Cluster Initiative for Superconducting CCT Magnet Innovation

Abstract

The Cluster Initiative aims to develop an innovative Canted Cosine-Theta (CCT) superconducting magnet and qualify as supplier to national and international research infrastructures such as CERN, the European Laboratory for Particle Physics, suppliers of medical equipment, and others. The Cluster collaborates with regional innovation-promoting activities.

Superconducting magnets are increasingly becoming an important tool in science, medicine and industry. The proposed project will be the first full development of superconducting magnets in Sweden and offers Swedish industry the chance to master the required technology.

1. Introduction

The Cluster Initiative aims to use its unique competence to develop an innovative Canted Cosine-Theta (CCT) superconducting magnet. The proposed magnet is based on specifications supplied by and of direct interest to the research infrastructure at the CERN European Laboratory for Particle Physics. These superconducting magnets are crucial to reach the optimal machine parameters for the experiments at CERN to perform their physics research. The proposed innovative CCT magnet can in the future replace existing magnets of an older type that have reached their end-of-life. Successful completion of the project will qualify the Cluster Initiative as a supplier of superconducting magnets to CERN.

The present technology used for superconducting accelerator magnets is based on a flat cable that is wound around a temporary mandrel. Two such windings are placed face-to-face around a cylinder through which the particle beam passes, as shown in Figure 1. The CCT technology offers an efficient and cheaper manufacturing method by abolishing the flat cable in favour of single wires that are installed in a groove inside a mandrel.

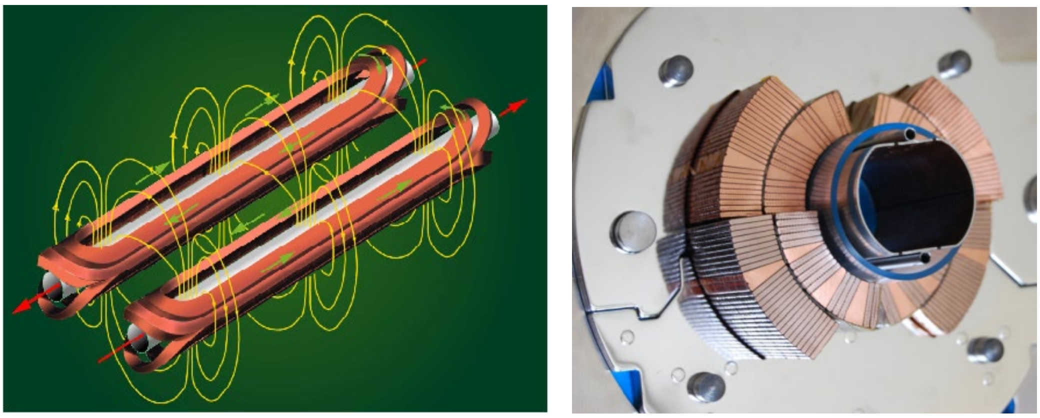

Figure 1: Schematic of a traditional dipole type accelerator magnet. Courtesy CERN.

2. Project Background

The canted cosine-theta (CCT) concept, first introduced in [MEY1970], is based on opposing canted solenoids. Two canted solenoids with opposite skew create a dipole field as the horizontal component of the magnetic field is canceled between the two solenoids while the vertical field is reinforced. The canted solenoids create a current density that is close to a perfect "cosine-theta" distribution and therefore a completely uniform magnetic field distribution that does not require field optimization unlike a classical cosine-theta design. The field volume is used very effectively and no special end effects are created, nor are any special end layouts required unlike a classical cosine-theta design. The mechanical construction and winding process can be simplified as compared to a classical cosine-theta design as the individual turns of the solenoid windings are positioned inside a groove in the mechanical support former. The Lorenz forces on the windings are thus redirected into the former. The circular coils and the compact structure of the resulting cylindrical formers simplify the handling and assembly processes.

