

Improved training in paraffin-wax impregnated Nb₃Sn Rutherford cables demonstrated in BOX samples

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Abstract

Resin-impregnated high-field Nb₃Sn type of accelerator magnets are known to require extensive training campaigns and even may exhibit performance-limiting defects after thermal or electromagnetic cycling. In order to efficiently explore technological solutions for this behaviour and assess a wide variety of impregnation material combinations and surface treatments, the BOnding eXperiment (BOX) sample was developed. BOX provides a short-sample test platform featuring magnet-relevant Lorentz forces and exhibits associated training. Here we report on the comparative behaviour of BOX samples comprising the same Nb₃Sn Rutherford cable but impregnated either with common resins used in high-field magnets, or with less conventional paraffin wax. Remarkably, the two paraffin wax-impregnated BOX samples reached their critical current without training and are also resilient to thermal and mechanical cycling. These rather encouraging results strongly contrast to those obtained with resin impregnated samples, which show the characteristic extensive training and at best barely reach their critical current value.

Keywords: paraffin wax, training, Nb₃Sn Rutherford cables, high-field accelerator magnets

(Some figures may appear in colour only in the online journal)

1. Introduction

Avoiding extensive training and/or performance degradation has proven to be a difficult challenge for epoxy-resin-impregnated high-field Nb₃Sn accelerator magnets wound from Rutherford cable [1–6]. Several recent magnets with designs ranging from canted-cosine-theta (CCT) [7–10] to classical cosine-theta [1, 11], exhibited severe training that complicates their application on a large scale in future

accelerators. Their windings built with Nb₃Sn Rutherford cables were vacuum impregnated with epoxy resins reinforced with fibreglass. The cable impregnation with resin is necessary to suppress conductor movement and most importantly to provide well-supported conditions for the Nb₃Sn strands in order to avoid severe critical current degradation due to transverse stress working on the Nb₃Sn filaments [4, 5, 12].

Earlier research has highlighted the possibility of using alternatives to epoxy resins. Either bees- or paraffin wax, have been proposed and assessed on dipole, quadrupole and solenoid [13, 14] magnets with promising results. These Nb–Ti [14–17], Bi-2212 [18, 19] and RE–Ba–Cu–O (REBCO) [20, 21] based magnets have shown in some cases substantial reduction in training, more reliable operation and reached high currents close to the critical current.

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In this paper, the results for resin and wax impregnated BOnding eXperiment (BOX) samples are shown. The resins used are the so-called Mix 61 [22], CTD-101K [15], CTD-701X [15] and MY 750 [23], and the wax impregnated samples used paraffin wax. The epoxy resins selected for the comparison with wax have been used in the fabrication of high-field magnets and have varying elastic, plastic and fracture toughness properties [24–26] that may influence the training and overall performance of such magnets. Here we assess training, fatigue behaviour and resilience of paraffin wax over multiple powering cycles and a thermal cycle.

Previous experiments with BOX samples have shown that these can reproduce the characteristic training behaviour of accelerator magnets impregnated with a variety of epoxy resins in a cost-effective way [27]. The BOX experiments aim to seek the best impregnation materials and best practices primarily for CCT magnets, as well as assessing their suitability for other accelerator magnet designs.

2. BOX sample fabrication

The effectiveness of the impregnation system is assessed with a Rutherford cable made of 21 strands of Bruker OST [28] RRP 108/127 Nb₃Sn 0.85 mm in diameter [29, 30] following the LARP QXF specification 150505 and insulated with fibreglass braid. The 21-strand CCT cable was manufactured by the Lawrence Berkeley National Laboratory (LBNL) and delivered to the Paul Scherrer Institute (PSI) as part of a collaboration between PSI and LBNL. Extracted strand RRR and critical current vs magnetic field measurements were performed separately for the production of a CCT magnet at PSI [31], which showed good agreement with referenced measurements [29, 30]. A summary of the strand and cable parameters are shown in table 1, a schematic of the sample is shown in figure 1, and a detailed description of the BOX experiments can be found elsewhere [27].

