A review on commercial HTS materials for large magnets: from wires and tapes to cables and conductors

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Abstract – High Temperature Superconducting (HTS) materials have the potential to generate magnetic field beyond the level obtainable with Low Temperature Superconducting (LTS). This review reports the past and present R&D on HTS cables and conductors for high field tokamaks, accelerator dipoles and large solenoids. Among the HTS wires and tapes available commercially, coated conductor tapes are the most appealing because of the outstanding critical strength and large improvement margin. Limitations are the weakness against peeling and shearing and the short piece length. The prices for technical superconductors are reviewed because they play an important role in large projects; moreover the perspective of industrial production of HTS wires and tapes is discussed considering the historical development of the LTS wire market. Various designs have been proposed for HTS cables and conductors: some are better suited for soft materials, while others can exploit the anisotropy of coated conductors (by aligning the tape with the field), providing the highest current density. The last decade has seen an increase in the size and complexity of the prototypes; however some peculiar features of HTS, such as high stability margin and high mechanical limits, have not yet been fully incorporated in the designs: for example the transposition requirements for HTS have not yet been studied in detail. Several facts indicate that tapes (even if anisotropic) can be used for manufacturing cables and magnets of any size and have advantages with respect to round wires.

Keywords: HTS cable, fusion magnet, accelerator magnet, superconducting solenoid, high field magnet

1. Introduction

After the discovery of superconductivity in 1911, one of the envisaged applications was the generation of magnetic field. Initial efforts were unsuccessful because Type I superconductors (the first to be discovered) have extremely low critical field. Type II superconductors, which are able to carry large currents in high magnetic field, were discovered in 1935. The first superconducting magnet was built in 1954 with Nb wires at University Illinois and was employed to study adiabatic demagnetization. In the 50's and 60's technical issues (such as flux jump and instability) were solved, leading to the concept of twisted filamentary wires [1]. During the 60's various laboratory superconducting magnets were manufactured employing NbZr, MoRe and NbTi.

The first large scale superconducting magnets for nuclear fusion and accelerators were manufactured in the 70's, just after the introduction of the first cable design. In the 80's the number and size of projects increased, and several cable concepts were developed [2]. At the same time the market for Magnetic Resonance Imaging (MRI) and Nuclear Magnetic Resonance (NMR)—the only commercial applications of superconductivity—was growing exponentially and fostered a corresponding exponential growth in the wire production capacity. In the 90's the superconducting wire industry had expanded enough to cope with larger and larger orders for scientific projects, leading to the present flagship applications: the Large Hadron Collider (LHC) at CERN (built between 2002 and 2008) and ITER, still in construction. R&D is now focused on the next generation of large machines: the Future Circular Collider (FCC) at CERN and the first prototype fusion power plants, which could be large tokamaks (such as EU-DEMO in Europe, K-DEMO in Korea, CFETR in China), helical reactor (in Japan), or compact, high field tokamaks (pursued by private enterprises in UK and USA). In general, these projects will benefit from an increase in the peak magnetic field and/or from higher operating temperature that are offered by HTS. Regarding commercial applications, there is a strong demand for higher and higher magnetic fields in NMR systems.

Resistive magnets are still in use to generate pulsed fields or fields that are not achievable by technical superconductors, superconducting magnets are preferred for steady state operation, because of economic reasons. For example generating a high field with a superconducting solenoid is cheaper than with a resistive one (see section 6), which requires large capital cost (MW range power supplies and water cooling systems) and is very expensive to operate (electricity and maintenance). In case of very large magnets, it would be technically impossible to supply the enormous power (and remove the corresponding heating) in a resistive magnet. This is clearly illustrated in the case of Fusion applications: copper tokamaks (operated in pulsed mode) are still in use to study plasma physics, while superconducting magnets are used when continuous operation is needed. Superconducting magnets are mandatory in fusion power plants otherwise the power dissipated in the magnet system would exceed the generated power by orders of magnitude. In short, superconductivity is either the most cost effective or the only feasible way to generate DC magnetic fields (>2 T) in large volumes (>10 cm^3).