The CCT concept has never before been used in a particle accelerator. It is now proposed to be used for the MCBC/MCBY orbit correctors for the CERN LHC accelerator. The CCT concept should be easier and thereby more cost effective to manufacture than a comparable classical cosine-theta magnet with ribbon wire which are presently used and manufactured in the early 2000's. These magnets have reached their end-of-life due to ionizing radiation damage. It is expected that the CCT type magnets will be more radiation resistant due to the manufacturing method as opposed to the ribbon wire in which the superconducting wires are kept together by a resin.

The CCT concept has not yet been proven in practical use and in series manufacturing. Therefore, it is essential to develop a first magnet in collaboration between industry and academia. The CCT design shall have the same volume, the same connections, and deliver the same magnetic field strength as the classical design presently in use at the CERN LHC accelerator. A major consequence being that it is limited to an operational current of only 100 A.

In 2018, Scanditronix Magnet AB received support from the Swedish's Innovation Agency VINNOVA to develop a short 50 cm model CCT magnet in collaboration with the FREIA Laboratory at Uppsala University and CERN. A view of the mandrel and winding tool is shown in Figure 2. The 50cm long mandrel, manufactured by the Oxford University mechanical workshop, has a groove to accommodate 10 strands of superconducting wire which are wound simultaneously. The completed winding is shown in Figure 3. Two mandrels with windings in opposite direction are prepared and then mounted inside each other. The 20 superconducting wires are soldered together in an internal connection box, shown in Figure 4, to create a single continuous wire and magnet winding. Additional so-called "voltage taps" are installed which are in fact simple copper wires soldered to the superconducting wire to monitor the voltage drop in the magnet. These voltage taps are important to monitor the behaviour of the magnet.

After completion of the model magnet, it was shipped to CERN in early 2019 for testing. Unfortunately, the magnet developed an electric short in its internal connection box. This has been repaired by Scanditronix Magnet AB and the magnet is now awaiting test at liquid helium temperature, delayed due to availability limitations at the CERN magnet test stand.

Figure 2: View of the mandrel and winding tool at Scanditronix Magnet AB.

