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Advances in the Development of a 10-kA Class REBCO cable for the EuCARD2 Demonstrator Magnet

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Abstract— **The objective of the EuCARD2 WP10 (Future Magnets) research activity is to demonstrate HTS magnet technology for accelerator applications, by building a short demonstrator dipole with an aperture of 40 mm, operating field of 5 T, and *understood* field quality. One of the magnet requirements is of small inductance, for use in long magnet strings, hence the superconducting cable must have large current carrying capacity, in the range of 10 kA at the operating conditions of 4.2 K and 5 T. An initial down-selection of the cable material and geometry resulted in the choice of REBCO tapes assembled in a Roebel cable as baseline layout. In this paper we describe the requirements derived from magnet design, the selection process that led to the choice of material and geometry, the reference design of the cable, and its options. Activities have started to address fundamental issues, such as tape performance and tape processing through the cable construction, and key performance parameters such as cable critical current under stress or magnetization. Here we report the main highlights from this work.**

Index Terms— **HTS, Roebel Cable, Accelerator Magnets.**

I. INTRODUCTION

HIGH FIELD SUPERCONDUCTING MAGNETS are the enabling technology for modern particle accelerators because the maximum energy that can be achieved by a particle beam is directly proportional to the bending field [1], [2]. Accelerator dipole magnets built with Low Temperature Superconductors (LTS Nb-Ti and Nb₃Sn) will most likely reach their ultimate performance in the range of 16 T [3]. To attain higher field and thus extend the particle energy reach it will be necessary to resort to High Temperature Superconductors (HTS) [4], profiting from the high critical field and exceptional critical current properties at the liquid helium temperature of 4.2 K [5]. Several initiatives worldwide are addressing the technology issues associated with the use of HTS materials in high-field magnets, for accelerators [6]-[14] as well as other fields [15], [16]. In the case of our work, the objective of the EuCARD2 Work Package 10 (WP10 - Future Magnets) is to demonstrate that HTS materials can be used to generate an accelerator quality dipole field of 5 T in a 40 mm aperture as a stand-alone magnet [14]. In addition, we consider a configuration where the HTS coil is used as an *insert* in the background field of a LTS *outsert* magnet, thus *boosting* the field up to the range of 20 T, i.e. much beyond LTS capability. Besides this challenging performance, an additional critical requirement is that the design should be scalable to long length magnets, as would be necessary for a large size collider in the post-LHC era.

In this paper we give an overview of the activities devoted to the specification, concept definition and development of the HTS conductor and cable for the EuCARD2 demonstrator magnet.

II. HTS CONDUCTOR SPECIFICATIONS

The above broad requirements, discussed in more details in [14], were translated into the performance specifications for the superconductor material summarized in Table I. Given the developmental nature of the work, for some of the parameters we have defined target values, as would be required to achieve optimal performance, as well as minimum requirements that are mandatory to make the magnet feasible.

First and foremost, the conductor engineering current density J_E at operating conditions should be sufficiently high to make the magnet cross section conveniently small, reducing material and magnet costs. Here we define J_E as the ratio of the critical current to the total conductor cross section, i.e. including the superconducting phase, the stabilizer, as well as all other constituents (precursors, substrates, buffers, barriers).

TABLE I
TARGETS AND MINIMUM REQUIRED PERFORMANCE FOR THE HTS MATERIALS CONSIDERED WITHIN THE SCOPE OF THE EuCARD2 MAGNET R&D

Parameter	units	target	minimum
J_E (20 T, 4.2 K)	(A/mm²)	≥ 600	≥ 400
$\sigma(I_c)$	(%)	≤ 10	
$\mu_0 \Delta M$ (1 T, 4.2 K)	(mT)	≤ 300	
Allowable $\sigma_{transverse}$	(MPa)		≥ 100
Allowable $\varepsilon_{longitudinal}$	(%)		≥ ±0.3
Unit Length	(km)	≥ 100	≥ 50

For practical reasons, the evaluation of the cross section is based on production data, i.e. the measured diameter in case of a wire, or the measured width and thickness in case of a tape. Deviations from the ideal round wire or rectangular tape are ignored. Taking as a benchmark the typical range achieved in LTS accelerator magnets [2], we have set a J_E target of 600 A/mm^2 at 4.2 K and 20 T perpendicular field. Only two industrial materials achieve performances in this range, namely YBCO (or REBCO, used to indicate the use of a Rare Earth other than Yttrium) and BSCCO-2212. In fact, the target J_E value quoted above is at the upper limit of the state of the art of long length HTS production. For this reason we have also set a minimum J_E of 400 A/mm^2 at 4.2 K and 20 T to be considered for magnet design.

