Effect of resin impregnation on the transverse-pressure dependence of the critical current in *Re*BCO Roebel cables

P. Gao[1,4], W.A.J. Wessel[1], M. Dhallé[1], S. Otten[2], A. Kario[2], J. van Nugteren[1,3], G. Kirby[3], L. Bottura[3] and H.H.J. ten Kate[1,3]

[1] University of Twente, P.O. Box 217, 7500 AE Enschede, The Netherlands
[2] Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany
[3] CERN, European Organization for Nuclear research, 1211 Geneva 23, Switzerland
[4] Key Lab of Levitation Technologies and Maglev Trains, Ministry of Education, Superconductivity R&D Center, Southwest Jiaotong University, Chengdu, Sichuan 610031, People's Republic of China

Abstract

*Re*BCO Roebel cables are being developed as one of the promising routes towards much higher-field magnets for future particle accelerators. The Lorentz forces generated in such magnets lead to sizeable transverse pressure on the superconducting cables, in the present 15 to 20 T magnet designs of the order of 100 to 150 MPa. Contrary to single *Re*BCO coated conductors, unprotected Roebel cable due to their uneven surface, start to degrade already with 40 MPa as shown in earlier work. Previous publications also showed that proper impregnation with epoxy resin can dramatically improve the transverse pressure tolerance of a relatively simple model cable with 10 *Re*BCO strands, assembled from SuperPower tape. However, the epoxy resins used until now are not suitable for large-scale magnet vacuum impregnation. For this reason, an alternative impregnation method using CTD-101K with S2 glass-fibers has been implemented. The present paper expands further on the effect of impregnation on the transverse pressure susceptibility of Roebel cables. Three cables, with an architecture that is directly relevant for the so-called EuCARD-2 accelerator demonstrator magnet, were investigated with a variable transverse mechanical load at 4.2 K in a 10.5 T perpendicular magnetic field. The new cables feature a relatively long transposition length of 226 mm and comprise 15 strands of either SuperPower or Bruker coated conductor. For reference, one of the new SuperPower-tape based cables was impregnated with the same resin as the one used in the earlier publications. The other cables were impregnated using the new method. The critical current at 4.2 K of the Bruker-tape Roebel cable is 2.5 to 3 times higher than that of the SuperPower-tape ones with similar architecture. Remarkably no critical current degradation was observed for transverse pressure up to 440 MPa in the SuperPower-tape cables and up to 370 MPa in the Bruker-tape cable. These values by far satisfy the design requirements of presently envisaged 20 T class accelerator demonstrator magnets.

Keywords: *Re*BCO Roebel cable, vacuum impregnation, transverse pressure effect

1. Introduction

One of the key goals of EuCARD-2, a CERN-led collaboration project supported by the European Union program FP7, is to explore the options for 20 T class particle accelerator magnets by using high temperature superconducting (HTS) inserts. Dipole magnet design and construction at CERN are focused on the so-called aligned-block lay-out based on *Re*BCO Roebel cables [1]. "Feather-M0" is an exercise model magnet to develop the coil-winding technique and quench protection, while "Feather-M2" is the formal EuCARD-2 demonstrator insert magnet [2-3]. It has a bore of 40 mm, a length of about 1 m and standalone and it can generate 5 T at 4.2 K. In the 100 mm bore of the FRESCA-2 dipole, which provides a background magnetic field of 13 T at 4.2 K, "Feather-M2" can boost the magnetic field up to 17 T [4].

Roebel cables feature a sufficiently high engineering current density to satisfy the magnetic field requirements of the project. Moreover, their tape-like strands are fully transposed, which is beneficial for limiting transient time constants and it improves current sharing [1-2]. In the aligned-block concept, the Roebel cable is wound with its wide face parallel to the local magnetic field, which results in the highest achievable in-field critical current but also in a large perpendicular Lorentz force. The transverse pressure calculated ranges from 110 MPa to 150 MPa in magnetic fields of 17 T to 20 T.

Single *Re*BCO tapes are known to be quite robust under uniform transverse compression, not showing any irreversible critical current degradation up to stress levels exceeding 100 MPa [5]. Also single Roebel strands have been reported to withstand transverse stress levels up to 100 MPa with a critical current degradation of less than 2 % [6]. However, bare (not-impregnated) *Re*BCO Roebel cables are much less tolerant to transverse stress, due to local stress concentrations at spots where the strands cross [6-9]. Fleiter *et al.* investigated the transverse stress distribution locally in two not-impregnated *Re*BCO Roebel cables and showed that the 10-strand cables manufactured by the Karlsruhe Institute of Technology (KIT) have an effective mechanical cross-section of only 24 % of their physical surface area, which implies that local spots experience much higher stress levels than the average value calculated using the full cable surface [6]. Uglietti *et al.* investigated the critical current under transverse stress of the bare 10-strand *Re*BCO Roebel cables fabricated by the Robinson Research Institute (RRI). A significant critical current reduction of some 20 % was observed at an average pressure as low as 10 MPa [7].