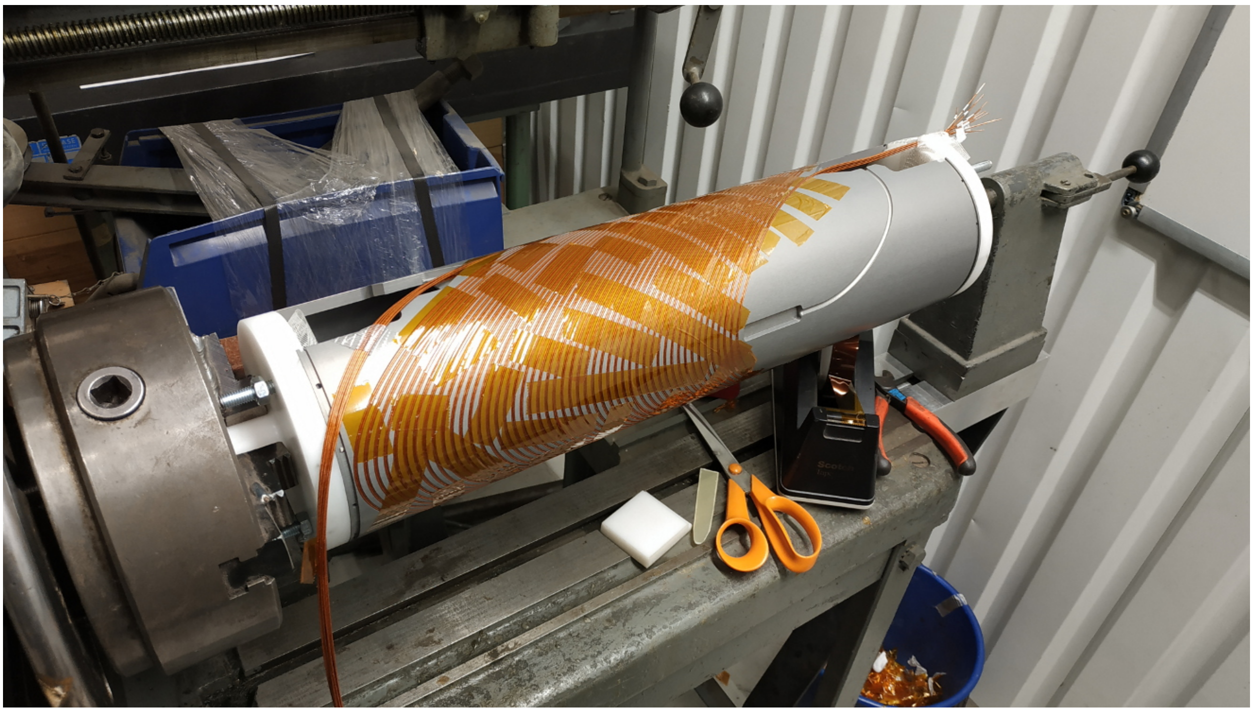

Figure 3: Winding of a short 50cm model CCT at Scanditronix Magnet AB.

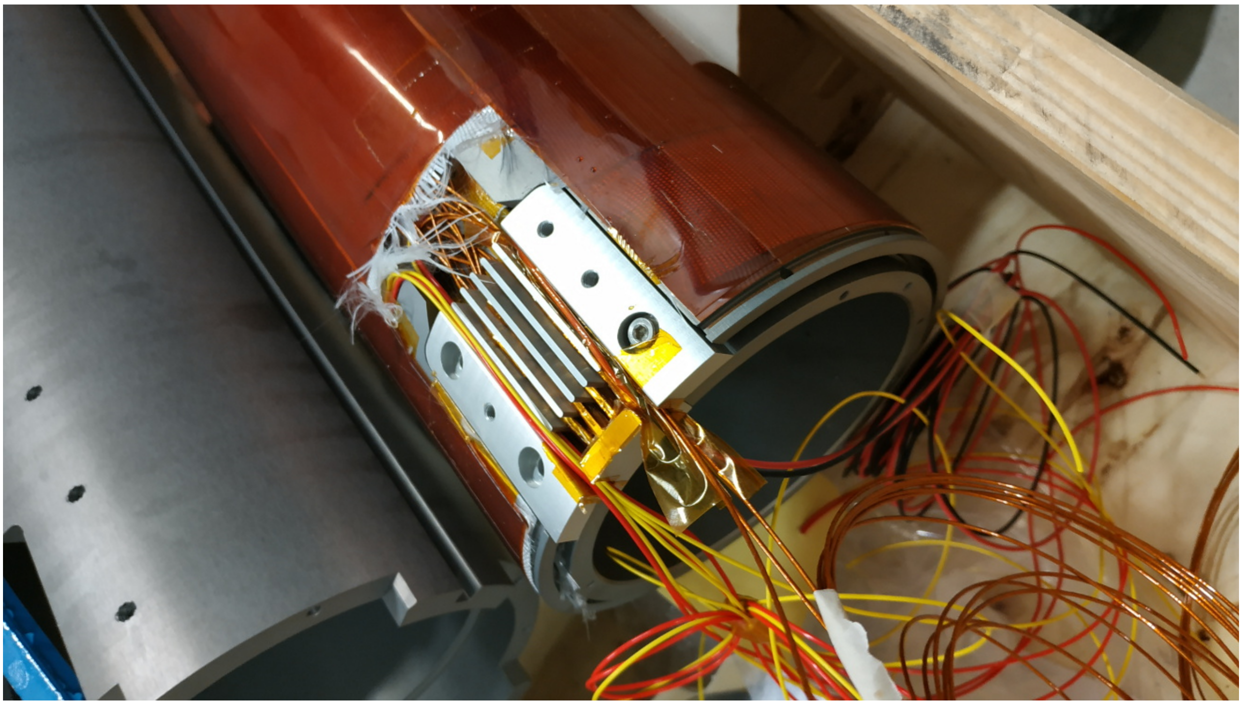

Figure 4: The internal connection box.

