NB$_3$SN ACCELERATOR MAGNETS - INSULATION REVIEW

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Abstract
In this paper we present a brief review of insulation techniques and consider the critical issues and limitations in relation to the technical challenge presented by future high field dipoles for accelerator application. We present the key issues and use these to define a preliminary insulation specification for a 15T magnet to be studied within the framework of the NED programme [1]. From the basic specification we outline a series of studies to be undertaken under the auspices of NED and look forward to see how we might improve insulation and magnet performance by improving our knowledge of materials.

1. INTRODUCTION

Electrical insulation is one of the most challenging issues governing the engineering exploitation of Nb$_3$Sn conductors. This is especially true for accelerator magnet applications where the requirement for high current operation and small bending radii dictate the wind and react manufacturing route. The status of insulation development for accelerator magnets has been reviewed by Devred [2].

2. INSULATION TECHNIQUES FOR ACCELERATOR MAGNETS

In this section we review the status of insulation technology and look at new or innovative developments which are underway. For convenience we refer to these as conventional and innovative.

2.1 Conventional

The conventional approach, established over some 10-20 years has been to use a glass or quartz tape wrap or a braid to insulate the basic cable. In some cases the glass insulation has been supplemented by mica film inserted between the turns e.g.: the University of Twente 11 T dipole [3]. In the earliest applications the tape or braid was applied to the cable with its commercial sizing intact. However, it was found that removal of this sizing at the Nb$_3$Sn heat treatment stage was difficult and could lead to poor electrical resistance levels between turns. Removal of the sizing is now usually done before applying the insulation to the cable. This does make the insulation stage more difficult and does make the insulation more fragile for winding.

Tape insulation is applied as a double layer wrap to give adequate overlap. Braid insulation can be applied using a specialised machine or for short lengths ~100 m the braid can be applied as a sleeve to the cable [4].

After insulation the cable is wound using a conventional machine but great care is required in handling of the cable, clamping and forming around the tight bends at the magnet ends. After winding the coil is clamped in a mould and undergoes the heat treatment process of ~1 week at 650 - 700 C. This heat treatment is carried out in a vacuum or inert (Argon) atmosphere. During heat treatment there is a risk of damage due to expansion movements. This risk will be increased for the long coils required for future accelerators.

After heat treatment the glass is extremely fragile and great care is required if the coil is to be transferred from a heat treatment mould to an impregnation mould. The final stage in coil manufacture is vacuum impregnation with epoxy. This is a relatively complex process with some risk of failure. It also represents a significant cost for large scale magnet production. Impregnation with epoxy means that helium is excluded from the winding and can play no part in coil stability or heat removal (except at the coil surfaces).

2.2 Novel/Innovative

While many variants/improvements on the conventional insulation route have been developed, the basic process remains similar to the one developed for some of the earliest Nb_3Sn filamentary magnets [5].

2.2.1 Sizing

Significant advances have been achieved by improvements in 'sizing' or in fact by 're-sizing'. Sizing is applied to the glass filaments by the manufacturer to allow commercial handling processes to be used to fabricate tapes.

The commercial sizing is organic and it is not easy to find the precise composition due to commercial secrecy. One approach has therefore been to remove the commercial sizing as a first step and to replace this with a known sizing material to aid conductor wrapping and coil winding. Such an approach has been successfully used by the Berkeley Group using palmitic acid to re-size insulation braid [4].

Apart from this improvement the other steps in magnet manufacture closely follow the procedure given in Section 2.1.

2.2.2 Inorganic/Ceramic route

A more radical approach is to replace the organic sizing with an inorganic or ceramic precursor. This approach is being developed at CEA Saclay and LBNL. In this approach the glass tape is impregnated with a ceramic precursor which fully penetrates the tape fibres. The tape is used to wrap the cable in the conventional way for coil winding.

The standard heat treatment to form the Nb_3Sn also achieves the heat treatment of the ceramic to give a robust insulation and a structurally complete coil. The coil will still have some porosity and the aim is to remove the impregnation stage. For this to be possible the insulation bonded with ceramic must have sufficient mechanical and electrical integrity for magnet assembly and operation. If some porosity can be maintained then helium will penetrate the winding to aid stability.

This route can also be finished by a vacuum impregnation. Significant advances have been made in tape preparation (see Fig. 1).