The minimum unit length (UL) of superconductor required is of the order of 50 m, which, pending more details on the magnet design, is largely in excess of the estimated length of a pole (at present the longest UL required for winding is 28 m). A target UL of 100 m has been set for the development. Such UL can be easily achieved for BSCCO-2212 wires (industrial production reaches routinely UL of the order of 500 m), but is a challenge for REBCO when combined with the request of a high and homogeneous J_E.

The next performance target in Table 1 is the homogeneity of the critical current in a unit length. This parameter affects the quench performance through the margin, as well as the field quality through the persistent current magnetization. Target homogeneity of 10 % (r.m.s. with respect to average value) has been retained as appropriate for an extrapolation of this work to accelerator applications. This is approximately ten times larger than industrial capability for Nb-Ti, and three times larger than experienced in the production of Nb$_3$Sn for ITER. At this initial stage of the R&D we are lacking sufficient statistics from industrial production, and we are not in the position to give a reasoned minimum specification for the homogeneity of the critical current. Note however that large spread of critical current may result in significant difference in performance among coils, and associated field errors generated by persistent current magnetization. The measurement of critical current and magnetization, as well as input from the magnet design studies, should provide further elements for a final assessment of the need and impact of the specified homogeneity.

The DC and AC magnetization of the superconducting cable (*persistent* and *coupling* currents) is expected to be one of the main contributors to the field errors at low field, and is therefore highly relevant to the design of an HTS accelerator magnet. The superconductor cross section in HTS cannot be subdivided in fine filaments to the same degree as LTS. As a result the total magnetic moment is expected to be large. A performance target of 300 mT has been taken for the magnetization amplitude $\mu_0\Delta M$ of the superconductor, wire or tape, in all orientations, in a background field of 1.5 T ramped at 10 mT/s. This is more than ten times larger than achieved in the LHC Nb-Ti production, and about three times larger than targets for Nb$_3$Sn for HEP applications. The above value is intended as total magnetization, including all mechanisms

contributing to the magnetic moment, whether originated by persistent or coupling currents. The wire or tape geometry and architecture, critical current distribution, the presence of resistive barriers, coupling, striation and transposition will affect the value and dependency of M on the field, field ramp-rate and field history. Clearly, such large value also implies the use of innovative magnet cross-section design, passive and active compensation to limit the field errors produced by the magnetization.

The two last performance target parameters concern the mechanical strength of the superconducting wire or tape. A minimum allowable transverse stress of 100 MPa and longitudinal applied strain range of ±0.3 % are specified, under which the superconductor shall retain mechanical integrity and at least 90 % of its virgin J_E (before loading). Mechanical loads are intended as originating from any source, i.e. fabrication, thermal and electromagnetic. The levels above are minimum requests for a high field accelerator magnet, and are challenging for both REBCO and BSCCO-2212, especially the transverse stress. The actual need depends on the magnet design, and could be reduced at the expense of efficiency by operating at a smaller overall current density.

Last and not least, in order to make the design scalable to a long string of magnets connected in series, and from elementary consideration of magnet protection, a high current cable is mandatory. The target set for the development is to produce a 10 kA-class cable at the operating conditions of 4.2 K and 20 T. This is a considerable advance with respect to all development programs in HTS magnets, mostly based on the use of a single wire or tape for winding.

III. HTS MATERIAL FOCUS

As indicated above, of the HTS materials presently available, only two achieve performances in the range of the selected target J_E at low temperature and high field: REBCO [17] and BSCCO-2212 [18].