Nowadays the generation of magnetic field exceeding the limits of LTS is probably the main opportunity offered by HTS materials. The operation at temperature > 4.2 K (in the range between 20 K and 50 K) is also considered as a further opportunity but the advantages are not always substantial. For example in fusion power plants the impact of cooling at 5 K on the total power consumption is modest (see section 5.1, reference [128]). Also the simplification of the cryostat and smaller refrigerators may have little impact on the total cost: for example in ITER the cost of the refrigerator and cryo-distribution is less than 1% of the total machine cost. However operation at higher temperatures is beneficial in segmented coils (containing several joints), to easily remove the large Joule heating, and in compact, high field tokamak, where the more intense nuclear heat load could be tolerated. In accelerator magnets the temperature is likely to be kept at 4.2 K, especially for upgrading existing machines, where a cryoplant exists already on site. When operating at higher temperature the dependence from Helium, which is considered a rare and costly resource, is strongly reduced, but not completely eliminated because He gas may still be used as coolant; as alternative liquid neon is too expensive and liquid hydrogen is a valid alternative, once safety issues are solved. One more potential advantage of HTS materials is the cost: even if at present they are more expensive (per unit mass) than LTS, the dream of low cost RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO) coated conductor is still not vanished and, if reached, would be sufficient to justify the replacement of Nb_3Sn at any magnetic field.

The challenges facing HTS materials are short piece length, limited production capacity, few customisation options and high costs. At cable and magnet levels, the challenges are the integration of the HTS, considering its brittle nature of the ceramic, and the high aspect ratio (tapes).

This review focuses on “large magnets” which are broadly defined by having over 100 kg of superconducting material, or >1 m of linear dimension. MRI, NMR magnets and small dipoles (for example for gantries) are excluded and are not usually built with cables; high resolution NMR magnets are not built with cables because the tolerances are not sufficient to achieve high field homogeneity. Large high field solenoids will also be mentioned, even if the need for cables is very limited. In this paper the following definition are in use: wires are round or rectangular with low aspect ratio; tapes have a high aspect ratio (>10); a cable is composed of several strands (wires or tapes); a conductor is composed of a cable plus cooling channels, segregate copper and a steel jacket. Section 2 summarizes the state of the art and characteristics (transport and mechanical) of the HTS materials that are available from industrial manufacturers. Section 3 presents briefly the general features of cables and large magnets (toroid for fusion, dipole for accelerators, solenoid). Section 4 is focused on cables for accelerator dipoles, section 5 on conductors for fusion magnets and section 6 will briefly discuss very high field solenoids. The review covers the historical development and the present status, suggesting directions for future developments.

2. Commercial HTS tapes and wires

The "short sample" critical current (I_c) of wires and tapes should be set ideally as a target when designing cables and conductors for superconducting magnets, of course at relevant operating conditions. In addition, the mechanical properties of HTS wires and tapes set limits (strain and stress) to be considered during cable manufacturing and operation. Therefore this section reports the historical development and the present performance (electrical and mechanical) of the only three HTS compounds have found the way to industrial production: $Bi_2Sr_2Ca_2Cu_3O_x$ (Bi2223), $Bi_2Sr_2CaCu_2O_x$ (Bi2212) and RE-$Ba_2Cu_3O_{7-\delta}$ (REBCO). All three compounds are ceramic, composed of plate like crystals, and are formed during a high temperature heat treatment; moreover the oxygen content in the ceramic should be carefully controlled to obtain optimal superconducting properties. Ag and its alloys are the preferred materials for HTS wire and tape fabrication because they are chemically compatible and transparent to oxygen. The remarkable differences in cross sections (see figure 1) are imposed by the fabrication process and not dictated by stability reasons, as it is the case for LTS wires (see [3]).

Bi2212 can be obtained from the liquid phase at a temperature lower than the melting point of Ag and satisfactory grain alignment and connectivity could be obtained during solidification; wires or tapes can be fabricated.

Bi2223 is a metastable phase (it decomposes during melting). Large critical current is obtained only if the grains are aligned in the same plane (misalignment at the c axis <15°). This is achieved via mechanical deformation (rolling) and heat treatments steps: for this reason only tapes can be manufactured.

REBCO can be formed from the liquid phase but at very high temperatures (incompatible with silver). Large critical current is obtained only in highly biaxially textured samples (misalignment <5°), in fact coated conductors are sometimes described as "a quasi-single crystal hundreds of meters long".