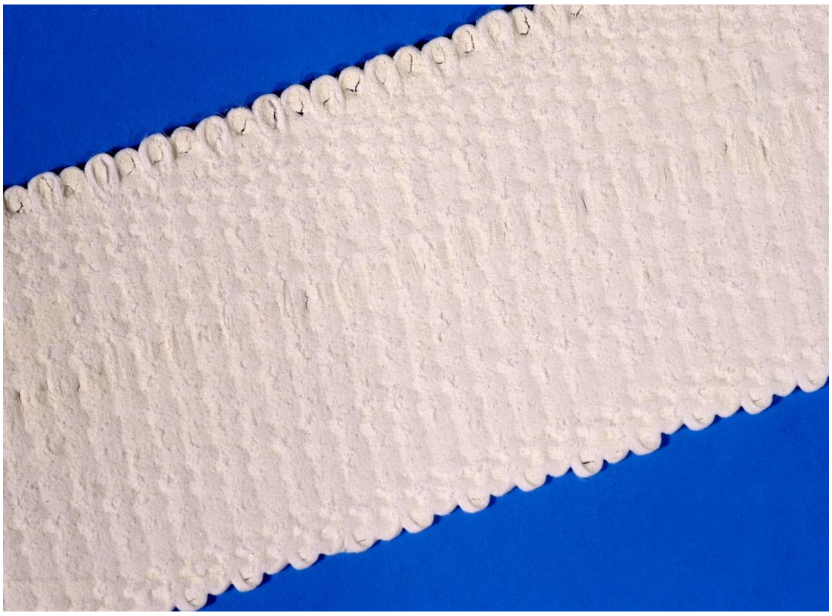

Fig. 1. Ceramic precursor on glass fibre tape produced by Saclay (Courtesy of Francoise Rondeaux)

3. INSULATION – KEY ISSUES, SPECIFICATION

In this section we address some of the key insulation issues and limitations and develop a target specification for a high field magnet.

3.1 Electrical Insulation Strength

The conductor insulation must have sufficient electrical integrity to withstand turn-to-turn voltages generated during a quench. Ground insulation i.e. to the coil support structure, will require a higher specification in terms of breakdown voltage but this can be achieved by additional insulation layers. In this context we consider only the insulation on the cable.

We estimate that the maximum turn-to-turn voltage generated in a quench of a 15 m accelerator dipole will be ~ 250 V which equates to an intrinsic voltage of ~ 600 V/mm for a typical insulation thickness of 0.4 mm turn to turn. Allowing for a safety factor of 4 these values translate into 1 kV turn to turn or 2-3 kV/mm in the insulation laminate. The dielectric strength requirements are therefore not especially demanding when compared with standard laminate (G10) materials which exhibit 20-30 kV/mm. However, these properties do have to be achieved through a complete winding, heat treatment, impregnation, coil assembly and thermal cycle process.

While dielectric properties are not so demanding the need for integrity is very high. Insulation failure will have serious consequences because of the high stored energy density in a 15 T dipole.

3.2 Thickness

Insulation thickness is important for 3 reasons:

3.2.1 Current density

Typically, the insulation will occupy ~20% of the winding space and will impact on current density overall. Current density improvement is therefore a driver to reduce insulation thickness

3.2.2 Thermal contraction

In a dipole winding the insulation will affect the azimuthal thermal contraction of the winding block. If the insulation is essentially a glass/epoxy laminate the transverse thermal contraction will be strongly dependent on glass content e.g. 50 % glass by volume will give an integrated thermal contraction 6-7x10^{-3} while 60 % glass by volume will give ~4x10^{-3} which is much closer to the conductor properties.

Low glass content will affect the pre-compression required at room temperature. However, the desire to compress the winding heavily at the impregnation stage to achieve high glass content must be tempered with the risk of crushing insulation and creating a fault. Over-compression at this stage may also prevent resin penetration which can also lead to reduced mechanical and electrical properties.

3.2.3 Winding modulus

Insulation thickness will affect the winding modulus and will influence movement under magnetic loads. Again the desire is to compress to reduce insulation thickness, increase glass content and hence modulus.

The above arguments are drivers for reducing insulation thickness. However, as discussed in Section 3.1 insulation integrity is paramount for production magnets. A very thin insulation, if it could be realised, would have little tolerance for cable imperfections and may be prone to damage at high loads. So the simple geometric spacing provided by the insulation is in itself an important factor which should not be discarded. In our view a robust insulation which facilitates coil manufacture with high integrity is more important than 10% improvement in current density.

Typically, for S glass, the minimum commercial tape thickness is ~0.1mm giving an insulation thickness on the cable of ~0.2mm with double overlap. The thickness can be reduced by using a single tape wrap with mica insulation inserted between turns [3]. Tape thickness is not so much a fundamental property of the materials but more one of commercial availability. In principle, tapes of 0.06-0.08mm could be made and used for winding.

Braid offers potential reductions in thickness because it is nominally a single layer.