All samples had the channel in which the cable is enclosed sand blasted. To remove most of the sizing on the fibreglass braid, cable and braid were washed for 10 min prior to winding using an ultrasonic bath of demineralised water with 1% Alconox detergent. Washing off the sizing helps to reduce carbon deposits in the channel during reaction heat treatment and improves bonding when impregnated with resin [27]. All samples went through the recommended heat treatment for this cable of 210 °C for 72 h, 400 °C for 48 h and 665 °C for 50 h in argon atmosphere. The samples are reacted within the main body with the faceplate tightly secured. The channel is sufficiently wide to accommodate the bare cable and dimensional changes resulting from the heat treatment with 1.025 and 0.75 mm of clearance for the width and height respectively. The cable is wound, reacted, impregnated and tested in the same main body. Prior to impregnation, the samples were dried under vacuum overnight. The impregnation of all samples occurred in a large vacuum vessel. The sample is contained within an ‘open top’ container in the vacuum vessel, which is filled with resin or wax to ensure complete filling of cable and channel.

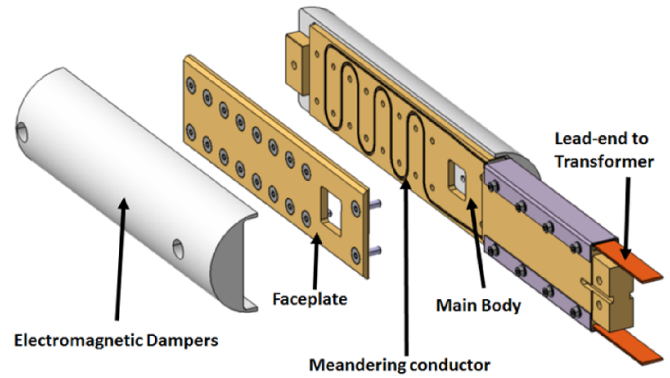


Figure 1. Overview of the BOX sample assembly, showing the meandering cable in the former, faceplate and aluminium half shell dampers. Further details can be found in Daly *et al* [27] (CC BY 4.0).

Table 1. Strand and cable parameters [30].

Parameter	Unit	Value
Strand diameter	mm	0.85
Sub-element	μm	≤ 55
Filament twist pitch	mm	19 ± 3
Cu/Sc ratio	—	1.2 ± 0.1
Sub-element configuration	—	RRP 108/127
Number of strands	—	21
Keystone angle	$^\circ$	0
Cable height without insulation	mm	1.475
Cable height with S2 insulation	mm	1.785
Cable width without insulation	mm	9.85
Cable width with S2 insulation	mm	10.16

A commercially available paraffin wax POLARIT[®] G 54/56 from TH. C. TROMM GmbH, also used for candle-making, was chosen for the wax impregnation for its low melting point between 52 °C and 56 °C and low viscosity ranging between 2 and 4 mPas at 100 °C. The wax was degassed in a separate pot at 1 mbar, stirred and heated to 90 °C. Prior to filling the sample, the mixing pot was brought to atmospheric pressure while maintaining the temperature between 80 °C and 90 °C. The pressure in the impregnation vessel was kept above 3 mbar and the sample was kept at 80 °C. The tubing and pump between the mixing vessel and impregnation vessel were kept at 70 °C using a ‘thermal shield’ to avoid localised cold spots causing wax blockages. The flow of wax was controlled to ensure slow filling thereby avoiding trapped gas as the wax fills the container and the sample from bottom to top. Once the container and sample were filled, they were slowly cooled down to room temperature over 6 h. Two wax samples were produced following the same fabrication to verify reproducibility of the training test results. Once fully hardened, excess wax in the container around the sample was removed. Importantly, no noticeable recess of wax was detected within the channel of the samples when removing the face plate for visual inspection. The Wax-1 impregnated sample is shown in figure 2(a) with the face plate removed. Both samples showed a good wax filling albeit with some local poor wetting of the fibre glass layer between the faceplate and the main body.