In our earlier work by Otten *et al.* vacuum impregnation of *Re*BCO Roebel cables using Araldite epoxy resin mixed with fused silica powder to match the thermal contraction of the resin mixture to that of the cable were investigated. Effect of transverse pressure on the critical current of a cable at 4.2 K in a 10.5 T background magnetic field, applied perpendicularly to the wide face of the cable was measured. For one of the cables, no critical current degradation was observed up to 250 MPa, for a second up to 170 MPa. Note that the critical current of a not-impregnated reference cable started to reduce already at stress levels as low as 40 MPa, similar to the Uglietti *et al.* results [9]. However, this work was done using simple SuperPower-type Roebel 10-strands cable impregnated with filled epoxy resin adjusted to the thermal expansion of the coated conductor [10].

The 10 kA-class cable design for the Feather magnets meanwhile uses 12 mm wide *Re*BCO Roebel cables with 15 strands and transposition lengths of 226 mm or 300 mm [2]. Braided glass sleeves as turn-to-turn insulation in the dipole magnets is commonly used at CERN. It was found that the 4 µm silica powder used by Otten *et al.* cannot pass this glass mesh, which resulted in incompletely impregnation [10]. For this reason, the more commonly used epoxy CTD-101K was considered [11]. CTD-101K was proven to be more suitable for large-scale magnet impregnation due to its lower viscosity (≈ 0.40 Pa.s at 40°C) and longer pot life (60 h at 40°C) than the epoxy used by Otten *et al.* (≈ 4.5 Pa.s and 3 h at 80°C) [10], [11].

In addition, the layered structure of *Re*BCO tapes is very sensitive to thermal stress. Takematsu *et al.* investigated the performance degradation of a *Re*BCO coil due to epoxy impregnation [12]. The observed critical current degradation was explained by a difference in thermal contraction, from room temperature down to 4.2 K, between the tapes (- 0.25 %) and the pure epoxy (- 1.33 %). An internal report of CERN [13] found the thermal contraction coefficient of *Re*BCO tapes and cables to be - 0.30 % ± 0.05 % from room temperature to 4.2 K. CTD-101K mixed with glass fibers shows some - 0.2 %, a value much closer to *Re*BCO than the epoxy used by Otten *et al.* (- 0.82 %) [10]. No tape delamination was observed in the earlier experiments, but further detailed investigation of this impregnation method with the newer cables remained mandatory, since understanding and mastering this issue is essential for its successful application in magnets.

In this paper, we present new transverse pressure results on three Roebel cables. Two were assembled from 15 punched SuperPower tapes and one from 15 punched Bruker tapes. The samples were impregnated using two different epoxy resins and impregnation scheme, as described in section 2.3. To investigate the impact of the resin material on cable samples of both tape-types, their critical current at 4.2 K in a transverse magnetic field of 10.5 T is presented as function of mechanical transverse pressure. To support the cable results, as well as to understand the impact of the impregnation on the critical current, the field-dependent I_c-value of short single Roebel cable strands are presented as well.

2. Experimental details

2.1. Cable characteristics

In our previous study [9], the transverse pressure tolerance of three Roebel cables assembled from the same tape batch was investigated. The three cable samples have the same geometry: 10 strands assembled with a transposition length of 126 mm, which in the present work is referred to as CABLE I. The goal of the previous study was to demonstrate the performance difference between a bare and an impregnated cable and to verify the reproducibility of the results. With three additional Roebel cables, the present work extends the study to a different cable architecture, a different tape type and a different impregnation method suitable for coil impregnation. All Roebel cables were manufactured at KIT.

Tape and cable characteristics of the four cables are presented in Figure 1 and Table 1. The strands of CABLE I to CABLE III were punched from 12 mm wide SuperPower tapes, while strands of CABLE IV were punched from 12 mm wide Bruker tapes using a punch-and-coat process [14]. In the punch-and-coat process Roebel strand after punching is enveloped with Ag and Cu materials, where in the case of the coat-and-punch process Roebel strand remain open at the punch edge to the environment, what is the case for Roebel strands using SuperPower tape. All punched strands have the same width of 5.5 mm in both their straight and their 'cross-over' sections. The tapes in CABLE I and CABLE II were punched from the same batch of *Re*BCO tapes. The average self-field critical current of the strands is 152 A at 77 K. The strands in CABLE III are from two different tape batches, with an average critical current of 158 A at 77 K. In contrast to CABLE I, the transposition length of CABLE II to CABLE IV is 226 mm. All cables contain 15 strands.

Key characteristics of the bare tapes are listed in Table 2. The substrate of the SuperPower tapes is 50 µm thick Hastelloy while the Bruker tape has a 97 µm thick stainless-steel substrate. The thickness of their *Re*BCO layers is 1.0 and 1.5 µm, capped with 2.0 and 1.8 µm silver protection layers, respectively. Both types are electro-plated with a 40 µm total thick copper stabilizer.

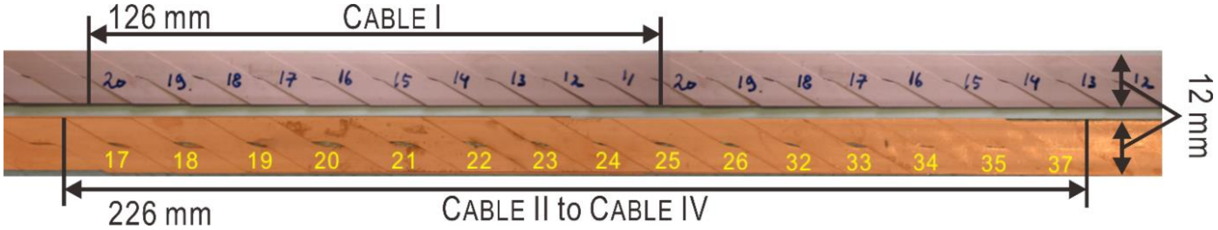


Figure 1. *Flat face of the ReBCO Roebel cables. CABLE I (top) was also reported about in* [9], *CABLE II to CABLE IV (bottom) are characterized for this work. The width of all cables is 12 mm.*

Table 1. KEY CHARACTERISTICS OF THE *RE*BCO ROEBEL CABLES INVESTIGATED.