It took only few years from the discovery to the commercialisation of the first Bi-based wires and tapes because the micaceous nature of the ceramic facilitates the texturing during mechanical deformation [4]. Instead coated conductor tapes (few meters long) were first manufactured almost 20 years after the discovery of the compound and after about 10 years of intense R&D effort in US, Europe and Japan. The 90's were the hot decade for Bi based wire and tapes development (see [5] for a detailed review of the fabrication routes); most of the advancements in coated conductor took place during the 2000's.

Regarding the operating temperature and field ranges, Bi2223 and REBCO can carry large currents up to 30 K–50 K in field and at 77 K in self-field, thus have been considered not only for high field magnets but also for electro-technical applications. Instead Bi2212 can be used only at low temperature (<20 K). The field dependence of I_c around 4.2 K is similar in all three materials, at least in the 10 T to 30 T range.

2.1 Bi2212

Already in 1989 Vacuumschmelze [6] showed that Powder in Tube (PIT) round wires could carry large current densities, demonstrating that these wires could be used to generate fields of over 20 T at <20 K. In the following years Showa (Japan), Oxford Sup. Tech. (USA), IGC (USA), Alcatel/Nexans (France) manufactured filamentary wires and/or tapes.

The initial [6] engineering current density was about 10^6 A/mm^2 at 4.2 K at 12 T and it did not change much in PIT wires till 2011, when it was shown [7] that the porosity in the ceramic (due to the formation of gas bubbles during heat treatment), rather than grain misalignment, was the main obstacle to larger critical current. It was found [8] that a high pressure heat treatment can strongly reduce the porosity, thus raising the engineering current density. By applying pressure up to 100 bar the improvement is almost one order of magnitude [9]. Low porosity could be obtained also after heat treatment at lower overpressure, by using groove rolling during manufacturing [10], or by previous cold isostatic compaction [11]. Also homogenous precursor powder with low impurity helps to reduce the porosity.

It should be stressed that high critical current densities (1000 to 3000 A/mm^2 in the ceramic), comparable to the ones of overpressure PIT wires, were obtained already during the 90's in dip-coated [12-13] or casted tapes, and later even on Ag-coated Ni substrate [13]; the reader can find a detailed review of these methods in [5]. These promising low-cost routes were not pursued further probably for two reasons: first, at that time electro-technical devices, instead of high field magnets, were the main application target for HTS, and Bi2212 is not suitable because of the low critical temperature (T_c). Second, twisted filamentary structure and round shape were considered a requirement for winding magnets and cables, but today is accepted that tapes (like coated conductors) can be used without major drawbacks.

Bi2212 wires never found commercial applications despite the demonstration of high field generation (for example in 1997 [14] and 2004 [13]), piece length >1 km (already at the end of the 90's), filamentary structure and the round shape [15] (making possible to manufacture Rutherford cables). Therefore the manufacturers gradually lost interest and halted the production. In the last years only Oxford Superconducting Technologies was still in business (producing round PIT filamentary wires, see figure 1, in various sizes); recently it has been acquired by Bruker EAS.

Electromechanical characteristics

Regarding the strain dependence of the critical current, it has been observed [16] that the reversible, elastic region (confirmed by X ray analysis in [17]) extends only between about 0% and the tensile critical strain, which is located between +0.2% and 0.6%, depending on the manufacturing method [18,19]. At higher strain the critical current drops abruptly. In longitudinal compression the critical current decreases slowly and irreversibly with strain. After compression is released the critical current does not degrade further even after cycling [20], i.e. a new wider elastic region is established at lower I_c; therefore the operating strain range can be extended (see figure 2), if some reduction of the critical current is accepted. This behaviour was initially attributed to micro-cracks at the grain boundaries [16] and related to the high porosity of the ceramic [20]. Nonetheless, the electromechanical tests of recent, very low porosity wires [21] have shown no clear improvement with respect to the non-densified wires. Probably the reason is the same postulated for Bi2223 tapes (see next section), i.e. large difference in Poisson modulus and low bonding between the silver matrix and the ceramic.