3. Project Technical Description

The Cluster Initiative aims to manufacture a complex and realistic superconducting CCT magnet, similar to a design that could actually be used in an accelerator. The CERN LHC accelerator incorporates so-called orbit corrector magnets which are grouped in double aperture magnet assemblies as shown in Figure 5.

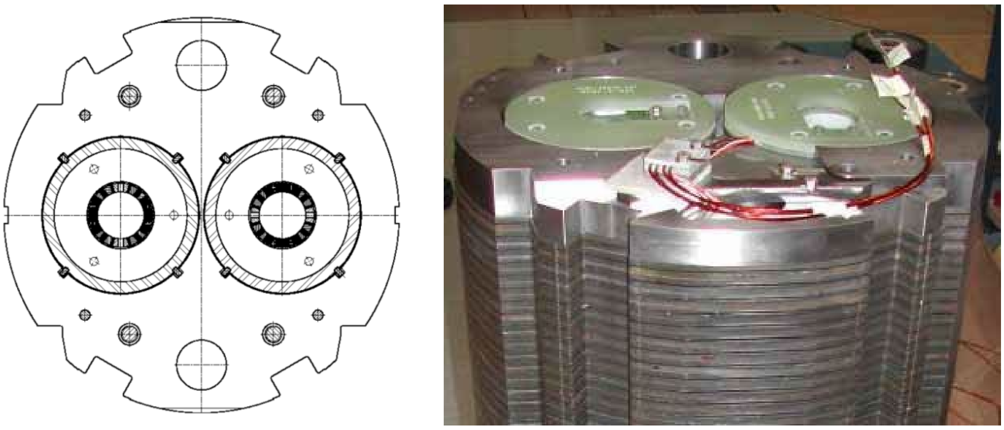

Figure 5: Cross section of a double aperture magnet assembly layout (left) and view of a prototype assembly (right).

3.1. Technical Requirements

The magnet shall provide a field of 3.11 T at a current of 100 A and temperature of 1.9 K. The magnets have an aperture diameter of up to 70.4 mm for the particle beam to pass through, a magnetic length of 900 mm, an overall length of 1100 mm and outer diameter of up to 475 mm. The design of these orbit correctors must fit with tight field quality requirements which is inherent part of the CCT concept due to the high field quality of a solenoid.

3.2. Conceptual Design Idea

The CCT concept, first introduced in [MEY1970], uses two canted solenoids with opposite skew to create a dipole field, as the axial field components of the two solenoids are opposite and cancel each other while the transverse components are parallel and thus reinforce each other. The canted solenoids create a current density that is close to a perfect "cosine-theta" distribution and therefore a completely uniform magnetic field distribution that does not, contrary to a classical cosine-theta design, require field optimization [RAB1934]. Furthermore, the field volume is used very effectively and no special end effects are created, nor are any special end layouts required unlike a classical cosine-theta design. The mechanical construction and winding process is much simplified as compared to a classical cosine-theta design as the individual turns of the solenoid windings are positioned inside a groove in the mechanical support cylinder called the mandrel or former. The Lorenz forces on the windings are thus redirected into the mandrel. The circular coils and the compact structure of the mandrel simplify the handling and assembly processes.

First, we will manufacture one full length test mandrel and winding to assemble a coil and test all steps in the manufacturing and assembly process. It could be wound using a copper wire in case the superconducting wire is not yet available. This set will be used to test the manufacturing equipment and train the personnel. Finally, we will manufacture three complete full-length coils. Two of the three coils will be integrated into an iron yoke to form a complete magnet. The third complete coil will be used as spare in case of a problem with one of the two main coils for the magnet and is available for destructive test and inspection methods.

3.3. Required Technologies

Each magnet assembly is composed of two dipole magnets integrated in an iron yoke with connecting superconducting current leads. Each dipole magnet contains two coil windings. A CCT type magnet has two independent windings in cylindrical formers sliding over each other, with a third former for mechanical support sliding over the outer most winding. The coil windings are joined through resistive splices. The magnets will be equipped with electrical and cryogenic instrumentation, including voltage monitoring of the splices.