REBCO is a highly anisotropic superconductor produced only in tape. Its performance and homogeneity depends critically on nature and quality of texturing of the buffer layer and of the REBCO. Homogeneous unit lengths of several tens of meters are achieved routinely, but extrapolation to several hundreds of meters remains a challenge. It is nonetheless produced on a small industrial scale in all world regions, in connection with the interest of this material for power applications. Most recently, under a developing interest in high field applications, and thanks to the introduction of various pinning mechanisms (the most effective being BZO nanorods [19]), the performance at low temperature of industrially produced REBCO has progressed steadily. At 4.2 K and 20 T in perpendicular field, industrially produced REBCO has attained record values of J_E in excess of 800 A/mm^2 [20], and the target performance of Table I was achieved by several production routes. In addition, the J_E potential does not seem to be fully exploited [21]. The REBCO superconducting layer has a thickness of one μm to a few μm, and a width of a few mm. The large aspect ratio adds

an element of difficulty in the control of the magnetization. A tape in parallel field has negligible screening, but as soon as the field has a perpendicular component, the large width results in an equivalent magnetic moment that largely exceeds the target set in Table I [22]. Striation of tapes over the complete length [23], [24] has been shown to reduce loss on short samples [25], but for long cables it only works if the tape is then twisted on itself, inducing transposition of the single striated filaments. Magnetization is hence an unresolved issue for the use of REBCO tapes in accelerator applications. Note that this is also an issue for NMR magnets, as shown in [26]. On the other hand, thanks to the robust supports used for the material deposition (steel or other high strength structural alloys), and a good bonding of the layers achieved by the present production techniques, the mechanical properties of REBCO tapes both in longitudinal tension and transverse compression [27] are excellent. In fact, possibly due to the very large value of the critical field and temperature, the reversible sensitivity to strain is remarkably low until catastrophic crack development and irreversibility takes over [28]. The tape (50 μm substrate) can sustain uniform longitudinal stress up to 700 MPa, and transverse stress (applied on the face) above 100 MPa with little to no degradation [26]. The thin tape remains however sensitive to folding, shear, traction among layers, and twisting, which should be avoided or limited during both magnet manufacturing and operation.

Industrial BSCCO-2212 is produced as a round wire, using procedures and tooling that resemble closely those used for the production of LTS wires. Lengths of several hundreds of meters are common practice. This is a great advantage for the use in cables, and many existing accelerator magnet technologies can be transposed directly from the "wind-and-react" experience in Nb_3Sn. BSCCO-2212 has been recently demonstrated to have J_E record values in excess of 800 A/mm^2 at 4.2 K and 20 T, irrespectively of the field direction [5]. To form the superconducting phase, BSCCO wires require heat treatment at 890 °C with tight temperature control (typically ±1 °C), controlled oxygen content (approximately 1 bar partial pressure is optimal [29]), and in a relatively large pressure atmosphere, of the order of 50 bar to 100 bar, to prevent the formation of gas bubbles in the filamentary region [5]. Such conditions pose issues of material compatibility for the coil structure and insulation, and will require significant tooling development to extrapolate the technology to large-scale magnet manufacturing. The BSCCO-2212 wire is multi-filamentary, where filament size, bridging and twisting can be controlled to limit magnetization using the same technology as for LTS wires, so that the target in Table I should pose no real challenge. From the mechanical point of view, the BSCCO-2212 wire is a composite of a brittle ceramic in a relatively soft Ag alloy matrix. Both the tensile and the transverse compressive sensitivity are relatively large, and irreversibility sets-in rapidly once the wire is subjected to a mechanical load. Initial data [30] suggested that under a given tensile load the critical current has an immediate irreversible degradation. Cycling within the initial loading range is however quasi-

reversible. More recent data [31], [32] indicate an extended reversible range. It is not clear how much of this behavior is affected by the porosity and connectivity features of early wires. The situation is similar for the sensitivity to transverse loading, measured on early cables [33] and indicating degradation at transverse pressure levels as low as 60 MPa (referred to the projected cable area). More recent data produced on over-pressure heat-treated single wires by the EuCARD2 Team in collaboration with the US-BSCCo program confirm that BSCCO-2212 is more sensitive than Nb_3Sn to transverse loads, even when compacted. This is not surprising given the low yield stress of the Ag matrix of the wire. Mechanical strength is definitely one of the major issues in BSCCO-2212, and a subject of active R&D. As a final remark, BSCCO-2212 is presently a "niche" material for high field applications, and is produced only at one site worldwide (Oxford Superconducting Technology).