One of the disadvantages of Bi2212 PIT wires is the presence of a soft Ag alloy matrix limiting the critical longitudinal stress (at cryogenic temperature) to values between 100 MPa and 180 MPa. Bi2212 wires can be mechanically reinforced by high strength alloys, for example [22] inserting the wire in an Inconel 601 perforated tube (the holes are needed to let oxygen diffuse during heat treatment). An investigation on possible reinforcement alloys was carried out in [23]: Inconel alloys can reduce the I_c in in the wires because Ag react with the Ni alloy producing cracks an pinholes through which Cu can diffuse, causing the formation of Cu poor phases in the filaments. Instead ferritic iron-chromium-aluminium does not react with any elements in the Bi2212 wires because of the formation of a superficial alumina layer. Recently [24] a proprietary alloy has been bonded by solid state diffusion on round and rectangular wires; the strain range is not enlarged (probably because the alloy has a thermal contraction comparable to the one of the ceramic) but the critical stress is increased by a factor 2 or 3, depending on the cross section of the reinforcement, reaching values as high as 300 MPa (about 180 MPa for non-reinforced wires).

Regarding the I_c dependence with transverse pressure, very low values of critical pressure (9 to 20 MPa) were measured in earlier wires [25] and tapes [26]. There are no recent measurements on modern wires (to our knowledge), but it is plausible that the values are similar to the ones of Bi2223 tapes (few tens of MPa). The strain and stress limits for present Bi2212 wires are summarised in table 1 together with the values of other HTS wires and tapes.

Table 1. Characteristics of commercial HTS wires and tapes

	Bi2212 – twisted, filamentary wire	*Bi2223 - non-twisted, filamentary tape*	*REBCO - monofilament tape*
fraction in the cross section:			
superconducting ceramic	20%–35%	30%–40%	<5%
Ag or Ag alloy	65%–80%	60%–70%	<1%
Matrix	-	-	50%–98% (Hastelloy)
Cu	-	-	0%–50%
*Engineering current density (*A/mm^2 *at 4.2 K, 15 T)*	500–1000	350–500 [b]	400–1800 [a,b]
*Non-Cu current density (*A/mm^2 *at 4.2 K, 15 T)*	-	-	800–4500 [c,b]
Critical longitudinal tensile stress (at cryogenic temperature)	Bare: 100–150 MPa Reinforced: 250 MPa	Bare: 130 MPa Reinforced: 270–450 MPa	400–800 MPa
Reversible longitudinal strain range	0% to 0.3%–0.6%	-0.1% to 0.25% (bare), 0.55% (reinforced)	-1.2% to 0.4%–1.0%
Critical transverse compressive stress (at cryogenic temperature)	not available on modern wires	~50 MPa bare ~150 MPa reinforced	300–750 MPa
Industrial manufacturers	Bruker-OST	Sumitomo	>10 companies
Piece length	>1000 m	>1000 m	50 m–300 m

[a] Including 50 micron thick copper (total thickness). [b] Perpendicular to the wide face of the tape. [c] 30 micron substrate.

2.2 Bi2223

Also for Bi2223 the preparation of the first tapes [27] took place only one year after the discovery of the compound [28] but, in contrast with Bi2212, the initial I_c values were modest. The critical current density increased by about one order of magnitude from 1988 to end of 1990. Coils and current leads were already fabricated in 1991 [29]. Tapes produced in the mid 90's by Sumitomo and Vacuumschmelze had critical current of few tens of amperes. American Superconductor (AMSC) set new records in critical current reaching about 100 A at the end of the 90's, >150 A in 2002 and introduced reinforcement by steel tapes lamination [30]. Other companies active in the 90's and beginning of the 2000's were Intermagnetics General (USA), Trithor GmbH (Germany), Nordic Superconductor Technologies (Denmark) and Innova Superconductor Technology (China). So many companies started the production because Bi2223 tapes were expected to find commercial applications in electro-technical devices (such as power cables, motors, transformers). In 2005 Sumitomo [31] introduced an overpressure process which decreased the porosity and improved grain connectivity; as a consequence the production yield was increased and I_c exceeded 200 A at 77 K, self-field. Despite several demonstration projects of electro-technical devices, no product entered the market; at the same time REBCO was gaining more and more interest and research activities on Bi2223 were gradually reduced. Sumitomo is now the only manufacturer, producing piece length in the km range with I_c>200 A or piece length of few hundred meters with I_c>250 A [32]. High current tapes are usually composed of non-twisted filaments; a schematic cross section of a reinforced Bi2223 tape is shown in figure 1.

