Nb3Sn Accelerator Magnets Insulation Review

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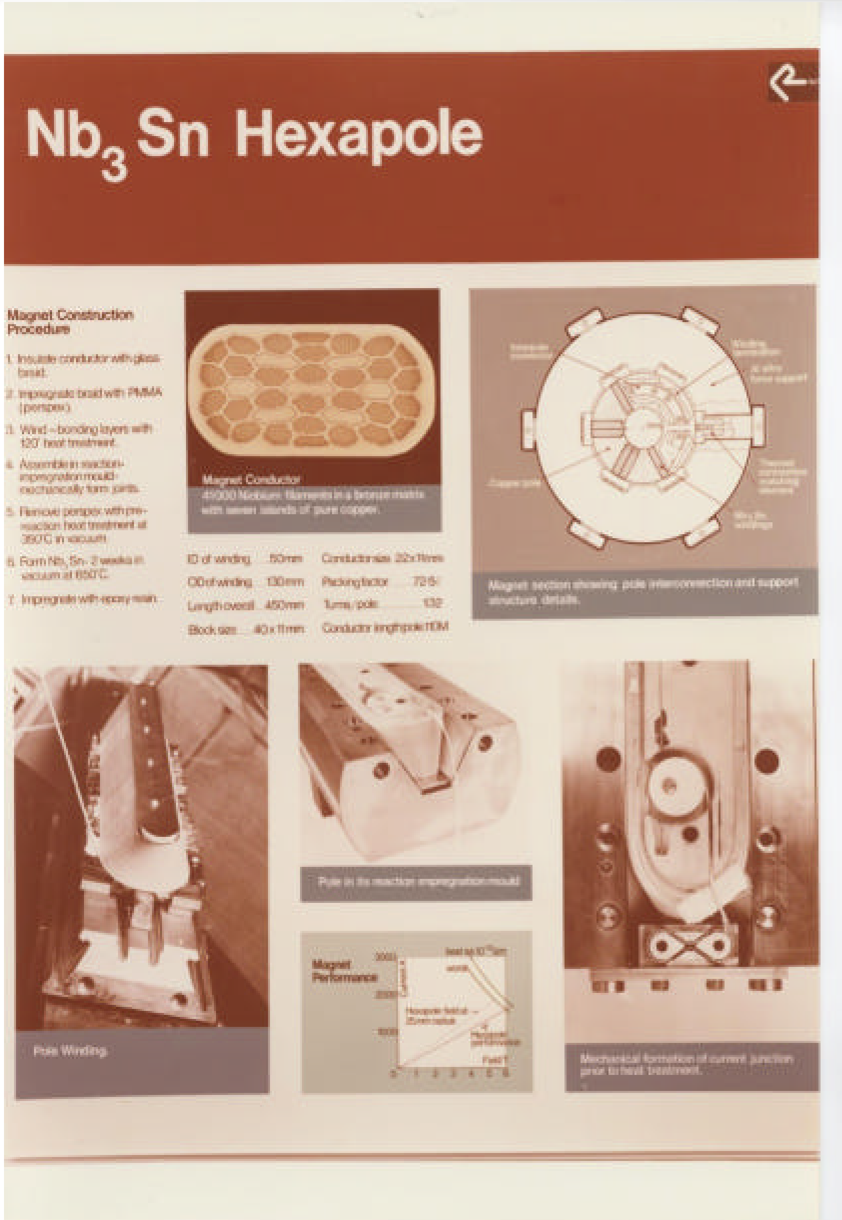
History



Filamentary Nb3Sn Hexapole Magnet manufactured by wind – react route - tested 1976

Extended studies of insulation techniques for Nb3Sn dipoles ~ 1980

Insulation Studies within the NED initiative - 2004

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Scope

- Brief review of insulation techniques for Nb3Sn accelerator magnets - Wind and React route
- Consider the critical issues and the limitations in relation to the the technical challenge presented by future high field dipoles
- Outline proposal of studies to be undertaken within the NED Programme
- Look forward to see how we might improve performance and reliability by improving knowledge of materials

Insulation Techniques

- Conventional
  - Glass/ quartz tape or braid
    - mica film
  - Removal of Sizing
  - Wrapping or sleeving of cable
  - Coil Winding
  - Heat treatment
  - Transfer to Impregnation Mould
  - Impregnation with epoxy

Insulation Techniques

- Novel Innovative
- Improvements in sizing – resizing
  - LBNL - Palmitic acid
  - Next steps follow “Conventional” – epoxy impregnation
- Replacement of organic sizing with inorganic or ceramic precursor - CEA Saclay/LBNL
  - Full bonding by ceramic route – removes impregnation – this is the target