Roebel cable	I[9]	II	III	IV
Strand / cable width (mm)	5.5 / 12	5.5 / 12	5.5 / 12	5.5 / 12
Cable thickness (mm)	0.5 - 0.6	0.7 - 0.9	0.7 - 0.9	1.5 - 2.0
Transposition length (mm)	126	226	226	226
Cross-over angle (degree)	30	30	30	30
Number of strands	10	15	15	15
Strand batch	SP-KIT-20131011	SP-KIT-20131011	SP-KIT-20131011 SP-KIT-20141125-2	Bruker-KIT-20150615
Strand I_c (77 K, SF) (A)	152	152	158	54*
Electroplated after punching	No	No	No	Yes
Impregnation resin	Araldite CY5538	Araldite CY5538	CTD-101K	CTD-101K
Impregnation filler in resin	Fused silica powder	Fused silica powder	Glass fibre	Glass fibre

*The value is not directly measured on the Roebel strand, only approximated from 12 mm tape results, as most of the Roebel strands have 45 % of the current.

Table 2. KEY CHARACTERISTICS OF THE TAPES IN THE CABLES.

Roebel cable	I to III	IV
Tape manufacturer	SuperPower	Bruker
Tape ID	SCS12050 - AP	T284D
Substrate (material/thickness) (μm)	Hastelloy / 50	Stainless steel / 97
Cu stabilizer (type/thickness) (μm)	Electroplated / 40	Electroplated / 40
Ag protection layer thickness (μm)	2.0	1.8
*Re*BCO thickness (μm)	1.0	1.5
Dimensions (w × t) (mm^2)	12 × 0.10	12 × 0.14
I_c (77 K, SF) (A)	393 & 398	120

2.2 Measurement setup

The transverse stress measurement setup at University of Twente was used extensively for the characterization of LTS Rutherford cables [15]. It consists of two main parts: a superconducting transformer injecting the sample current and an electro-magnetic press generating the transverse force on the cable surface. The primary current of the transformer can be swept from -50 to +50 A, which induces a maximum current of 100 kA in the secondary coil to which the sample is connected. The mechanically loaded section of the sample is situated in the center of an 11 T solenoid and all measurements are made at 4.2 K.

The press is schematically shown in Figure 2 and essentially consists of two anti-series connected NbTi flat coils that repel each other. The top coil pushes a custom-made pressure anvil against the sample via a piston; the bottom coil is connected to the sample holder by a thick steel sleeve and fixation pins. The maximum force that can be applied to the cable surface is 250 kN, corresponding to a transverse pressure of 830 MPa over a surface area of 26 × 12 mm^2.

The precise force, including a correction for the interaction between the main magnet and the press, was determined with two independent methods [16]. The displacement of the upper coil is measured with an extensometer. In addition, two strain gauges glued to the short sides of the pressure anvil allow to monitor its deformation.

The Roebel cables are bent into a flat-bottomed "U"-shape, with corners of radius 20 mm. Earlier measurements on these cables at KIT showed no critical current degradation at bending radii down to 10 mm [10], [17].

To reduce the influence of friction between the anvil and the two-clamping side-plates, a layer of Kapton covers the inner face of the plates. The U-shaped cable is then fixed on the sample holder and vacuum impregnated.

2.3 Sample preparation

CABLE I and CABLE II were impregnated following a KIT recipe, while CABLE III and CABLE IV were impregnated using the standard method used by CERN for Nb_3Sn cables. The KIT recipe uses Araldite CY5538 epoxy resin with hardener HY5571, mixed with FW600 EST fused silica powder in a mass ratio of 1:1:2. The mixture is poured in a temperature-controlled container at 80 °C, brought into the impregnation chamber that already encloses the sample holder with the cable sample and pumped to a rough vacuum pressure of 5 mbar. Once the outgassing of the mixture slows down, after about 5 minutes, the pre-heated sample holder is slowly inserted into the mixture and kept there for 20 minutes. Then the chamber is vented and re-pumped a number of times to facilitate the penetration of the resin into the cable voids. Finally, the holder is taken out of the chamber, a Teflon dummy anvil is attached to the flat bottom of the cable sample and the whole is transferred to a furnace for curing at 100 °C for 24 h. The impregnation steps are similar for the CERN procedure, except that the resin is CTD-101K with a mixing ratio of 200:180:3 and that the cable is encased with an S2-glass sleeve. Also, to fill the space in the middle of the Roebel structure, a glass fiber is inserted in this central channel prior to mounting the sample on the holder.

