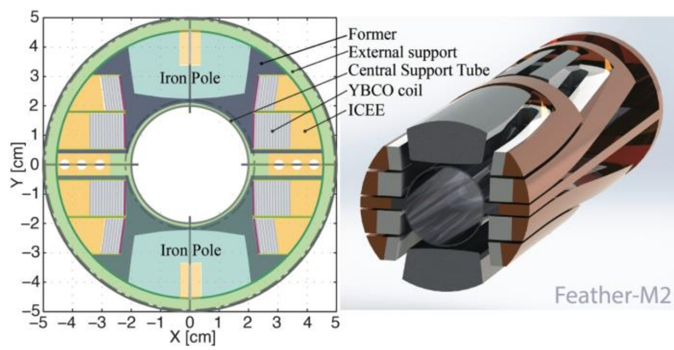



Fig. 5. (left) Feather-M2 magnet cross-section, (right) Inductively Coupled Energy Extraction copper rings (ICEE's). Magnetic poles top & bottom.

## VI. Test Planning

### A. Feather-M0

Feather-M0 is planned to be tested in liquid nitrogen at 77 K, ~1.5 kA, then tested in liquid helium at 4.5 K list of operating currents (see Table I ), to fine tune the quench detection system.

### B. Feather-M2

A mechanical model is foreseen to be able to estimate stresses during cool-down. Feather-M2 will be equipped with a quench detection system optimised during testing of feather-M0. Room temperature field quality measurements are foreseen, and then testing at higher temperatures 80 K, then in steps down to liquid helium operation at 4K will be performed. Dynamic field quality will be measured.

## VII. Conclusion

The EuCARD-2 project to develop a 5 T standalone operation, 40 mm aperture, HTS dipole that approaches accelerator quality is advancing rapidly. In a second step it is foreseen to approach a 17 T central field when inserted in a

13 T high field magnet. Model coils are under construction, cables and magnet designs are progressing. Models will test dynamic field quality and confirm if it is possible to detect and protect the *ReBCO* high current density present in the aligned Roebel cable design. Mechanical stress in *ReBCO* tapes needs careful design to avoid degradation. A design based on a cosine-theta is also under consideration.

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