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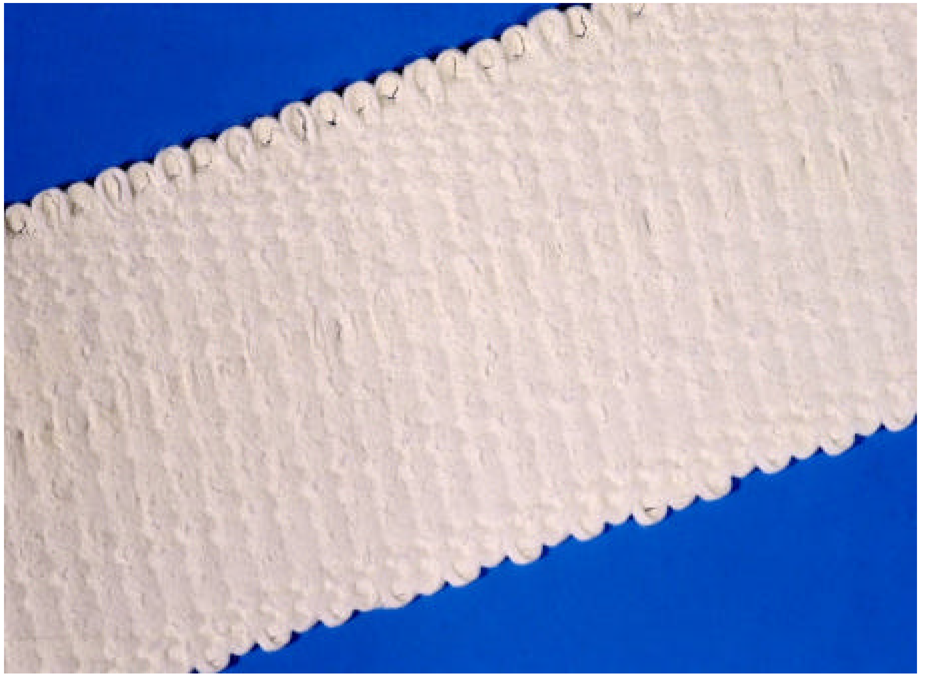
Insulation Techniques

- Innovative

•Glass tape is impregnated with a thick layer of ceramic precursor



• Ceramic penetrates entirely the fibers

•Tape can be used to wrap the cable in a conventional way

•Standard Nb3sn heat treatment for reaction also achieves heat treatment of the ceramic to give a structurally complete coil

Courtesy of Francoise Rondeaux CEA Saclay

What are the Key Issues (1)

- Electrical Insulation Strength
  - Do not require high breakdown voltage
    - typically 100 – 200 V/turn during quench
    - Conductor spacing of 0.4mm = 250 – 500 V/mm
  - Do require high electrical integrity
    - Failure will have serious consequences because of the high stored energy density

What are the Key Issues (2)

- Thickness is important for 3 reasons
- Current density
    - 1.5mm cable 0.15mm ins – 20% J reduction
- Thermal contraction
    - Pre-compression
- Modulus of the winding
    - Movement under magnetic loads
- However, very thin insulation will have little tolerance for cable imperfections or inclusions and may be prone to damage at high loads – so spacing may be a safety factor
- In the limit a robust insulation with high integrity is more important than 10% current density

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What are the Key Issues (3)

- Mechanical properties
  - – Cable taping - flexibility – tight bends
  - – Winding – abrasion – bending – clamping
  - – Heat treatment – 1 wk >650C
  - – Assembly loading – collaring – 200MPa
  - – Cooldown - thermal stresses
  - – Operation – compressive loading – shear

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What are the additional Issues

- Radiation Hardness
  - Increasingly important for high beam intensities
- Thermal conductivity
  - High would be nice
- Porosity to helium
  - Would be nice

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Conventional Insulation – Limitations (1)

- Glass or quartz tape or braid
  - Thickness
    - S Glass tape – usually >100micron – double layer with overlap will give >200micron – effect on overall current density is significant
      - Can be reduced by single wrap with mica sheet – UT
    - Tape thickness limitation is not so much a fundamental property but more one of commercial availability
    - Braid offers potential advantages in thickness
      - Sleeving is only possible for short lengths – otherwise a specialist machine is needed
    - Linear wrapping can also offer the potential for thickness reduction
  - Basic material is fragile for insulating and winding of a large cable – especially so when sizing is removed