To ensure parallelism between the sample surface and the pressure anvil, a second impregnation step is implemented at room temperature, as shown in Figure 3. Two 12 mm wide layers of woven glass-fiber are wetted with Stycast 2850FT/23LV and added to the cable surface. The 30 mm-long anvil is positioned on top of the still wet glass, with a 50 μm thick Kapton tape glued to its surface. During curing, the anvil is fixed with respect to the sample holder by two fixation pins, which are also fixed to the two side-plates. The distance between the sample holder and the anvil is 1.5 mm for CABLE I to CABLE III and 2.5 mm for CABLE IV. The thickness of the impregnated cable structures is 1.45 mm and 2.45 mm, respectively. More details of this process are given in [9].

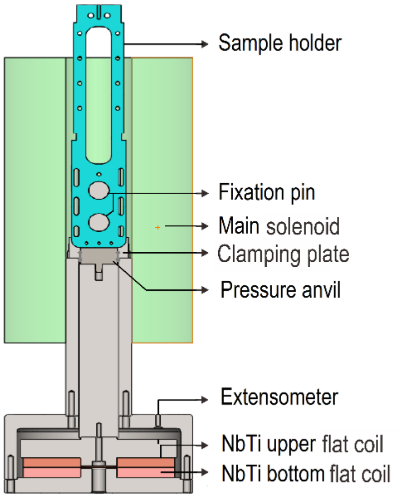


Figure 2. *Schematic of the electromagnetic cryo-press, sample holder and main solenoid* [15].

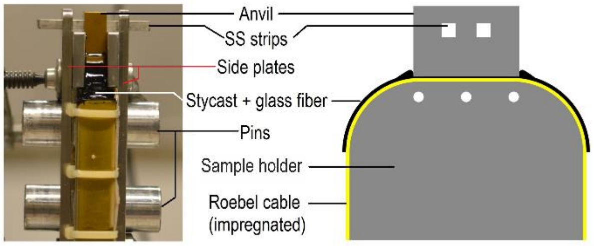


Figure 3. *Set-up used for the second impregnation.*

The U-shaped sample is then soldered to the terminals of the secondary coil of the transformer. The solder joints need to be as low-resistive as possible, since they determine how long a steady current can be maintained [15]. Soft solder In97Ag03, which melts at 143 °C, is used since excessive heat may cause current degradation in the strands [18].

Another factor to consider in the lay-out of the joints is the current distribution in the cable, which for a proper critical current measurement has to be as homogeneous as possible. This requires that the contact resistances to individual strands are near-identical. For the 10-strand CABLE I with a transposition length of 126 mm, this is achieved by making the soldered joint length equal to the transposition length (Figure 4). However, this is not possible for the 15-strand CABLE II to CABLE IV, whose transposition length of 226 mm exceeds the length of the secondary transformer terminals. This implies that not every *Re*BCO face of the 15 strands can be soldered directly onto current lead terminal. The solution is to solder only half a transposition length of the cables to the current leads terminals, while keeping the cable section length in-between the joints equal to an integer multiple of the transposition length. This way, half the strands have their *Re*BCO side facing the terminal in one joint, the other half in the second terminal. As a consequence, all 15 strands will have about the same contact resistance. Note that an extra copper plate on the non-*Re*BCO side of the cable is used to reduce the overall contact resistance and to ensure a homogenous heat distribution during soldering.

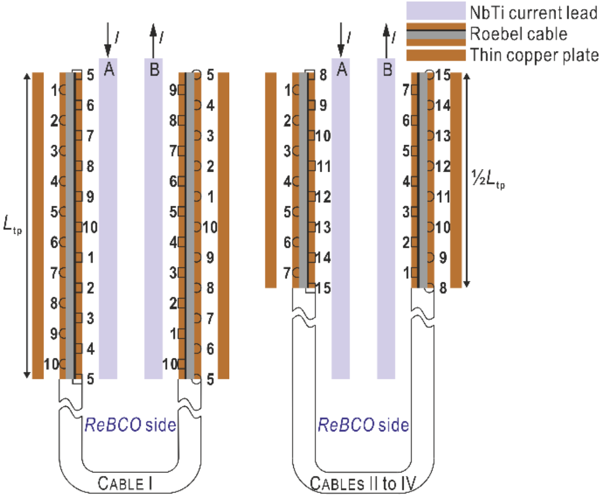


Figure 4. *Schematic lay-out of the soldered joints to the secondary of the superconducting transformer.*

Table 4. JOINT RESISTANCE TO TRANSFORMER SECONDARY.

Cable sample	Joint resistance (nΩ)
I	6.8 ± 0.9
II	3.5 ± 0.5
III	3.97 ± 0.03
IV	2.07 ± 0.01

The joint resistance can be derived from the exponential time constant of the current decay in the transformer's secondary circuit [10] and is reported in Table 4. All values are lower than 10 nΩ, enabling an adequate current holding time.

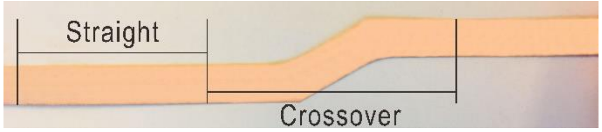


Figure 5. *Single strand of SuperPower-type Roebel cable.*

By comparing the overall I_c values of the cable samples with the $I_c(B)$ values of single strands at 4.2 K, the impact of the vacuum impregnation on the transport properties of the cables can be investigated. The strands in CABLE I to CABLE III were selected before assembling the Roebel cables. The strands in Bruker-tape CABLE IV were extracted from the ends of the cables. All strands were characterized with voltage tap pairs spanning both straight and 'crossover' sections of the punched strands (Figure 5) in a perpendicular magnetic field of up to 14.5 T.