It is clear from the discussion above that REBCO and BSCCO magnet technologies will be inherently very different. The scope of EuCARD2 being limited in time and funding, a strategic decision was taken early in the program to focus mainly on one of the two materials, i.e. REBCO, and thus avoid excessive diversification. This choice was driven by technical considerations on the higher J_E potential, better mechanical properties, and simpler magnet technology. In addition, REBCO is produced industrially by one of the beneficiaries of the EuCARD2 Consortium (Bruker HTS), and in several other industries worldwide. Finally, this choice provides complementarity among the EuCARD2 and US-based programs, where BSCCO-2212 is supported by the US-DOE Conductor Development Program [34] and the Bismuth Strand and Cable Collaboration (BSCCo) [5]. EuCARD2 (through CERN) has provided precursor powders (from Nexans SuperConductors) for the fabrication of BSCCO-2212 wires, participated to the optimization of the precursor and to the analysis and characterization of the wire performance [29], [35].

IV. CABLE OPTIONS AND BASELINE DESIGN

A robust and efficient HTS cable configuration suitable for use in large-scale magnets is a desirable and yet very elusive goal. Apart for the case of BSCCO-2212 round wire, that can be cabled in a Rutherford configuration [34], [36], there is no consensus on which geometry is best suited to thin tapes, the form in which REBCO HTS is available at present. Among the attempts performed so far, only a few geometries appear to be suitable for the high-current density required by HEP accelerator magnets. Table II reports a condensed summary of the cable configurations most relevant to our work, the engineering current density that has been demonstrated, our estimate of the potential J_E for the geometry of relevance in accelerator magnets, as well as references to other performance indicators such as the typical range of cable current and the tolerance to stress and strain. Table II is intended as a snapshot of the present status, restricted to cables that are of relevance for our goal, and not necessarily a complete overview of all possible HTS cable configurations.

TABLE II
SUMMARY OF THE PERFORMANCE INDICATORS FOR THE VARIOUS REBCO CABLE CONCEPTS CONSIDERED. MEASURED VALUES IN BOLDFACE.

Cable concept	I_{op} (kA)	J_E (A/mm^2)	J_E^{max} (A/mm^2)	$\sigma_{transverse}$ (MPa)	$\varepsilon_{longitudinal}$ (%)	Comments
Tape stacks	2.8 [37] 5 [44]		≈ 600	As for tape		Not transposed
Twisted stacked-tape (TST)	**3 (4.2 K, 12 T)** [53] **4 (4.2 K, 19.7 T)** [41] 8…100 (4.2 K, 16 T) [42]	273 (4.2 K, 16 T) [42]	300…400			Partially transposed; 140 mm bending radius: 3.6% degradation; Sensitive to transverse e.m. loads
Helically twisted stacked-tape (HTST)	10…60 [46]	**100 (4.2 K, 12 T)** [53]	≈ 100	< 30 [53]		Partially transposed; Sensitive to transverse e.m. loads
Conductor on Round Core (CORC)	**7** [50]	**250 (4.2 K, 17 T)** [50]	≈ 300		+0.7 %	Transposed; 40 mm bending radius: 2.5% degradation; Core deforms under e.m. load and folds tapes; joint resistance 40-200 nΩ;
Roebel	**3…10** [54]	**400 (4.2 K, 10 T)** [54]	≈ 500	> 150 [55]		Transposed e.m. loads are concentrated at cross over surfaces

A. Stacked Tapes

A stack of tapes is the simplest form of a *cable*, formed by a number of tapes stacked and bound by, e.g., the electrical insulation such as a polyimide wrap. An assembly of this type, consisting of two sets of two soldered tapes in parallel with a nominal operating current of 2.8 kA, will be used to wind the 6 T HTS insert within the scope of the EuCARD WP7 [37]. A tape stack has the highest possible compaction *C*, which we define as the ratio of tape to cable engineering current density once wound, excluding insulation. Neglecting the effect of surface flatness, stacked tapes have an ideal compaction of 100 %. Tape stacks can be wound very well in the direction of the tape width provided the number of tapes is limited. If the winding can be arranged so that forces are mainly normal to the tape, then the mechanical behavior is sound. The disadvantage is that the cable is not transposed. In principle the currents induced by the magnet ramp can result in strong inhomogeneity in the current distribution. This effect is more severe when increasing the number of tapes, and is amplified by the fact that the electrical contact resistance between tapes tends to be large. This is inherent to the presence of the substrate in the tapes, and applies to all cable configurations. Soldering at the joints as a means to redistribute the current is only effective for short cable lengths (a few meters), i.e. much shorter than a whole magnet (tens to hundreds of meters).