Conventional Insulation – Limitations (2)

- Magnet heat treatment in stages
  - removing sizing is not easy and some residue will remain – effect on electrical properties
  - There is a risk of damage during heat treatment – expansion movements – will be increased for long coils
  - After full heat treatment the glass is extremely fragile – great care is required in any handling before impregnation
- Impregnation with epoxy
  - relatively complex process – cost for production
  - helium is excluded from the winding - stability

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NED Insulation Programme

- Programme of insulation development for 15T large aperture dipole
- 2 R&D strands
  - Conventional – RAL
  - Innovative – CEA building on existing programme
- Programme phases
  - Insulation Review and Specification
  - Programme definition
  - Materials selection
  - Processing routes to evaluate
  - Test Programme definition and execution

Insulation Specification

- What target properties should we will be aiming for :
  - Thickness
    - target total 150-200 microns
  - Electrical
    - Turn to turn voltage ~ 200 V - safe to 800V
    - ~2-3 kV/mm in insulation laminate
  - Thermal contraction
    - Transverse 3-4X10e-3
  - Mechanical
    - Compressive – transverse working 150-200MPa
    - Fracture properties ??; Tensile; Shear
  - Porosity
  - Radiation Hardness

NED Test Programme

- Generic Tests
  - Materials and process route characterisation using basic resin and insulation laminate samples
    - Electrical insulation - thermal contraction
    - Mechanical: tensile – compressive – shear - work of fracture
- Special test samples
  - Conductor+insulation stack to simulate winding
    - Compression
    - Short beam shear

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Mechanical Testing

- 100kN Servo-hydraulic machine
- Standard tests 300K,77K,4.2K
- Tensile, Compression
- Short beam shear
- 3-point bend
- Shear/compression
- With extensometry
- Comprehensive control and data acquisition software

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Materials Characterisation

- DMA (Digital Mechanical Analyser)
- Measures response of a material to a stress (dynamic or static) as a function of temperature or time
- LN2 to 500°C
- 3-point bend, tension, parallel plate
- Rapid Characterisation of resins eg Tg

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Materials Characterisation

- DSC (Dynamic Sampling Calorimeter)
- Calorimetric device
- Reaction kinetics, transition temperatures
  - Very fast ramp rates

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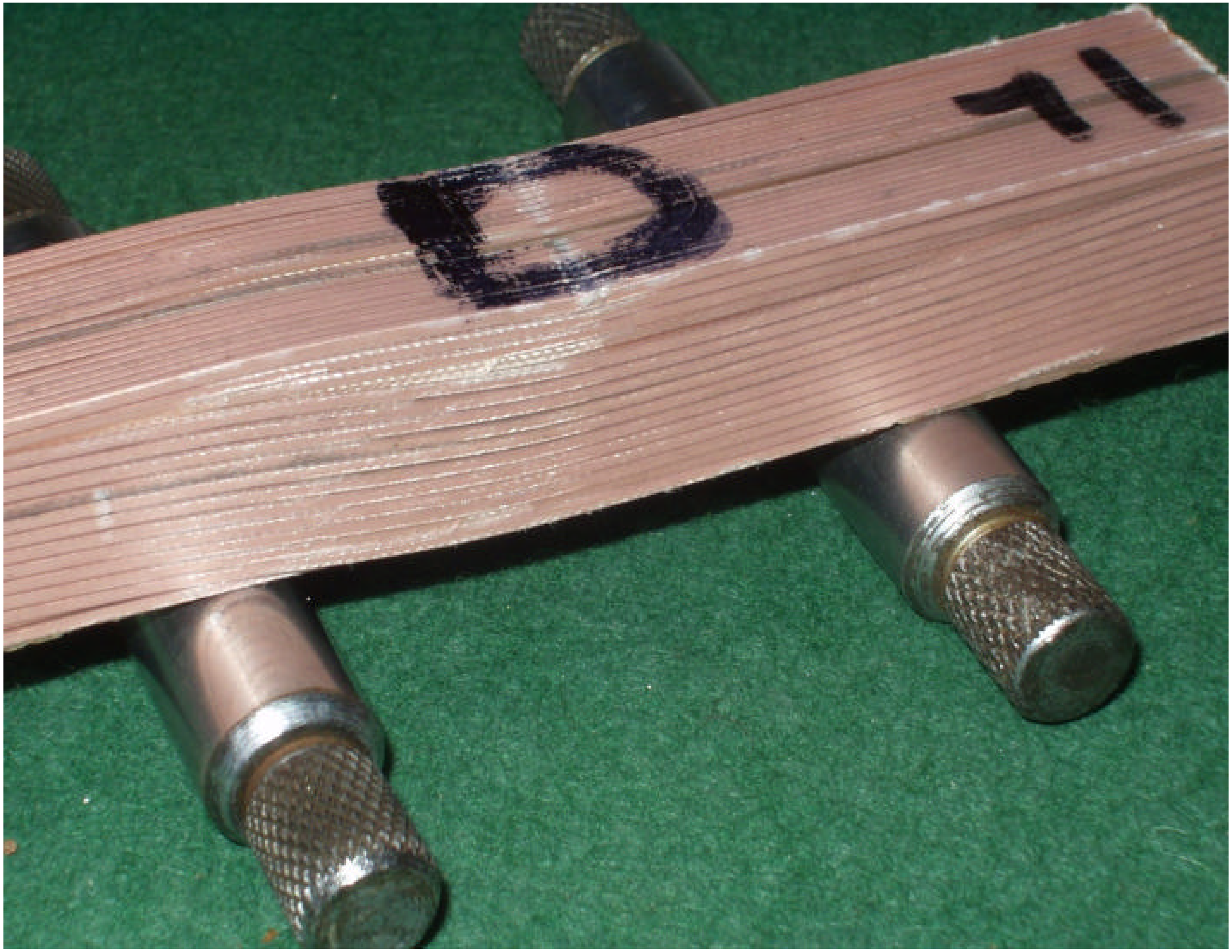
Typical test – short beam shear