Electromechanical characteristics

The model describing the strain dependence of the critical current in Bi2223 tapes [33] is very similar to the one developed for Bi2212 wires. It has been experimentally verified [34] that the value of the critical tensile strain depends on the thermal pre-compression exerted by the matrix. The reversible behaviour is attributed to the variation of T_c with strain [35]. The irreversible reduction of I_c in longitudinal compression is similar to the one of Bi2212 wires: also in Bi2223 tapes a wider elastic region can be established at the expenses of I_c. The I_c reduction under longitudinal compression is observed also in overpressure treated tapes, which have very low porosity: a possible explanation [36] is the detachment of the silver matrix from the ceramic due to the low bonding and large difference in Poisson modulus.

Sumitomo has also improved the laminated mechanical reinforcement that was first introduced by AMSC, and the new type HT-NX tape (called HT-XX in [37]) has tensile stress >500 MPa (at about 0.5% tensile strain) at 77 K, close to the value of coated conductors. Under transverse pressure, non-reinforced tapes can withstand between 70 MPa [38] and 100 MPa [39] at 77 K, while the reinforced tapes can withstand as much as 150 MPa [38] (see table 1). These recent progresses, combined with the filamentary structure (low magnetization) and piece length of >1 km make DI-BSCCO a serious alternative to coated conductors for high field NMR inserts (see for example [40-41]).

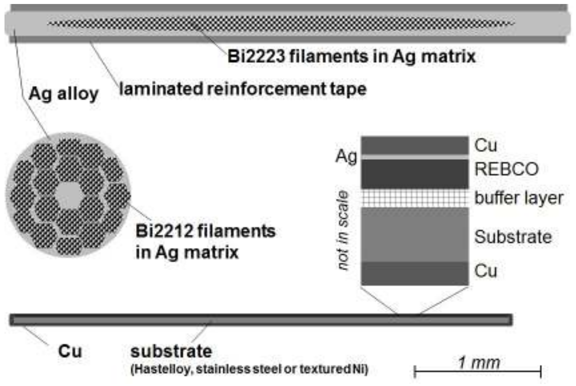


Figure 1. Schematic cross sections of a Bi2212 wire (left), a reinforced Bi2223 tape (top) and a REBCO coated conductor (bottom), in scale. The REBCO magnified insert is not in scale.

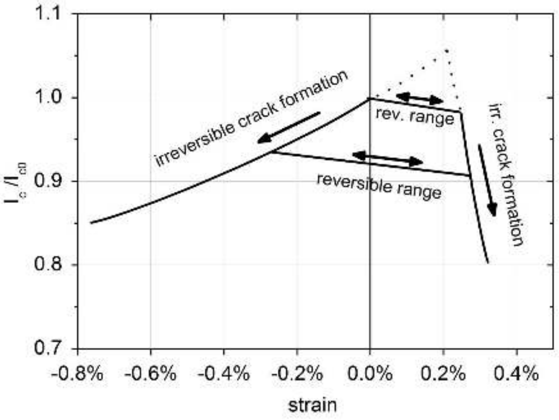


Figure 2. Semi-qualitative behaviour of the critical current versus strain in Bi2212 wires and Bi2223 tapes, as reported in [16] and [20].

2.3 Coated Conductors (REBCO)

REBCO PIT wires were made [42] before Bi2212 wires and Bi2223 tapes, but those earlier wires had very low critical current in applied field because of the weak links among grains. Later [43] it was found that biaxial texture is required to obtain large current density and a lot of effort (in Japan, US and EU universities and research labs) went into the development of techniques to manufacture long tapes with biaxial texture [44]. The first one meter long tape was processed around 1999 but it took till 2003 to process lengths exceeding 10 meters by AMSC [45] and SuperPower [46] (at that time a subsidiary of Intermagnetic General). Few years later REBCO coated conductors were available to customers.