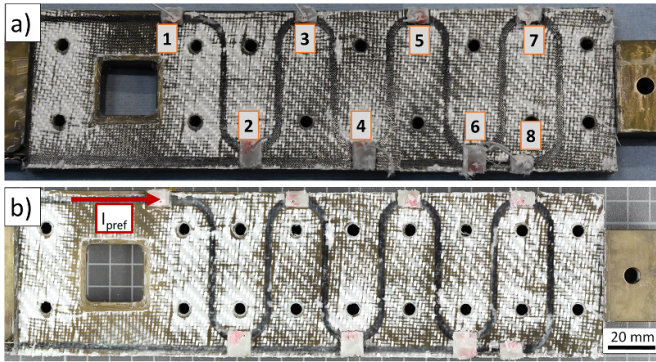


Figure 2. Image of sample Wax-1 after impregnation (a), and after testing (b). The face plate is removed exposing the cable channel. Positions of voltage taps are shown in picture (a). Quenching segments are identified as the cable lengths between V-taps such as segment 1–2, 2–3, 3–4, etc. The preferred current direction for the experiment is also indicated (I_{pref}).

The resin impregnated samples were prepared using the same equipment and procedure but following their respective temperatures for processing and curing. No noticeable porosity or damage were noticed on the resin impregnated samples when removing the face plate after impregnation. Once the impregnation quality of the samples was checked, the face plate was put in place using M6 screws and tightened to 4 N m prior to testing.

All samples were instrumented with eight voltage taps to identify and locate the serpentine cable segments quenching the most.

3. Test results

The test program for the wax-filled samples consisted of verifying training behaviour up to the critical current and assessing thermal cycling and fatigue resilience in a background field of 7.5 T applied perpendicular to the broad face of the straight cable segments yielding the highest Lorentz force on the cable at its critical current. All tests were performed at 4.2 K with a current ramp rate of 200 A s^{-1} . The preferred direction of the current (I_{pref}) for most tests was in the direction from V-taps 1–8. The training results for all resin samples and the first five quenches for the wax samples prior to fatigue cycling are shown in figure 3. The ‘fatigue and thermal cycle’ behaviour for the wax filled samples are shown in figures 4 and 5, and results of the current-reversal stability studies are shown in figure 6 for the wax filled samples and three resin impregnated samples.

3.1. Training

Both wax filled samples did not exhibit any training and reached immediately a higher current of approximately 24.5 kA (Wax-1) and 24.6 kA (Wax-2) than the critical current of $23.8 \pm 0.2 \text{ kA}$ as determined by $V-I$ measurements on a few segments. In sample Wax-1, segment 4–5 was primarily the quenching segment while in sample Wax-2, segment

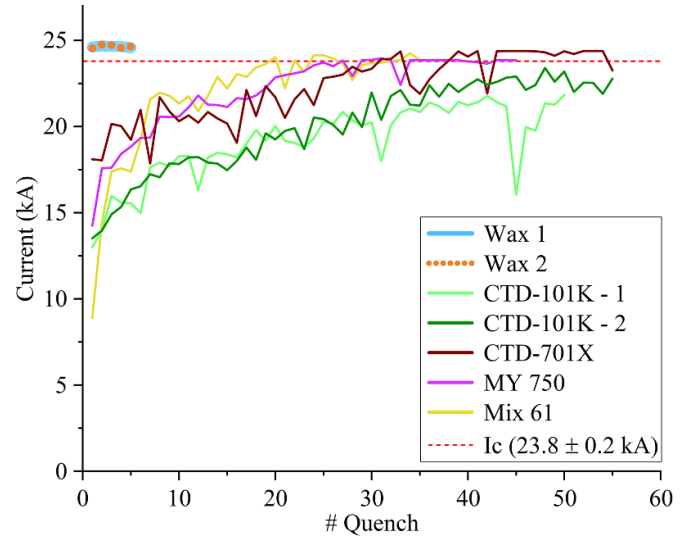


Figure 3. Training curves of seven BOX samples. The two wax filled samples (top left) show no training and notably reach values beyond the critical current at the first quench. Note: only the first five quenches of the two wax samples are shown as cycling tests were performed thereafter.