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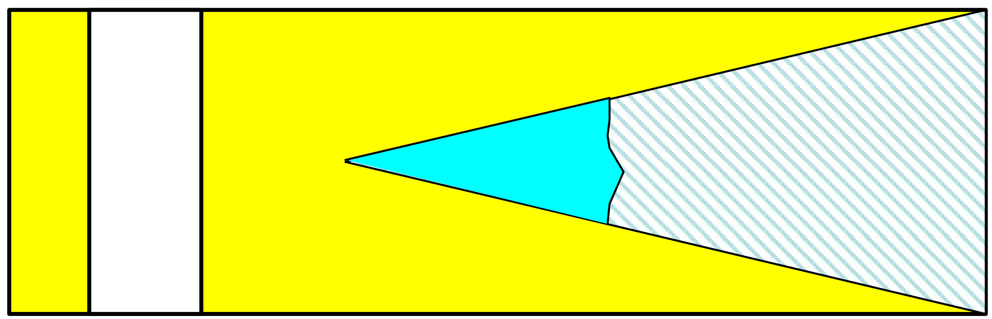
Materials Improvement

- Aim to devote a part of the programme to study new materials, new processes and new tests which could offer improved performance
  - Tests – work of fracture
  - Resins – increased toughness improved thermal contraction matching
  - Insulating materials with high temperature potential

Work of fracture

- Significance of Fracture Properties
  - Cracks induce quenches
  - Cracks depend upon:
    - Size of local stress field
      - Magnetic loads (design issue)
      - Thermal contraction (materials issue)
      - Cure shrinkage stresses (materials issue)
      - Toughness of insulation system (materials issue)
  - How are insulation materials related to stability and magnet performance
  - How do the properties of ceramic bonded systems compare with resin bonded

Chevron compact tension specimen to arrest cracks in brittle materials



Crack spreading, width increases and crack should arrest

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Resins - improvement

- Dendritic hyperbranched polymers (HBP)
- "Dendritic hyperbranched polymers 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 10phr of modifier. These property improvements were obtained without affecting the viscosity, and thus the processibility, nor the glass transistion temperature of the epoxy resin" - Mexxenga et al, Comp Sci Tech 2001

Resins - improvement

- Nanofillers (clay)
- "Layered clays were used as nanoparticle fillers in fiber-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. 5phr]...Overall this work showed that nanoclays can easily be used to modify traditional fiber-reinforced composite materials and enhance their resistance to thermal cycling induced stresses" -Timmerman, Comp Sci Tech 2002

Summary

- Insulation for Nb3Sn magnets remains one of the most challenging issues limiting the engineering exploitation of Nb3Sn conductors
- Design, processing route, materials properties, and end product are totally interdependent
  - Developing materials is not an isolated activity
  - Materials technology is always advancing – look at the techniques for processing HTS – so there are potential solutions out there
- In the next few months we will be looking at new technologies as we define the R&D programme and tests for NED
- We welcome input on techniques and tests from co-workers in the field
- Within the limits of the programme we would very much like to develop samples and do benchmark tests with collaborators

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