Next generation materials for future magnet development at CERN

Glyn Kirby
CERN, Route de Meyrin 385 · 1217 Meyrin, Switzerland
Glyn.Kirby@cern.ch

Abstract. Looking into the future of CERN’s higher energy Accelerators, as in the Future Circular Collider (FCC) and beyond, 16T magnetic fields and above are needed. High Temperature Superconductors (HTS) are now delivering ultra-high fields, with 30 Tesla and higher being achieved by many groups around the world. CERN has the first results of using a high current (10 kA) HTS, with REBCO cables, in an Accelerator type magnet development. This paper presents the multiple technologies and new concepts that were used in the design, build, and testing of a set of high current dipole models. We present the technology advancements in the areas of: advanced modelling, materials used in the magnet construction, quench detection and protection, and field quality. Finally, we take a glimpse at CERN’s exciting 20+ Tesla accelerator conceptual magnet designs.

1. Summary of the talk
The talk looked at the studies on future circular high energy colliders that have been proposed. A critical parameter is the magnetic field that can be produced to deflect the beam, this keeps the size of the device manageable.

There followed a brief review of high field superconducting magnets (most of which are solenoids). The technology for these magnets uses HTS (High Temperature Superconductor) coil inserts to produce fields in excess of 30T. The highest to date is the 32T magnet at the National High Magnetic Field Laboratory in Tallahassee, Florida, US.

Existing high field accelerator magnets (Dipoles and Quadrupoles) can give up to 11T (CERN high luminosity project) which are based on Nb:Sn technology. In development are magnets to give fields in the region of 16 to 20T. Several laboratories around the world are engaged in this endeavour. Highlighted was the CERN Fresca2 14.6T 100mm aperture dipole.

In the quest for even higher fields HTS superconductors at low temperatures can be used. The limit for the use of these materials is far beyond 20T although they are limited by the expense. The Rare Earth Barium Copper Oxide (REBCO) conductors hold the promise of being affordable in a few years.

The processing of the material using the Powder In Tube (PIT) method to produce multifilamentary wire was described – this uses a silver tube on the outside. Early coils made from this process exhibited leakage caused by bubble formation and chemical incompatibility. Improvements resulting from new processing techniques have nearly doubled the current carrying capacity of the wire.

BSCCO (Bismuth Strontium Calcium Copper Oxide) wire has good performance but the heat treatment requirement is extremely demanding, particularly in that a gas over pressure, with a flow of Oxygen is needed to prevent wire leakages. For large coils a pressure vessel system is required.

REBCO (Rare Earth Barium Copper Oxide) conductors are usually made in tape form, which is available from a variety of suppliers. Long lengths are available. The options for manufacturing cables...
from HTS superconductors was explored and different geometries described, including the Cable On Round Core (CORC), Roebel type (used by CERN) and the twisted stack. The Roebel design was first made in 1914 by Ludwig Roebel for use with low loss copper cables.

With REBCO conductor the Roebel cable was found to give the highest current density at 20T over the other geometries but have the expense of cutting about 50% of the material out of the tape. The Roebel cable was produced by Karlsruhe Institute of Technology does not use a straight tape – it requires meanders which are produced with “punch and coat” method. The cables are then assembled with dedicated tooling. Epoxy impregnation was required to prevent adjacent tapes from cutting each other and degrading the performance of the cable. Different resins with glass sleeve insulation were investigated. The way that the coil is wound should try to direct the forces onto the steel tape, this is important – the force should push the thin superconducting layer on to the steel backing. If not, there is a chance that the superconductor will delaminate from the supporting steel tape.

The plot of critical current as a function of magnetic field and field angle to the conductor has been plotted and a numerical fit to the data established. One major advantage of HTS conductors is the stability arising from the high quench energies.