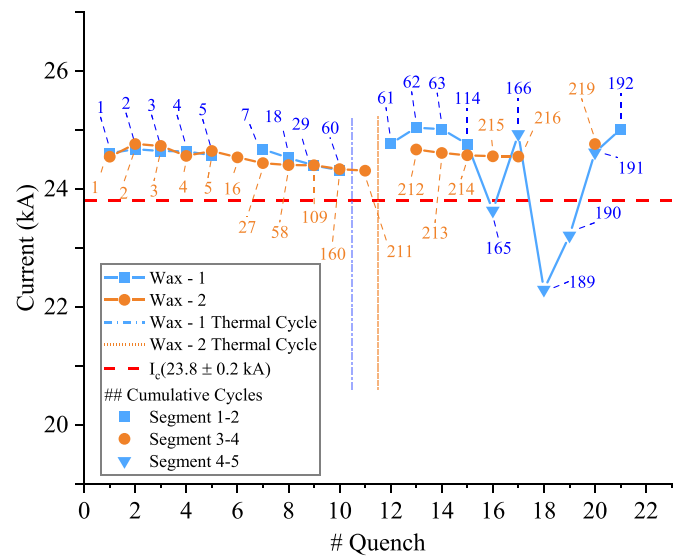


Figure 4. Quench current versus quench number of the two wax filled samples with intermezzo's of multiple cycles up to 23 kA. The symbol markers indicate the quenches while the numerical markers show the number of intermediate energizing cycles at or above 23 kA.

3–4 was exclusively the quenching segment when powering the sample in the preferred current direction. Both segments are within the high and homogeneous magnetic field region of the solenoid.

All resin-impregnated samples exhibited extensive training as usually seen in resin-impregnated CCT magnets, and did not reach the high quench currents observed in the wax filled samples. The CTD-701X sample quenched first at a relatively high current of 18.1 kA while the Mix 61 sample quenched first at 8.9 kA. In addition, the resin impregnated samples clearly suffer from instabilities during the training with sometimes

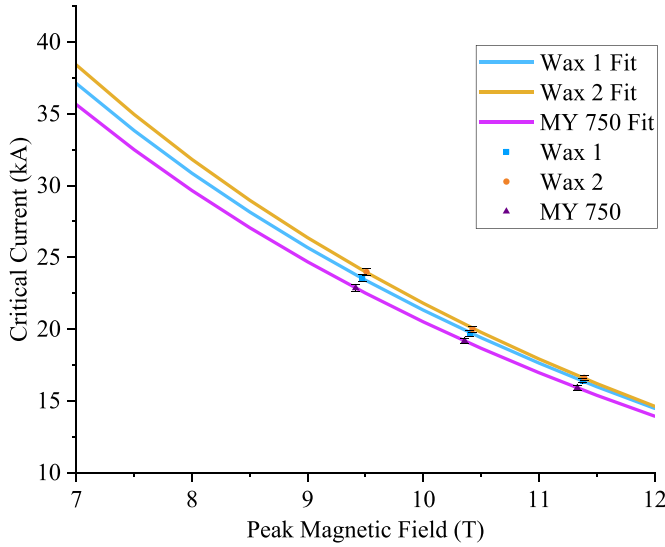


Figure 5. Critical current versus peak magnetic field of samples Wax-1, Wax-2, and MY 750. Dots are measured data with 1% error bars indicated, lines are a curve fit using the Godeke scaling law [32].

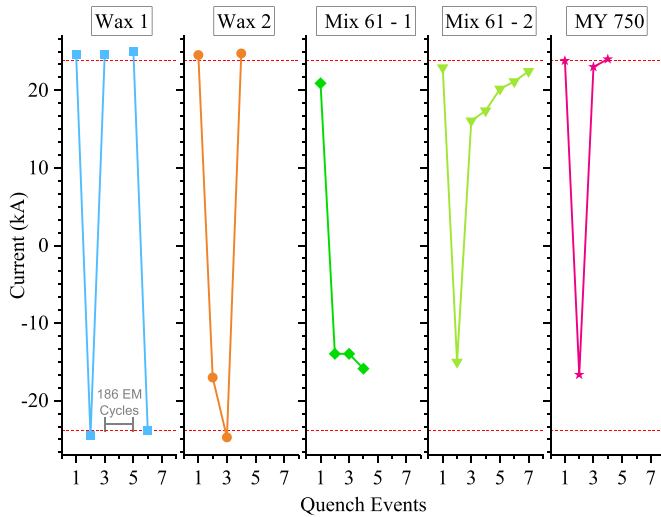


Figure 6. Result of current reversibility studies on the two wax filled samples, the MY 750 impregnated sample and two earlier Mix 61 impregnated samples [27].