3.3 Mechanical Properties

The mechanical properties of the insulation must be compatible with all phases from cable taping, through winding, heat treatment, impregnation, assembly (collaring ~ 200 MPa), cool down (thermal stresses) and magnet operation. We have already commented on the winding requirements. In this section we will address the operational requirements. In a cos-theta or block type design the principal loading in the straight section will be compressive, applied through the cable and insulation laminate thickness see Fig. 2. Typically, magnetic loading will be 150-200 MPa (average) with high local stresses due to the cable structure.

For a standard, G10 type, laminate a compressive strength of 600-800 MPa through the thickness is readily achievable. For an insulation laminate made in-situ with heat treatment, i.e. magnet fabrication conditions, ultimate compressive strengths are not known.

The design of a high field dipole will aim to eliminate tensile stresses and minimise shear stress in the straight sections. However, it is clear that localised shear and tensile stresses will be present in the straight sections and it is difficult to eliminate more global shear stresses in the coil ends. The insulation should therefore have capacity to resist shear and tension loads. The scale of these stresses should form part of the NED magnet design study.

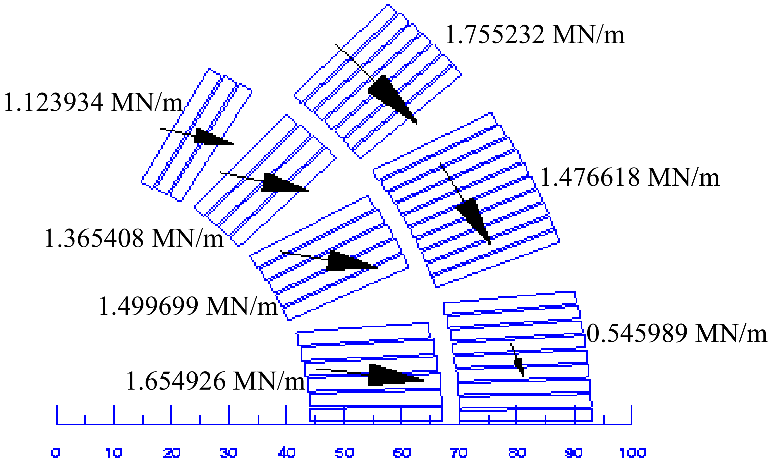

Fig. 2. Mechanical forces on a 15 T, 88 mm aperture dipole [6].

3.4 Radiation Hardness

For an LHC upgrade or future high energy accelerator applications increased radiation hardness of the coil insulation is important. Currently radiation resistance of this insulation is a limiting factor.

Conventional epoxy-glass materials are limited to doses of 10^8 Gy. Dipoles used in interaction region applications may receive doses in excess of this, although the dose can be reduced by an order of magnitude by design - for example block coil as opposed to cos-theta. The block coil design moves the sensitive winding away from the damaging particles [9]. Cyanate-ester resins, although expensive, have received attention by the fusion community and may offer increased radiation resistance compared to epoxies. However they are also organic materials and will be susceptible to radiation induced damage, particularly by high-energy neutrons. An inorganic material should offer the ultimate solution to radiation stability, hence the interest of CTD and Saclay in this area.

Testing of radiation hardness should be a part of the NED programme as it will be a critical factor in the design and determination of useful lifetime of the dipole.

3.5 Thermal Conductivity

Thermal conductivity of the insulation is a parameter which can be important for magnet operation. Between cables it will have some influence on stability (MPZ) but is unlikely to be high enough for the effect to be significant for magnet performance. Thermal conductivity will also influence the peak temperature due to steady state or transient beam losses. For a laminate of glass/epoxy conductivity is dependent largely on the epoxy content. Typically, a laminate will have transverse thermal conductivity ~ 0.05 W/m/K. There is not much scope to improve this in a Nb_3Sn dipole [10].

3.6 Helium Porosity

An insulation system that allows penetration of helium to the internal part of the cable is an objective of the innovative, ceramic-bonded insulation. With ‘conventional’ epoxy-impregnated, helium porosity is not feasible. Overall, the benefits of porosity with its potential for improved conductor stability will need to be balanced against the mechanical properties required at 15 T. Porosity will reduce the mechanical properties of the insulation/winding and could lead to movements or stress cracking under high stress conditions.

3.7 Outline Specification

The target specification for insulation is given in Table 2.

4. NED INSULATION DEVELOPMENT PROGRAMME

An R&D programme for insulation development has been set up under the overall Next European Dipole Programme (NED). Two R&D strands are planned:

(i) Conventional insulation development by CCLRC, Rutherford Appleton Laboratory

(ii) Innovative insulation development by CEA Saclay. This programme will build on the existing CEA developments with the aim of meeting NED specification level.

4.1 R&D Programme Overview

The programme will include all facets of insulation development from magnet design and analysis to define mechanical requirements and specification through to testing of large scale samples.