Modelling Roebel cable in an application is challenging – the wide tapes act as a single filament and the slow normal zone propagation velocity following a quench was thought to make protection difficult. Using an inductive voltage cancelation coil, imbedded in the main HTS coil showed that the large temperature margin was in fact giving several seconds of voltage signal that gives time to react and fully protect the coils. This has now lead to the possibility that such a system can protect the HTS coils so that they may never need to quench.

The Feather-M2 insert magnet was described. This development was done under the EuCARD2 programme and was one of the first HTS dipoles constructed using Roebel cable. The former was printed using additive manufacture from 316L stainless steel. The design cost was 30% of that using conventional techniques. The formers were hollow and light weight.

Samples showed an increase in the Yield stress from 260 M Pa to 470-530 MPa over the bulk material. The outer support for the final insert magnet will be manufactured from Inconel 718 using additive manufacturing. Heat treatment of the Inconel parts raised the Yield Stress from around 1000 M Pa to 1400 M Pa. The first set of magnet coils were tested in a variable temperature helium gas flow system. The test started at 80K with low current and low energy in the magnet. Then gradually the temperature was reduced and the current increased until the magnet was in 4.5 K liquid.

A test result on this magnet showed a 160% difference between the critical current at 10 μV/m and the eventual quench current. The conductor exhibited a stable regime above the critical current. It was found that if the electric field drifted, a current reduction of 100A resulted in immediate recovery. It is possible that this technique could be used to protect higher current density HTS magnets. This contrasts with the behaviour of low temperature superconductors for which there is little or no indication of a quench. Further investigations showed a temperature drift prior to the quench which is another useful indicator. Joining a Roebel cable is difficult and a new type of joint was used - “FinBlock”. Joint resistances using this method were 10-20nΩ and had a copper-like resistivity dependence with temperature. Persistent current effects were observed and these showed as a field difference between ramping up and ramping down of the magnet. These magnet developments are continuing and the next version will be made with ultra-high Jc cable manufactured by Bruker.

Future conductor development is continuing within the Aries collaboration with an aim to get a REBCO coated conductor with a Jc > 1000 A/mm².

Longer term, CERN is initiating a 10 year development programme to develop dipole magnets with magnetic fields beyond 20T. The Feather-M2 magnet previously described used the anisotropy of the critical current with respect to the field angle to optimise the performance. With artificial pinning in the more modern conductors this is less of an issue. In future magnets it may be necessary to reconsider the cable options. The Roebel cable has been discussed but there are the options of the cable on round core and twisted stack solutions. As cost is a major driver for HTS coils, we expect to develop new technologies, possibly simple stacked tapes with non-insulated coils. The problem of persistent currents is potentially solved by complex control loops or other new ideas.

There are two options for a high field dipole. The hybrid magnet approach has the disadvantage of needing to separate the forces from the Nb₃Sn outsert as this has a 150 M Pa pressure limit. This is not
an issue if we go to a full HTS magnet which can withstand pressure up to 400 M Pa. The full HTS magnet option seems to be easier to fabricate.

A conceptual design of a 20T dipole magnet has been considered and a critical design feature is the tight bend radius at the coil ends where the wire returns to the magnet body. A possible solution to this problem is to adopt a “clover leaf” geometry which takes the bend away from the dipole. Relatively large amounts of iron are required to reduce stray fields which may be impractical. An alternative could be to use active shield coils in a quadrupole configuration.

Some other CERN HTS projects are described including the development of a 150kA MgB₂ lead, the design of a proton gantry for hadron therapy and a HTS version of the ALPHA magnet spectrometer on the space station.

2. Conclusions

- HTS conductors are now being used to develop high field magnets.
- There are great opportunities to be inventive.
- BSCCO looks good for small coils
- ReBCO / YBCO has high Jc, long lengths, is expensive but there are many opportunities to take advantage of.
- I haven’t talked about MgB₂, and the Iron based conductors but they are coming.
- For accelerators HTS at low temperature 20 or 30 K may be the way to go!
- For the ReBCO tape we seem to have a way to protect using cables, or non-insulated coils.