significant drops in current as known to happen in magnets with this type of Nb_3Sn cable as well. To ensure reproducibility in training behaviour of the samples in this experimental setup, two samples impregnated with CTD-101K were fabricated and showed practically the same training behaviour.

3.2. Fatigue behaviour by electro-mechanical (EM) cycling

The wax-filled samples were tested further for fatigue due to mechanical stress caused by Lorentz force by cycling the current between 0 and 23 kA, a value just below the critical current, thereby avoiding a quench in the sample. The fatigue cycle runs typically lasted for 10, 30 and 50 consecutive ramping cycles. The cycle runs started after the first five

quenches to high current shown in figure 3 to assess the maximum achievable current of the samples for reference and comparison hereafter. Once multiple cycles were completed, the samples were ramped up to quench again to check for degradation as shown in figure 4.

The wax filled samples showed very little degradation over time and only dropped by 1%–2% in maximum current over 60 to approximately 200 cycles. Some instability in segment 1–2 of sample Wax-1 was observed in the latter stages of cycling but it recovered. This first segment (1–2) behind the sample's electrical connection has also proven unstable in resin impregnated samples, which may indicate a sample entry effect independent of the impregnating medium used. This segment is closest to the un-impregnated leads located at the top end of the solenoid and within the more non-uniform solenoidal field region.

3.3. Thermal cycle behaviour

Both wax samples were warmed up to room temperature after a number of electro-mechanical (EM) cycles, cooled back to 4.2 K and ramped again to maximum current. Sample Wax-1 underwent the single thermal cycle after 60 EM cycles and sample Wax-2 after 211 cycles. Importantly, in both samples no retraining was observed and the maximum current reached was higher than earlier achieved in the last phase of testing prior to warm-up indicating a good memory and an absence of permanent degradation.

3.4. V–I measurements for testing degradation

V–I measurements for the determination of the critical current of the cables were performed on both wax-filled samples before cycling, after cycling and after thermal cycling as summarised in figure 5. The wax filled samples showed equally good stability as the MY 750 resin impregnated sample with barely noticeable changes (within 1% error bars) in critical current indicating negligible conductor damage after EM cycling and a thermal cycle.

3.5. Current reversibility studies

The cable segments in the BOX layout exposed to Lorentz force are either pushed in or out of the channel depending on the direction of the current in the sample. This behaviour can be altered by changing the current direction. The resilience in training behaviour against current reversal was tested for both wax filled samples and compared to what was found with three resin impregnated samples. The results are shown in figure 6. Sample Wax-1 immediately reached an equivalently high reverse quench current while sample Wax-2 had one quench in entry segment 1–2 before reaching a similarly high current. In clear contrast, the resin impregnated samples started to retrain in the opposite current direction, and in some cases retrained when the sample was powered in the original current direction. While force-reversal is not typically observed in accelerator magnets (with the exception of combined-function magnets),

the experiment demonstrates the high degree of resilience of Nb₃Sn Rutherford cable impregnated with paraffin wax.

As a final remark after testing the wax-filled samples we note that no clear damage was apparent on the surfaces of the samples as shown in figures 2(a) and (b). Subjectively, a slightly whiter ‘crazed’ wax may be noticed on the straight segments 1–2, 3–4, 5–6 and 7–8 that were pushed out most frequently during the test with some small white patches possibly indicating minor detachment from the fibreglass interlayer.