So much effort went in the development of REBCO coated conductors because they were expected to be a cheaper alternative to Bi2223 tapes (there is no expensive Ag matrix in coated conductors); AMSC [47] developed coated conductor maintaining the same cross section of Bi2223 tapes in order to facilitate the replacement in electro-technical devices without need to modify the winding equipment and radically change the design. Today, a decade after the introduction of commercial coated conductors and despite advancements in performance and manufacturing, the promise of cheap tape is unfulfilled, but still pursued [48]. One of the reasons for the high price seems to be the low manufacturing yield. The typical piece length for coated conductor is between 50 m and 300 m and probably just few percent of the production is composed of tapes longer than 500 m. For comparison, the piece lengths of Bi based wires and tapes can be > 1 km and the ones of LTS wires are between 10 km and 200 km. Today there are over ten producers (more than the number of LTS manufacturers), among which: SuperPower, AMSC and Superconductors Technology Inc. (STI) in USA; Bruker EAS, DeutscheNanoschicht and Theva in Germany; Showa and Fujikura in Japan, SuperOx in Russia, Shanghai Superconducting Tech (SST) in China, SuNAM in S. Korea. This large number is in contrast with the absence of a commercial market: in future merging and consolidation should be expected either because of lack of demand or by price competition.

One of the most striking feature of coated conductors is that the cross section of the superconducting ceramic is few percent of the non-Cu cross section (see table 1), instead in classical LTS and Bi based wires/tapes the superconducting cross section varies from 20% to 40% of the total cross section. Hastelloy (rarely stainless steel) is used as substrate by most of the manufacturer; few manufacturers have chosen textured Ni alloy, which is softer than Hastelloy but does not require the deposition of a textured buffer layer. The substrate thickness is usually between 50 and 100 micron, but SuperPower, and recently Shanghai Sup. Tech., are now offering 30 micron substrates (experimental tapes have been produced with 20 micron substrate). Various tape widths are now available, from 1 mm (SuperPower, SuperOx) till 40 mm (AMSC); some manufactures provide also custom width. Coated conductors are often electroplated with copper (RRR<100), but it is possible to purchase also bare tapes (substrate+ceramic+Ag protection layer). A review of commercial coated conductors for high field applications (such as NMR) can be found in [49]. A schematic cross section of a coated conductor is shown in figure 1.

Among the manufacturers, two companies stick out for their unconventional fabrication techniques: DeutschNanoschicht and THEVA. DeutschNanoschicht [50], and their partner Oxulutia, have a radical approach towards low cost production, choosing textured Ni substrate and fully non-vacuum fabrication (ink-jet printing). At present it is not yet clear if this approach will be really able to reduce the fabrication cost, and thus the price, by at least an order of magnitude. The process used by THEVA for the deposition of the ceramic layer [51] is the only one capable to deposit arbitrary thick layers; for all other methods the thickness is usually limited to less than 2 μm [52], even if thicker layers have been produced on R&D equipment. Instead, THEVA has demonstrated the production of 8 μm thick ceramic layer without loss of current density.

The critical current of commercial coated conductors covers a wide range of values, from about 100 A to over 250 A at 77 K, self-field (for a 4 mm wide tape). Also at low temperature, in field, the range covers almost a factor 7: a glimpse of the situation is plotted in figure 3 for various tapes measured in the last five years at the Swiss Plasma Center, together with recent values from [53] and [54]; the reader can find more characteristics and specifications in [52]. In order to improve the critical current values in field some manufacturers add artificial pinning centres (APC) in the ceramic layer; this technique was first introduced by SuperPower, adding Zr to the ceramic precursors. During heat treatment barium zirconate (BZO) nano-columns are formed in the ceramic layer. APC is still extensively studied in academic laboratories. In tapes manufactured by Bruker [54] the APC are of two types: BZO and local stoichiometry deviations, both acting as additional pinning centres. However it should be pointed out that deliberate APC additions are not necessary for high critical current, in fact STI does not introduce APC, but demonstrated one of the highest critical current. Conversely, APC addition seems to be the cause of the variation in I_c from batch to batch [55].

A feature of coated conductors is the strong anisotropy of I_c with respect the direction of the magnetic field: a sharp peak in I_c appears when the magnetic field is almost parallel to the wide face of the tape, as shown in figure 4 (SuperPower has APC while the other manufacturers did not introduced APC). More values and physical discussions can be found in [56].