Generic tests will be developed to characterise materials and process routes. These tests will include; electrical insulation, thermal contraction, and a range of mechanical tests including tensile, compressive, shear and work of fracture.

In addition special test samples will be developed to give better simulation of real winding behaviour e.g. compression stacks and short beam shear. These samples will be characterised in standard testing machines with capability to operate at 300 K, 77 K and 4.2 K.

For characterisation of epoxy systems specialised equipment such as a Dynamic Mechanical Analyser and a Differential Scanning Calorimeter will be used. A DMA can be used to evaluate temperature dependence of mechanical properties. A DSC can evaluate parameters such as reaction kinetics and T_g (glass transition temperature).

4.2 Materials Improvement

The aim of the programme will also be to develop new processes and tests with the objective of improved performance.

Work of fracture is a materials property that is not well understood in resin and composite materials at low temperatures. Fracture properties are significant for magnet performance because crack propagation can induce quenches and crack propagation is determined by fracture toughness. A better understanding of fracture properties in insulation materials could lead to enhanced magnet performance. Reducing or eliminating cracking at relatively low stresses has more relevance to magnet stability than improving the ultimate strength.

Historically epoxy resins have been formulated for use at low temperature by either using high levels of filler to reduce thermal contraction, or by making the epoxy inherently tough. High filler loadings are not compatible with vacuum impregnation processing routes. There are opportunities to improve fracture properties of the basic resin systems using recently developed materials such as:

Table 2. Tentative target specification.

1	GENERAL	Design
1.1	Insulation thickness per cable	0.2 mm
1.2.1	Winding compatibility: capable of being applied to the cable and formed into a dipole winding by a semi-automatic winding system	Minimal fraying or abrasion at winding
1.2.2	Conductor bend radius minimum	20 mm
1.3	Compatibility with Nb_3Sn heat treatment cycle	Minimal degradation of basic components
1.4	Thermal cycles to low temperature:	10
1.5	Running cycles:	100
1.6	For conventional organic insulation scheme and innovative scheme if applicable: ability to be impregnated with liquid of viscosity up to	200 mPa.s
2	MECHANICAL (design stresses are before irradiation)	Design
2.1.1	Applied conductor winding load	50 kgf
2.1.2	Compression during heat treatment	20 MPa
2.1.3	Coil re-shaping after heat treatment before impregnation	10 MPa
2.1.4	Compressive stress after coil fabrication – at 300 K and 4 K	200 MPa
2.2	Shear: Short-beam shear strength at 4K	50 MPa
2.3	Tension: Transverse tensile strength of insulation laminate at 4K	25 MPa
2.4	Fracture specification: need to know properties at 300K and 4K	TBD
2.5	Thermal contraction (to match conductor contraction). Integrated thermal contraction [300K to 4K]	0.003 to 0.004
2.6	Thermal conductivity at 4.2K	>20mW/mK
3	ELECTRICAL	Design
3.1	Breakdown voltage inter-turn	1000 V (2500 V/mm)
3.2	Breakdown voltage inter-turn tested in helium at 300K	500 V
4	RADIATION	Design
4.1	Lifetime	10 years
4.2	LHC Interaction region, maximum 10% reduction in mechanical and electrical properties after the following exposure:	
	Cos-theta design dose	650 MGy
	Fluence >0.1 MeV	$30x10^{16}$ cm^{-2}
	Block coil design Dose	55 Mgy
	Fluence >0.1 MeV	$2.5x10^{16}$ cm^{-2}
	Neutron dose at high energy (>10 MeV)	

(i) Dendritic hyperbranched polymers, which have been shown to be able to double the interlaminar fracture resistance of epoxy based composites and to reduce the internal stress level by as much as 80 % with only 10 phr of modifier. These property improvements were obtained without affecting the viscosity, and thus the processibility, nor the glass transition temperature of the epoxy resin [7].

(ii) Nanofillers (clay). Layered clays were used as nanoparticle fillers in fibre reinforced polymeric materials (epoxy composites). Transverse cracking in response to cryogenic cycling was significantly reduced when nanoparticle fillers were used at concentrations much lower than those used for traditional fillers e.g. 5 phr. Nanoclays have been shown to modify traditional fibre reinforced composite materials and enhance their resistance to thermal cycling induced stresses [8].

5. SUMMARY

Insulation for Nb_3Sn magnets remains one of the most challenging issues for the engineering exploitation of Nb_3Sn conductors in future accelerators. The design, processing route, materials properties and end product are totally interdependent. The aim through NED is to achieve a better specification for insulation in a 15 Tesla dipole magnet – this will be an interaction between magnet design, fabrication route and materials.

The aim is also to explore and develop new materials with appropriate characteristics for this critical application.

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