4. Discussion

At 7.5 T applied magnetic field and a cable current of 25 kA, the Lorentz force pushing the cable in or alternatively out of the channel in the sample holder is 6.6 kN, equivalent to 186 kN m⁻¹, and working on the 35.5 mm long central straight segments in the serpentine-shaped sample. This results in 11 MPa of mean shear stress at the wax/channel-wall interface assuming a fully bonded interface. Similarly, the pressure on the thin edge of a flat rectangular cable may be in the range of 30–135 MPa when assuming a fully bonded or a frictionless sliding interface, respectively.

The absence of training in the wax impregnated Nb₃Sn cable samples is highly significant, but not necessarily unexpected as previous experiments using wax as impregnant for cables and coils showed promising results [16]. Importantly, these earlier experiments were performed on other conductors than Nb₃Sn.

Possible reasons for the absence of training and critical current degradation in the wax impregnated samples rely on a number of assumptions, namely:

- Low energy failure events as a result of the low fracture toughness of the wax showing typically a K_{IC} value that is a factor 10 lower at cryogenic conditions than in epoxy resins so far used in high-field magnets [33–36].
- Low shear modulus and minimal bonding between the wax and the channel wall and/or cable surface;
- Limited transmission of the failure energy within the insulating medium;
- The wax being fully confined within the channel and not allowed to flow out, thus providing sufficient mechanical support and mechanical stability for the conductor.
- Wax acts as a low-friction moderating medium, impeding any sudden conductor movement.

These assumptions are to be independently verified at 4.2 K in dedicated experiments to confirm values found in literature and to account for the presence of fibreglass in the composite.

The next steps in the program will aim to address a number of issues identified during the fabrication and testing of the BOX samples. These issues are listed below:

- The BOX sample results presented here will be complemented by testing the response to transverse compressive pressure on identical wax filled Nb₃Sn cables within the University of Twente’s test facility by which transverse

pressure can be applied up to 200 MPa onto the broad face of the cable at 4.2 K, representative for the transverse pressure load on cables in 11–16 T high-field accelerator magnets [37].

- Furthermore, the fatigue properties of the wax-filled cable samples deserve further investigation. Comparative studies with commonly used epoxy resins are to be performed to see if the measured behaviour is unique to waxes. Moreover, we plan to test new mixtures of epoxy resins in an attempt to reproduce wax-like training properties.
- Noticeable wax shrinkage and subsequent wax recess from within the open-top impregnation mould was observed after wax solidification. Similar melting temperature waxes typically exhibit 12%–16% shrinkage [34] during cooling. To adapt paraffin wax for accelerator magnets, wax reservoirs with sufficient wax inlets and appropriate heat control would be required. In addition, carefully placed fibreglass improves the wicking and retention of the wax as well as reducing the impact of shrinkage. Furthermore, wax additives may help to improve mechanical and shrinkage characteristics. Further tests would be necessary to validate these approaches. It is worth noting that very little modifications of the impregnation process and procedure took place for the resins or wax except for the use of a ‘thermal shield’ to reduce wax cooling in the tube lines.
- So far little literature information is present concerning the mechanical, radiation-resistance, and dielectric properties of paraffin wax and wax-fibreglass composites at 4.2 K.

The research issues listed above need to be investigated for providing the confidence to introduce wax in accelerator magnets and predict coil behaviour in finite element models. Furthermore, it will enhance our understanding of the observed behaviour that allows wax impregnated samples to reach very high quench currents while eliminating training entirely for the BOX sample configuration.

5. Conclusion

The impregnation with paraffin wax of a characteristic Nb₃Sn Rutherford cable insulated with standard S2 fibreglass braid in BOX samples greatly contributed to eliminating training at up to 11 MPa mean shear stress on the cable broad face and up to 135 MPa of pressure on the short cable edge. Furthermore, the samples showed very good fatigue behaviour up to 200 EM cycles and an excellent memory after one full thermal cycle to room temperature.

These new and remarkable results are in stark comparison with those of resin impregnated samples suffering from classical prolonged training and in some cases severe limitations in current.

The rather positive results presented in this paper highlight the possibility of practically eliminating training in certain Nb₃Sn Rutherford cable based magnets and reaching critical current using paraffin wax. The V – I measurements on the wax samples highlighted further the stability offered by the fibreglass wax composite.