All welded, sealing, and epoxy resin solutions shall comply with and will require specific manufacturing precautions (in particular choice of materials, machining and quality) and industrial controls according to strict procedures and non-destructive testing methods (X-rays, etc.). All cryogenic and mechanical supporting systems shall be in non-magnetic metal or low thermal conductivity composite materials. Thermal contraction compensating elements like bellows and flexible houses are very critical elements and will have to be supplied by qualified specialized manufacturers.

All winding and assembly process shall be performed in an environment free of dust, metallic particles, or other contaminants. The facility shall be equipped with all necessary services and infrastructure. The assembly will entail precise mechanical fitting, pressurized and heated application of epoxy resin, soldering of superconducting splices, routing of electrical circuitry.

All tests and measurements carried out during all stages of the production, from raw material procurement up to delivery, shall be individually recorded and documented per magnet in the Quality Control records.

4. Innovation Solutions

The CCT magnet design in itself is an innovative solution as it has never been used as a functional magnet in a working accelerator or instrument.

The main problems identified that require innovative solutions are explained below.

4.1. Superconducting Rope Cable

The 50cm model CCT prototype manufactured by Scanditronix Magnet uses a 0.3 mm diameter superconducting wire. Prototypes manufactured at CERN use the same wire. This wire can be used up to 400 A electric current, and typically, 10 windings are made in the mandrel slot giving an effective electric current of 4'000 A. For this design however we are limited to 100 A electric current in order to use existing power supplies at the CERN LHC. To reach the same current density the amount of wires has to increase. An idea is to use a rope type cable with 7 wires: 4 superconducting wires at 100 A each, and 3 copper wires for quench protection. Each wire would be 0.3 mm diameter with individual electric insulation. The combined rope wire would be 1 mm diameter but would not be insulated to enhance inter-rope quench propagation.

4.2. Soldering of the Superconducting Cable

A dipole magnet requires two canted solenoids connected in series. Each of the solenoids has ten windings in its mandrel. Using the 7-strand rope wire suggested above required an interconnection of 7 x 10 x 2 = 140 wires in the internal connection box. Voltage taps shall be added. The ground insulation resistance shall withstand a voltage of at least 1.5 kV DC between the conductor and ground.

4.3. Mandrel Manufacturing

Until recently the accurate manufacturing of the mandrel was the main dilemma. Nowadays this has become possible with the advent of accurate multi-axis milling machines that can prepare large objects. These are however not yet widely available and only a handful capable manufacturers have been identified in Europe so far by CERN. The minimum safe distance between slots in the mandrel is assumed to be 0.3 mm. If the slot distance is smaller, it becomes mechanically unstable. A larger distance decreases the winding density and thereby the electric current density and magnetic field strength of the magnet.

4.4. Passive Quench Protection

A quench simulation of the magnet shall be performed to verify if a passive quench-back is sufficient to protect the magnet or if active quench heaters or current extraction is required. Quench-back heating is obtained by the copper strands in the rope cable and the (aluminium) mandrels.

4.5. Cost Effective Iron Yoke Laminations

Stamping of the iron yoke laminations is expensive due to the cost of the tooling. Laser cutting is an option, but this requires additional wire cutting of some final and accurate details. An innovative alternative is to use cutting by water jet of the whole lamination.

5. Project Schedule

An overview of the project time line is shown in Figure 6. Qualification of the 50cm short model already manufactured by Scanditronix Magnet AB shall be performed at the FREIA Laboratory during the fall of 2020. The conceptual and engineering design of a full scale 1m long magnet will be prepared under 2020 and 2021. This includes the studies and possible engineering modifications required for passive quench protection. During the second half of 2021 the manufacturing drawings are prepared for a test winding, which is manufactured and tested during 2022. During 2023 the final windings will be manufactured, assembled into a complete magnet, and tested.