B. Twisted Stacked-Tapes (TST)

A way to partially limit the issue of current distribution in a stack of tapes is to twist the stack with a pitch length compatible with the strain limits of the tape (several tens of cm), producing a so-called Twisted Stacked-Tape (TST) [38]-[42]. This configuration is shown schematically in Fig. 1.

The transposition with respect to an external field is not perfect, but helps current redistribution, still maintaining a relatively high packing factor of the stack. The disadvantage of this configuration is that its helical surface geometry is not

well adapted to compact winding. In general, electromagnetic loading is experienced in all tape directions, which can be critical as discussed earlier. The overall compaction of the cable that can be achieved in a TST is given by the circle inscribing the stack, i.e. 64 % at best when the cable stack has square cross section. As the final cable envelope is round, a further space is lost in coil winding or spacers, which reduces the effective compaction to $C \approx 50$ %.

A variant of the TST is to execute the twist while winding, in the coil ends, i.e. introducing transposition only once every half-turn [41], [44]. Although attractive because of the high compaction that can be achieved in the straight part of the magnet, it is not clear whether the single twisting is sufficient, nor whether the twisted stack can sustain the mechanical loads at this location. Studies are on-going on this subject [44].

C. Helically Twisted Stacked-Tapes (HTST)

An alternative to the twisted tape stack, where one stack is twisted on itself, is to helically wrap one or more stacks on a core with grooves that provides mechanical support, and can be an additional quench protection shunt [40], [45], [46]. This configuration is shown schematically in Fig. 2. The stacks are well protected against mechanical loads, and they are partially transposed. The degree of transposition in this configuration is better than in a TST, especially if the stacks are thin and they
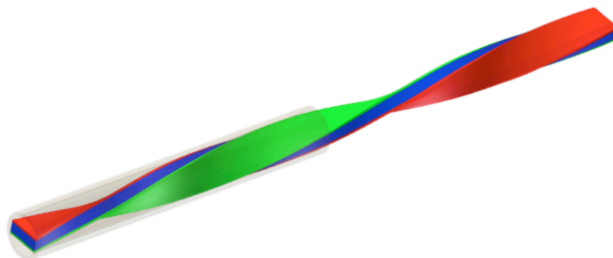

Fig. 1. Schematic representation of a TST cable [43].

are wrapped at a large radius. The disadvantage is that the cable contains a core, and the stacks only occupy the grooves, both of which dilute the current density of the tape stack. The effective compaction of the final cable can achieve values of the order of 20 % to 30 %. As for the TST, the final cable is round, and the effective compaction is further reduced in the coil to values that are around $C \approx 20$ % or smaller.

D. Conductor On Round Core (CORC)

This cable configuration, shown schematically in Fig. 3, consists of tapes wrapped around a round core that can be either hollow (e.g. a cooling pipe) or massive (e.g. a compact round cable made with copper). This cable configuration, similar to classical transmission line cables, has been recently proposed on a small diameter central pipe and has been conventionally called Conductor On Round Core, or CORC [47]-[50]. The cable is transposed with respect to the external field, and the tape wraps can have alternate directions to improve transposition with respect to the self-field. Mechanically, a CORC is more robust than the TST, close to the HTST conditions thanks to the core.