Further quantifiable investigations into the mechanical and fracture properties of paraffin wax are still required. The mechanisms of low energy failure and the fully confined cable/channel configuration that may drive the successful outcome of these wax impregnated BOX samples are yet to be fully understood.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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References

- [1] Stoynev S, Riemer K, Zlobin A V, Ambrosio G, Ferracin P, Sabbi G and Wanderer P 2019 Analysis of Nb₃Sn accelerator magnet training *IEEE Trans. Appl. Supercond.* **29** 5
- [2] Devred A 2002 Insulation systems for Nb₃Sn accelerator magnet coils manufactured by the wind & react technique *IEEE Trans. Appl. Supercond.* **12** 1232–7
- [3] Dotsenko V I and Kislyak I F 1991 Effect of epoxy debonding and cracking on stability of superconducting composites *Cryogenics* **31** 906–12
- [4] Maeda H and Iwasa Y 1982 Heat generation from epoxy cracks and bond failures *Cryogenics* **22** 473–6
- [5] Fujita H, Takaghi T and Iwasa Y 1985 Experimental and theoretical investigation of mechanical disturbances in epoxy-impregnated superconducting coils. 4. Prequench cracks and frictional motion *Cryogenics* **25** 323–6
- [6] Prestemon S 2019 CCT magnet development: results and next steps *Int. HFM Meet* (available at: <https://conferences.lbl.gov/event/264/>)
- [7] Prestemon S 2018 Status update from LBNL MDP—FCC—EuroCirCol meeting history of CCT dipole tests at LBNL MDP-FCC-EuroCirCol Coordination Meet. 06 (available at: <https://indico.cern.ch/event/776591/>)
- [8] Brouwer L 2016 Canted-cosine-theta superconducting accelerator magnets for high energy physics and ion beam cancer therapy *DNA Mediated Assembly of Protein Heterodimers on Membrane Surfaces* p 67 (available at: <https://escholarship.org/uc/item/98384265>)
- [9] Caspi S et al 2014 Canted-cosine-theta magnet (CCT)—a concept for high field accelerator magnets *IEEE Trans. Appl. Supercond.* **24** 4001804
- [10] Bordini B et al 2019 Nb₃Sn 11 T Dipole for the High Luminosity LHC (CERN) In: Schoerling, D., Zlobin, A. (eds) *Nb₃Sn Accelerator Magnets. Particle Acceleration and Detection* (Berlin: Springer) 223–58
- [11] Luguang Y et al 1982 Experimental investigation of a 60 cm bore wax-filled superconducting solenoid with different winding current density *Proc. Ninth Int. Cryogenic Engineering Conf.* pp 142–5
- [12] Luguang Y, Huidong L I, Zuxian Y E, Decheng L, Changlian Y I, Hongda M A and Guangsui L I 1981 Experimental investigation on wax-filled superconducting solenoids *IEEE Trans. Magn.* **17** 1638–41
- [13] Smith P F 1971 Superconducting synchrotron magnets—present status *Proceedings, 8th International Conference on High-Energy Accelerators, HEACC 1971 CERN, Geneva, Switzerland, September 20–24, 1971* C710920 pp 35–46 (<https://inspirehep.net/literature/73273>)
- [14] Composite Technology Development Inc. 2019 Material selection guide electrical and thermal insulation, adhesives, and specialty resins for harsh and demanding environments and applications *Material Selection Guide* (LAFAYETTE)
- [15] Smith P F and Colyer B 1975 A solution to the ‘training’ problem in superconducting magnets *Cryogenics* **15** 201–7
- [16] Hou Z, Zhu Z, Zhang K, Zhao L, Wang M, Zhou J, Li P, Hu X, Zhang Y and Wang Z 2018 Excitation characteristics of magnets impregnated with paraffin wax *Cryogenics* **94** 22–25
- [17] Zhang K et al 2018 Tripled critical current in racetrack coils made of Bi-2212 Rutherford cables with overpressure processing and leakage control *Supercond. Sci. Technol.* **31** 105009
- [18] Shen T et al 2019 Stable, predictable and training-free operation of superconducting Bi-2212 Rutherford cable racetrack coils at the wire current density of 1000 A/mm² *Sci. Rep.* **9** 1–9
- [19] Matsumoto S, Kiyoshi T, Miyazoe A, Otsuka A, Hamada M, Maeda H, Yanagisawa Y, Nakagome H and Suematsu H 2013 Operation of wax-impregnated GdBCO layer-wound coil using cryocoolers *IEEE Trans. Appl. Supercond.* **23** 4602704
- [20] Ge Y, Lewin R, Cahill R, Mortensen N and Jones H 2012 Construction and performance of small-sized coated conductor pancake coils for surgical applications *Phys. Proc.* **36** 878–83
- [21] Brennan A B, Miller T M, Arnold J J, Huang K V, Gephart N L and Markewicz W D 1995 Thermomechanical properties of a toughened epoxy for impregnating superconducting magnets *Cryogenics* **35** 783–5
- [22] Huntsman Advanced Materials 2004 Huntsman Araldite casting and laminating resin system product data
- [23] Brem A et al 2021 Elasticity, plasticity and fracture toughness at ambient and cryogenic temperatures of epoxy systems used for the impregnation of high-field superconducting magnets *Cryogenics* **115** 1–11
- [24] Yin S, Swanson J and Shen T 2020 Design of a high toughness epoxy for superconducting magnets and its key properties *IEEE Trans. Appl. Supercond.* **30** 4004305
- [25] Yin S, Arbelaez D, Swanson J and Shen T 2019 Epoxy resins for vacuum impregnating superconducting magnets: a review and tests of key properties *IEEE Trans. Appl. Supercond.* **29** 7800205
- [26] Daly M et al 2021 BOX, an efficient benchmark facility for the study and mitigation of interface-induced training in accelerator type high-field superconducting magnets *Supercond. Sci. Technol.* **34** 115008