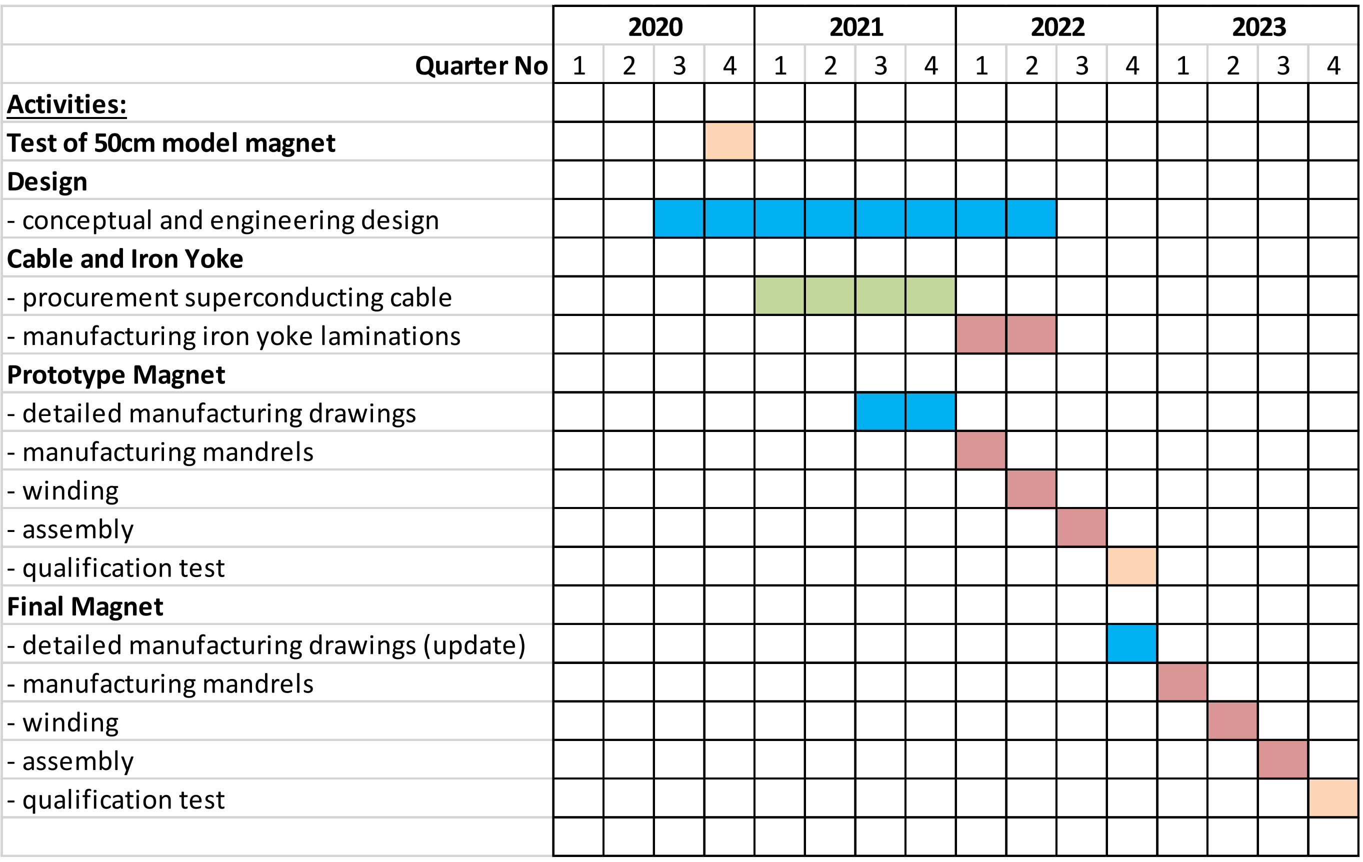

Figure 6: Time schedule for the magnet development.

6. References

[MEY1970] D.I. Meyer and R. Flasck, *A New Configuration for a Dipole Magnet for Use in High Energy Physics Applications*, Nucl. Instr. Meth. **A80** (1970) 339-341.

[RAB1934] I.I. Rabi, *A method of producing uniform magnetic fields,* Rev. Sci. Instr. **5** (1934) 78.