The presence of a core, however, reduces the effective
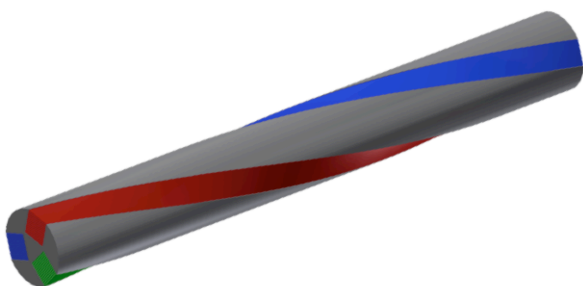

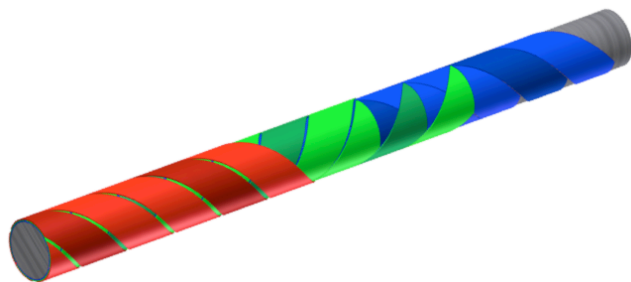Fig. 2. Schematic representation of a HTST cable [43].

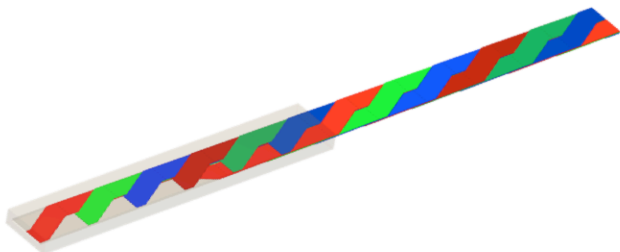Fig. 3. Schematic representation of a CORC [43].

Fig. 4. Schematic representation of a Roebel cable [43].

compaction unless the cable is made relatively large. Assuming a core diameter in the range of 2 mm to 5 mm, the cable compaction that can be achieved with present tape technology is of the order of 20 % to 40 % (depending on the number of tape wraps). The final conductor has a round shape, and as discussed earlier this brings a further reduction of cable current density in the winding, yielding a total effective cable compaction in the range of $C \approx 30$ %. The compaction can be improved making the CORC larger, but given the small winding radius necessary used in accelerator magnets this is not practical.

E. Roebel Cable

This configuration, shown in Fig. 4, is based on punched tapes, assembled in a compact configuration inspired by the high current transposed conductors used in electrical machinery [51], [52]. The Roebel cable has the advantage of a relatively compact configuration, it does not require bending of the tapes, it is flexible, and the tapes are transposed with respect to the external field. The main disadvantage of the Roebel cable is that it requires punching of the tape, with material loss and potential degradation associated with the fact that one edge of the tape is cut open. This has been resolved recently by changing the fabrication sequence, i.e. punching the tapes before coating with the Cu stabilizer. Other disadvantages are that the cable does not behave as a mechanical unit, but rather as an assembly of sliding tapes. Also, a Roebel cable is rather stiff when it is bent in the non-easy direction. As a result the insulation and winding processes may be delicate and need to be demonstrated for the specific geometries of relevance. Once wound, transverse loads are mainly acting normal to the face of the tape, which is good, but the presence of crossovers in the cable results in stress concentration. As to the cable compaction, the Roebel cable consists of stacked tapes, but requires a cavity at the center, necessary for the assembly process. In addition, the tapes crossovers on the wide face increase the overall dimension of the cable with respect to the numerical sum of the thickness of the tapes. With the typical dimensions considered here and detailed later, the maximum cable compaction that can be achieved is $C \approx 86$ %, similar to a Rutherford cable made out of round wires.

F. Baseline Cable Selection

The choice of a baseline cable configuration was taken based on the following criteria:

- High engineering current density in the coil. Considering both the compaction of tapes in the cable, as well as the final coil cross section, this corresponds to the highest values of C;
- Full transposition. The need of transposition is a basic paradigm that holds for LTS cables, but may not apply, in part or at all, to HTS cables. Indeed, a verification of this paradigm is a part of the conductor development;
- Suitable mechanical properties. Tapes have excellent longitudinal tension and transverse load strength, when

the load is applied on the broad face.