3. Results

To compare the critical current of the cables and the strands, the self-field of strands as well as cables was calculated using COMSOL. A peak self-field factor of 0.24 mT/A was calculated for the straight strand section and 0.30 mT/A for the crossover. For Cable I to Cable IV, the values are 0.091, 0.090, 0.087 and 0.098 mT/A, respectively. With these corrections to the background magnetic field applied, the critical current density (J_c) - values of Cable I to Cable III are compared to the $J_c(B_{peak})$ data of the SuperPower strands in Figure 6. The measured J_c values of the crossover strand section are ~ 20 % lower than those of the straight sections, illustrating how the crossover regions can impact on the overall strand I_c. Comparing the bare sample of Cable I to the 'crossover' strand data, no J_c degradation due to cabling is observed. The two other impregnated samples of Cable I, on the other hand, do show a J_c-reduction of 10 % and 20 %, respectively. Similarly, reductions of 6 % and 17 % were found in the impregnated samples of Cable II and Cable III. These observations indicate that impregnation with both types of resin causes some critical current degradation in the SuperPower-type Roebel cables.

A similar analysis for the Bruker-tape Cable IV was not possible given the limited availability of un-impregnated strand material for testing.

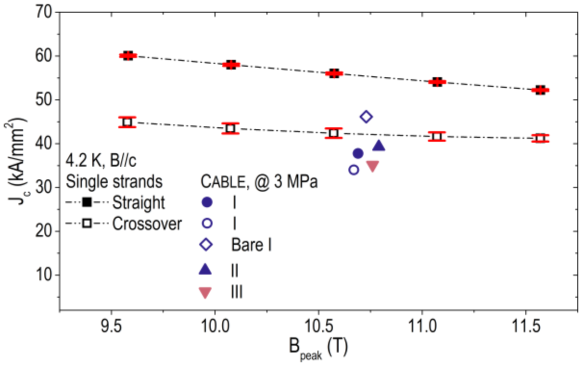
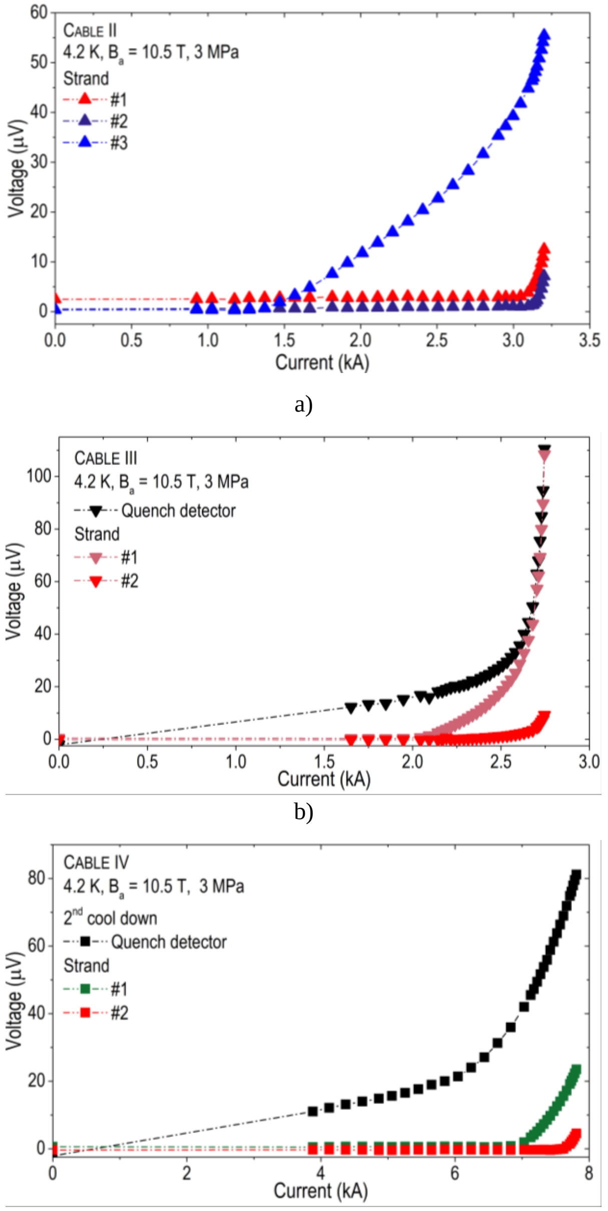


Figure 6. *Critical current density versus peak magnetic field in SuperPower-tape single strands and Roebel cables.*

For the cable measurements, at least three voltage tap pairs are attached, each probing a single strand over a half-integer multiple of the transposition length.