- [27] Bruker Corporation 2022 LTS superconductors niobium-tin (Nb_3Sn) (available at: www.bruker.com/en/products-and-solutions/superconductors/)
- [28] Ferracin P *et al* 2016 Development of MQXF, the Nb_3Sn low- β quadrupole for the HiLumi LHC *24th Int. Conf. on Magnet Technology (MT24)* vol 1
- [29] Ferracin P *et al* 2019 The HL-LHC low- β quadrupole magnet MQXF: from short models to long prototypes *IEEE Trans. Appl. Supercond.* **29** 2–9
- [30] Montenero G, Auchmann B, Brouwer L, Calzolaio C, Caspi S, Rolando G and Sanfilippo S 2018 Mechanical structure for the PSI canted-cosine-theta (CCT) magnet program *IEEE Trans. Appl. Supercond.* **28** 4002805
- [31] Godeke A, Haken B T, Kate H H J T and Larbalestier D C 2006 A general scaling relation for the critical current density in Nb_3Sn *Supercond. Sci. Technol.* **19** R100–16
- [32] DeSain J D *et al* 2009 Tensile tests of paraffin wax for hybrid rocket fuel grains *45th AIAA/ASME/SAE/ASEE Joint Propulsion Conf. & Exhibit (August 2009)* (<https://doi.org/10.2514/6.2009-5115>)
- [33] Freund G, Csikos M, Keszthelyi R and Mozes S 1982 Paraffin products *Paraffin Products: Properties, Technologies, Applications* vol **14** (Netherlands: Elsevier) pp 3–335
- [34] Hossain M *et al* 2009 Experimental study of physical and mechanical properties of natural and synthetic waxes using uniaxial compressive strength test *Proc. 3rd Int. Conf. on Modeling, Simulation and Applied Optimization* pp 1–5
- [35] Akono A-T 2011 Scratch tests: a new way of evaluating the fracture toughness of materials *Master of Science in Civil and Environmental Engineering* Massachusetts Institute of Technology
- [36] van de Camp W 2012 Critical current versus transverse stress and thermal stability of RRP Nb_3Sn Rutherford cable *Master Thesis* (available at: <http://purl.utwente.nl/essays/62400>)
- [37] Devred A 2012 *Quench Origins* vol 1262 (July 2008) pp 1262–308