The considerations above have guided the choice towards a Roebel cable, satisfying at least in part the above criteria, and in particular a high C, full transposition, and demonstrated ability to carry currents in the range of 10 kA [54]. The Roebel cable has delicate locations where the meandered tapes cross the cable width, resulting in stress concentration. In addition, tensile forces on a Roebel cable also result in large deformation, associated with the meandered shape of the tape and stress concentration. Particular attention is required for coil winding and transverse load redistribution. Tests performed on cables with comparable geometry have shown that impregnation with resin spreads the transverse load, and reduces load concentration to the point that the critical current loss is negligible up to loads in the range of 150 MPa to 250 MPa [55]. In addition, we decided to pursue within the scope of EuCARD2 activities on stacks of tapes with local twist at the magnet ends, also offering the highest J_E potential, mainly to explore the issues of transposition and stress tolerance associated with this concept in large magnets. Magnetization is a common concern for both configurations, whereby no direct solution at the level of the cable can be found.

G. Cable Design

The nominal parameters for the tape and the Roebel cable are summarized in Table III. A cable width of 12 mm is a good compromise for magnet designs based either on the classical blocks or cos-theta configurations [56]. This is the initial width of the tape, which is cut in meanders with a residual tape width of 5.5 mm and a periodicity of 226 mm (based on existing tooling). Taking into account the meander shape, including rounding angles, up to 17 tapes can be assembled in the Roebel cable. The tape thickness depends mainly on the substrate and on the Cu layers, all other layers being negligible. The tapes produced within the scope of the EuCARD2 work at Bruker HTS have a substrate thickness of 100 μm, and a copper layer of 40 μm (total). The ideal Roebel cable thickness (perfect stacking) would then be 1.1 mm. Considering tapes from other sources, of minimum total thickness 0.1 mm, and typical variability in the Cu deposition process, it is expected that the Roebel cable thickness may vary from 0.8 mm to 1.2 mm. A benefit of the Roebel cable is that it is possible to modulate the thickness of the cable by changing the number of tapes, which however requires accommodating the resulting change in the critical current.

The critical current of the cable, 4.2 kA at 4.2 K and 20 T, has been estimated taking the minimum density of 400 A/mm^2 and a "degradation" (due to punching and material inhomogeneity) of 10 %. As mentioned earlier, latest developments show that a tape J_E of 800 A/mm^2 is possible, which would result in a cable critical current of 8 kA. Taking benefit of the increase in J_E in parallel field (depending on tape composition and doping, up to an order of magnitude), this simple calculation shows that this configuration is indeed capable of achieving the 10 kA range of current. This prediction is substantiated by tests performed on similar tape and cable geometries quoted earlier [54].

The minimum UL of cable required for winding is 28 m per magnet pole, which gives a need of about 1 km of tape per magnet. The total production for the whole EuCARD2 program (two demonstrator models and additional R&D cables and windings) is hence approximately 3 km of 12 mm tape.

V. STATUS OF THE R&D

The first priority of the R&D was naturally directed towards the production of suitable lengths of high-performance 12 mm tape at EuCARD2 beneficiary Bruker HTS. After an initial phase based on the production of short lengths of 4 mm and 12 mm tape, the main result of the program is the production of significant lengths of tape, 20 m and longer, with J_E at 4.2 K and 18 T consistently approaching and above the specified 600 A/mm^2, and in all cases well above the minimum value of 400 A/mm^2. A summary of the performance of the tapes delivered within the scope of EuCARD2 is reported in Fig. 5. The best results were achieved by introducing double-disorder in the YBCO layer. The extrinsic pinning obtained via precipitates of BZO in the form of nanorods, is complemented by intrinsic pinning created by intentional variation in the stoichiometry of the deposited layer [20]. It must be underlined that these tapes have a rather thick substrate, 100 μm of steel, and the reported values of J_E correspond to a layer J_C(4.2 K, 20 T) well exceeding 50 kA/mm^2, which, to our knowledge, is the highest value reported to date for industrial tapes.