The voltage versus current curves measured on Cable II to Cable IV are shown in Figure 7. All curves were measured at 4.2 K in a perpendicularly applied field of 10.5 T with a rather low 3 MPa pressure applied, just enough to keep the anvil in contact with the sample. Strand 3 of Cable II showed a premature transition with a low n-factor, presumably related to some delamination effect, which was also observed in a post-mortem microscopy analysis. The variations in the onset of the transition are less important for the other cables (~ 20 % for Cable III and ~ 10 % for Cable IV) and become even smaller (~ 1 %) when only the higher-voltage part of the transition is taken into account. The I_c-values are determined at the usual criterion of 100 µV/m by fitting a power-law like VI behavior. The thus determined I_c-values for Cable II probed on strands 1 to 3 are 3.23 kA, 3.22 kA and 3.26 kA, respectively. The I_c values of Cable III and Cable IV are 2.62 kA and 7.75 kA, respectively. The initial slopes in Figure 7b and 7c can be attributed to inter-strand resistance since the voltage taps were not soldered on the same strand.



a)

b)

c)

Figure 7. *Voltage-current curves measured on Cable II to Cable IV at an initial low reference pressure of 3 MPa. The I_c criterion used is 100 µV/m.*

It has to be emphasized that this significant difference between the low-temperature, high-magnetic field I_c values of SuperPower tape CABLE I to CABLE III on the one hand and the Bruker tape CABLE IV on the other reflects the different R&D strategies followed by both manufacturers. Whereas Bruker aims mainly for application in the ultra-high field 4.2 K NMR market, the SuperPower tapes are developed mainly for electrical power applications at lower magnetic field and higher temperature [19].

Note also that the cited value for CABLE IV, extracted from the data in Figure 7c, was measured in a second cool-down campaign, i.e. after the impregnated cable was exposed to a thermal cycle between room temperature and 4.2 K. Figure 8 shows the same data, this time also including the VI curves measured after first cool-down. Remarkably, from the first to the second cool-down, the critical current degraded by some 18 %, from about 9.5 kA to 7.8 kA.

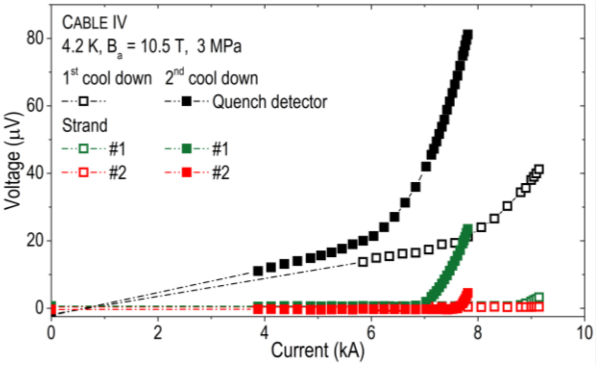


Figure 8. *VI curve of sample of CABLE IV illustrating I_c degradation due to one thermal cycle.*

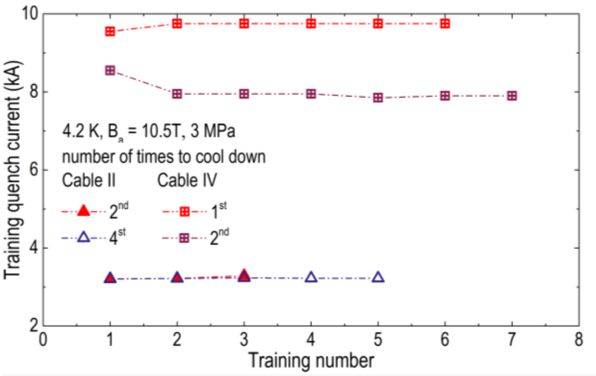


Figure 9. *Quench current versus number of training steps showing the effect of a single thermal cycle on samples CABLE II and CABLE IV.*

The cables assembled from SuperPower tape did not show this effect. In Figure 9 the training quench currents of sample CABLE II are compared to those of samples of CABLE IV (after each cool-down, the cable sample needs to 'settle' against the lateral side-plates before proper VI characteristics can be recorded and the corresponding quench currents are recorded for different cool-down campaigns). No reduction in training current is observed from one cool-down to the next for CABLE II, while CABLE IV clearly shows the 18 % reduction mentioned above. The origin of this sensitivity to thermal cycling of some cable samples and the relation with tape layout and epoxy properties remains to be investigated further.

Once the training behavior subsides, the VI transition can be measured reproducibly up to the level of 10 to 100 µV and the transverse pressure dependence of the critical current can be measured by gradually stepping up the force transferred by the pressure anvil. The results for all four cables are presented in Figure 10. The main conclusions that can be drawn are:

1) The difference in critical current between the two impregnated samples of the 10-strand cable CABLE I is smaller than 10 %. Also the difference between the two 15-strand cables CABLE II and CABLE III is about 10 %. Moreover, the ratio between the I_c-values of CABLE II and CABLE III on the one hand and CABLE I on the other is close to 1.5, i.e. close to the I_c ratio of strands in the cables. These observations show that cable performance for a given strand type is reproducible, irrespective the cable architecture, the used epoxy resin and the surrounding insulation material.
2) Provided a correct vacuum impregnation is performed, both resins used in our experiments are suitable to enhance the cables' mechanical properties.
3) All impregnated cables easily survive the 150 MPa design criterion imposed by the Feather-M2 HTS insert magnet design.
4) No critical current degradation was observed in samples of CABLE II and CABLE III for transverse pressures up to the remarkable value of 450 MPa.
5) No critical current degradation was observed in CABLE IV for transverse pressure up to 370 MPa.
6) At higher pressure levels, the cables show a gradual but significant and irreversible reduction in critical current up to the maximum pressured applied.