TABLE III
TAPE AND CABLE BASELINE DIMENSIONS

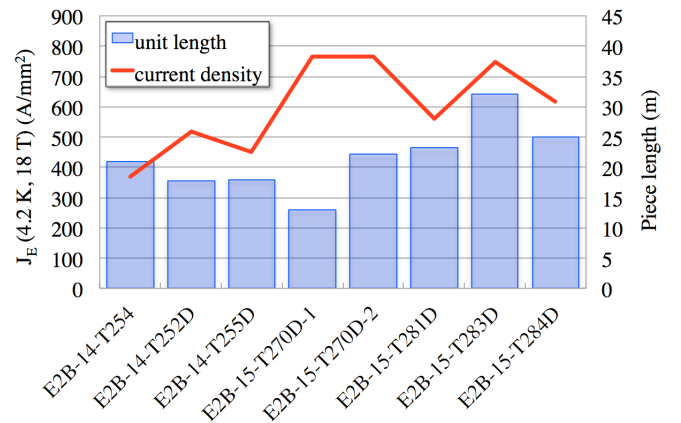|		
Tape width (before punching)	(mm)	12
SC layer	(μm)	1…2
Cu layer	(μm)	2 x 20
Tape thickness (total)	(mm)	0.1 … 0.15
Critical current (4.2 K, 20 T)	(A)	≥ 670
Number of tapes in cable	(-)	≤ 15
Cable width	(mm)	12
Cable thickness	(mm)	0.8 … 1.2
Cable transposition pitch	(mm)	226
Critical current (4.2 K, 20 T)	(kA)	≥ 4.2

Fig. 5. Engineering current density J_E (4.2 K, 18 T) and piece length produced by EuCARD2 beneficiary Bruker-HTS within the scope of the work reported here.

As to the Cu plating, initial attempts were made to deposit a relatively large thickness, 50 μm per side, with the aim to make protection easier. Such thickness results in areas of concentrated deposition, and excess thickness and width of as much as 150 μm (dog-boning). Besides the mechanical issues related to the flatness of the tape, such dog-boning increases the cable thickness and lowers the cable J_E. A maximum Cu layer thickness of 20 μm per side, and an optimization of the geometry of the plating electrodes and bath current, was necessary to minimize the dog-boning.

To date approximately 250 m of YBCO tape were produced. Further procurement of approximately 1 km of tape is on-going at various worldwide manufacturers (SuperPower, SuperOX, Sunam, Fujikura), to explore other manufacturing routes. The final production of tapes for the magnet winding is expected to start by end 2015.

The Roebel cable production was first tested using dummies made of steel strips, as shown in Fig. 6, which were useful for winding trials and other mechanical tests. We found that the 15 tapes assembly with 226 mm transposition pitch is usable but delicate (as expected) when winding over small radii (the tapes tend to slide differentially in the cable), as well as for the layer jump (the tapes buckle when the cable is bent in the non-easy direction). In the early production we tested alternative configurations, with co-layered Cu strips, identical in shape to the meandered tapes (one Cu strip per tape). This configuration made the cable thicker, and exacerbated the difficulties of handling. Finally, we introduced an alternative manufacturing procedure, whereby the tapes are punched right after the Ag cap layer deposition, and Cu is electroplated in meandered geometry. The tests performed showed that the virgin tape critical current is degraded by less than 5 %, with no change of the *n*-index. This *punch-and-coat* sequence has the advantage of sealing the slit sides of the tape, and combined with optimized Cu deposition is possibly the best route for Roebel production.

So far more than 50 m of dummy cable, and 10 m of superconducting cable were produced for qualification purposes, and winding of the first test coil. Work is in progress, to address basic performance (critical current and stress sensitivity tests planned for 2015), as well as the magnetization properties (first data indicate that the Roebel cable behaves as the sum of the single tapes, dominated by hysteresis, and little coupling [57]).

Other open issues, to be addressed in the near future, are compatibility with the insulation system, and in particular the resin used for magnet impregnation, as well as quench detection and protection.

V. CONCLUSIONS AND PERSPECTIVES

The EuCARD2 WP10 (Future Magnets) initiative is providing a strong focus to the development of HTS cables for large-scale accelerator magnets. The program has converged on REBCO tape in a Roebel configuration, of which we have described here the rationale and baseline specification. Tape production and procurements are on going, and most

Fig. 6. Samples of Roebel dummy cables produced within the scope of the EuCARD2 activities: SS tape (top) and assembly of SS and Cu tapes

performance targets appear to be within reach.

Cable samples were manufactured and are ready for characterization, before proceeding to the manufacturing of the lengths for magnet winding. Besides the cable performance, and comparative analysis of different materials, (a) compatibility with coil winding technology, including resin impregnation and joints, (b) quench detection and protection, and (c) magnetization, are the most critical steps that require validation on medium lengths (a few meters of cable) by the magnet R&D program [58].

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