After the $I_c(\sigma_{trans.})$ experiments, the samples were carefully removed from the U-shaped holder, cut transversely in their pressed section and polished. The cross-sections were examined under a microscope to verify the impregnation quality and to check for visible damage to strands.

From Figure 11 it is concluded that all cables are indeed fully impregnated, with the epoxy resin filling all voids without significant residual voids. However, several tapes in CABLE II show clear signs of delamination, especially near to the surface of the cable (Fig. 11a). This might be correlated to the premature transition of strand 3 mentioned above (Fig. 7). Also CABLE III shows some signs of delamination in its outermost tapes (Fig. 11b). This is likely a consequence of thermal stress between strands and resin that, as discussed in [9], is corroborated by the difference in the

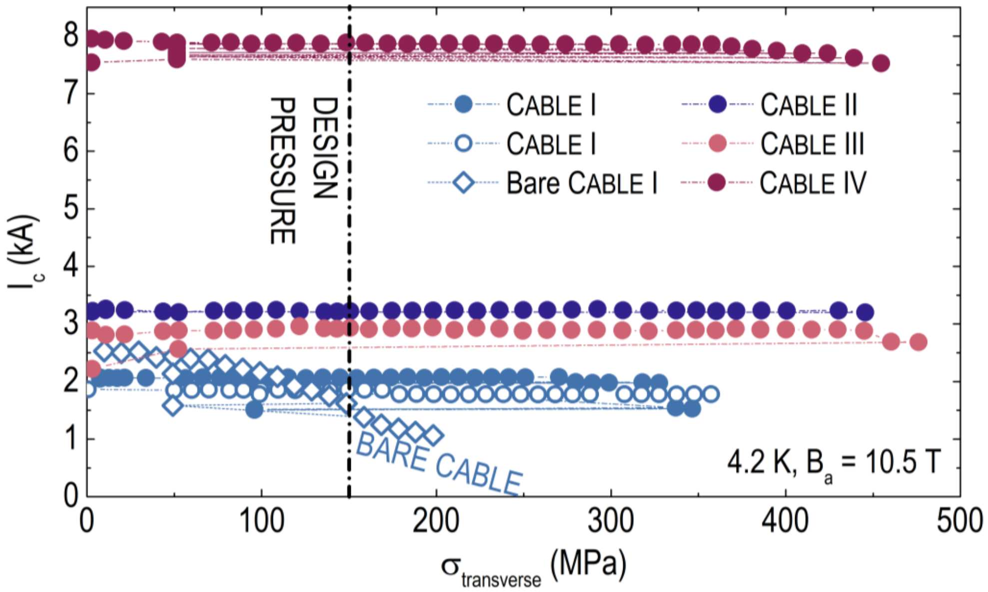


Figure 10. *Critical current versus applied transverse pressure for all tested ReBCO Roebel cables.*

zero-pressure I_c values of bare and impregnated samples of Cable I (Fig. 10). Cable IV does not show any obvious signs of delamination (Fig. 11c). Whether this is a consequence of the different type of tape or of the extra electroplating step that these strands received after punching, describead earlier as punch-and-coat, is not clear at this point.

4. Discussion and Conclusion

Following up on earlier work on 10-strand SuperPower tape based *Re*BCO Roebel cables [9], three new magnet-relevant 15-strand cables were investigated for the effect of vacuum impregnation and choice of resin on the transverse pressure dependence of their critical current. In order not to change more than one parameter at a time, the 15-strand Cable II is assembled from the same SuperPower tape as the earlier 10-strand Cable I and impregnated with the same method. Cable III is assembled from the same tape, but impregnated with a different method using CTD-101K and glass fibre. Cable IV is assembled from Bruker tape processed using the so-called punch-and-coat process. The impregnation method used for Cable IV is the same as for Cable III.

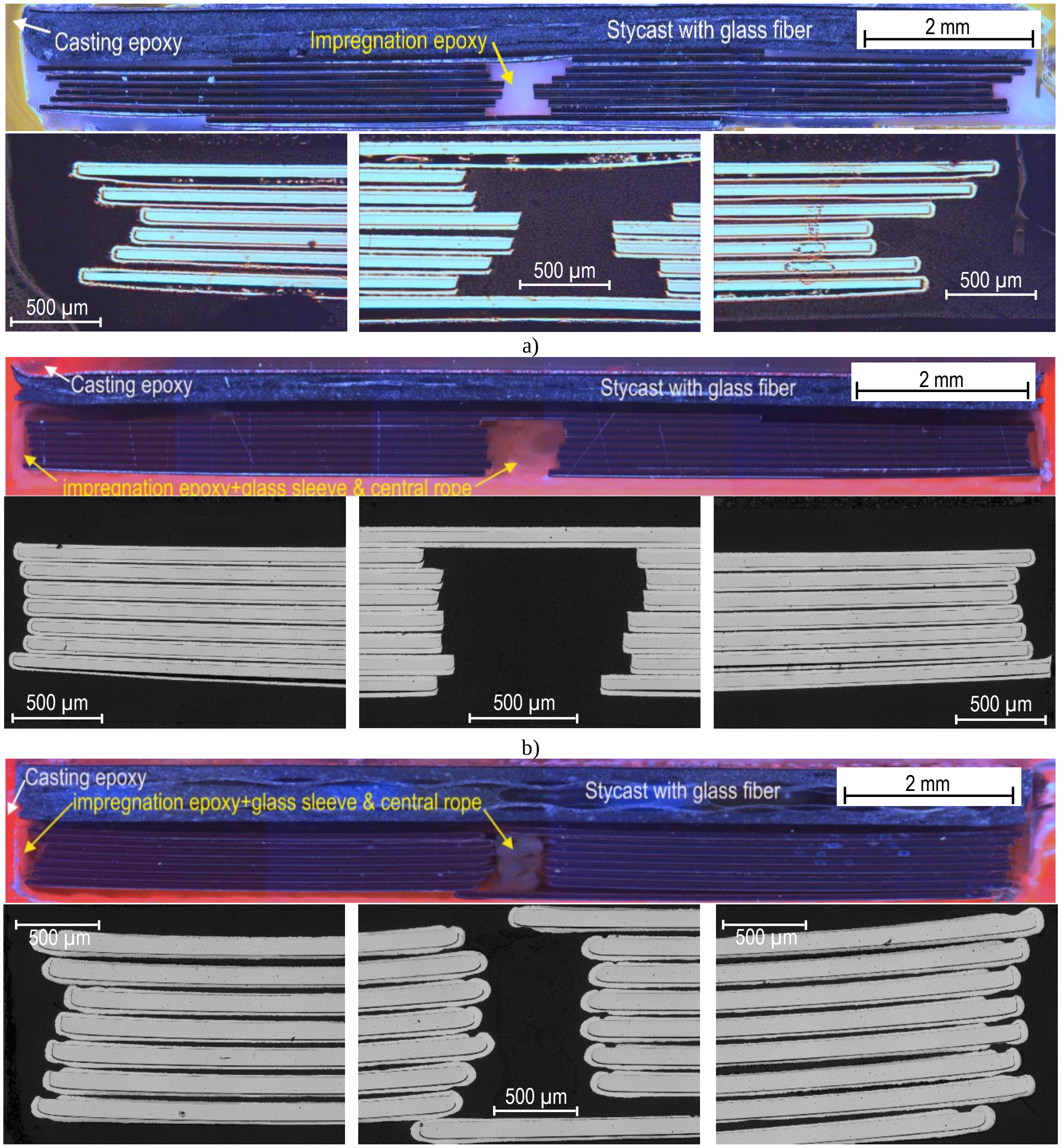
All cables were impregnated successfully, without bubbles or significant residual voids. The critical current of the Roebel cables was measured at 4.2 K in a perpendicular applied magnetic field of 10.5 T. Without significant pressure applied, the critical current of Cable II is 3.2 kA, of Cable III 2.6 kA and of Cable IV 9.5 kA. The comparison of the measured critical currents with the critical current values of SuperPower witness strands reveals that both impregnation methods result in some 10 % to 20 % degradation in critical current.

Layer delamination was observed in Cable II impregnated with Araldite CY5538 filled with fused silica powder. Whether this is due to the combination of tape punching, which leaves edges of the strands directly exposed, the impregnation procedure or impregnation materials, or to the build-up of thermal stress between the resin and strands during cool-down is yet unclear. However, no significant delamination was observed in Cable III and Cable IV, which were impregnated with CTD-101K and glas fibre. Therefore, the new impregnation method using a combination of CTD-101K resin and glass fibre suitable for application in coil windings was convincingly demonstrated.

Repeated cool-down cycles had no further effect on the critical current of the SuperPower tape based cables, but caused a 20 % critical current reduction between first and second cool-down in the Bruker-tape based cable. In Cable I, impregnation caused an increase in the transverse pressure tolerance of the critical current dramatically from 30 MPa to 275 MPa. No critical current degradation was observed in impregnated SuperPower-tape based Cable II & Cable III when loaded with applied transverse pressure up to a record value of 440 MPa. The transverse stress susceptibility of 15-strand SuperPower-tape cables is similar for both impregnation methods. The transverse pressure above which irreversible current reduction starts, is more than 150 MPa higher than for the 10-strand impregnated SuperPower-tape cables. The results are at first instance independent from the type of coated conductor. No critical current degradation was observed for impregnated Bruker-tape Cable IV up to the very high stress level of 370 MPa. All these values amply meet the 150 MPa design requirement of state-of-the art *Re*BCO insert dipole magnets.

The main conclusions of this study are:

1) Epoxy resin CTD-101K is suitable for the vacuum impregnation of large-scale magnets with *Re*BCO Roebel cables covered with S-2 glass-fibers.
2) Provided a correct resin/filler combination is chosen for vacuum impregnation, coated conductor based Roebel cables enable the construction of high current density, high-field and thus high-stress magnet applications i.e. 20+T class accelerator type magnets.
3) 15-strand *Re*BCO Roebel cables with correct vacuum impregnation are able to withstand transverse pressures far beyond 300 MPa without noticeable degradation in critical current.
4) For the first time the transverse pressure effect was measured on 15-strand Roebel cables made from Bruker coated conductor and no critical current degradation was found up to 370 MPa.
5) The transverse pressure tolerance of 15-strand SuperPower Roebel cables was demonstrated up to a record level of 440 MPa



a)

b)

c)

Figure 11. *Cross-sectional views of the pressed sections of (a)* Cable *II, (b)* Cable *III and (c)* Cable *IV. A general overview of the cable layouts is presented each time in the top pane, while close-ups of the edge- and central parts are shown in the bottom one.*

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