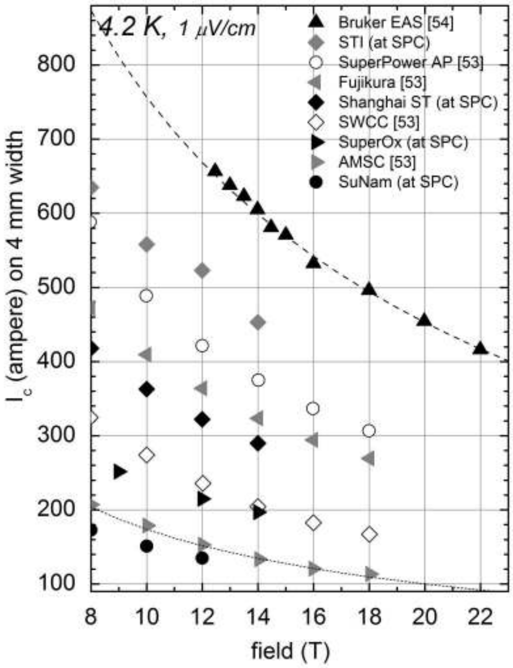


Figure 3. Overview of field dependence of I_c for several commercial coated conductors (field perpendicular to the wide face of the tape). Values measured at SPC, from [53] and from [54]. Variations from production runs cab be up to 50%. Substrate thickness varies between 50 and 100 μm. Lines are guides for the eye.

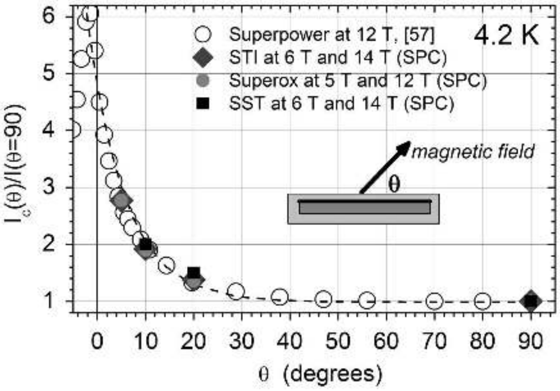


Figure 4. Angular dependence of the critical current in coated conductors for various manufacturers. The angle is between the magnetic field and the wide face of the tape. Values at different magnetic fields overlap. Line is a guide for the eye.

Electromechanical characteristics

One of the advantages of coated conductors (maybe the most important) is the high value of critical stresses at cryogenic temperature: >800 MPa in longitudinal tensile direction [58] (about 700 MPa at 100 000 cycles [59]) and between 300 MPa and 750 MPa (depending on Cu thickness) in transverse compression [60]; if textured Ni is used as substrate the critical transverse pressure is smaller [61]. These values are much higher than the ones of Nb_3Sn, non-reinforced B2212 wires and Bi2223 tapes and are marginally superiors to reinforced Bi based wires and tapes. Such high critical stress is a very important feature to exploit the full J_c in high field, because high field brings also huge mechanical loads.

When coated conductors are loaded in other directions the critical stresses have much lower values [62]: 10–100 MPa for transverse tensile, 20 MPa for shearing and <1 MPa for peeling and cleavage. Therefore the critical stress anisotropy (over a factor 100) is much larger than the I_c anisotropy (a factor five, as shown in figure 4): when designing cables, conductors and magnets, peeling/shearing loads, or pulling forces on the wide face of the tape should be carefully avoided because they could cause delamination and significant reduction of I_c. The delamination limits span a wide range of values because of the brittle nature of the ceramic. In transverse tensile tests, values from 10 MPa to 60 MPa [63] has been measured on samples cut from the same tape and the Weibull distribution was used to describe the probability of having a certain delamination strength value. Recently [64] the energy needed to delaminate the ceramic has been measured for tapes from various manufacturers.

Coated conductors have set new records also in term of longitudinal tensile critical strain, with values from 0.4% to 0.7% [58], depending on the manufacturer, and even 1% has been reported on AMSC tapes [38]. In longitudinal compression coated conductors can withstand -1.2% strains [65] without reduction of I_c (at low temperature, in field). I_c versus strain follows a parabolic curve at 77 K self-field [66] (similar to the one of Nb_3Sn), but at low temperature, in field, the critical current remains almost constant within the tensile and compressive irreversible limits. Nevertheless, it was found [67] that the full excursion from tensile to compressive limit may damage the ceramic, probably as a consequence of the large plastic deformation of the metals in the tape. See table 1 for a direct comparison with the other HTS materials.

2.4 Summary of tensile strain limit: Bi2212, Bi2223, REBCO and Nb_3Sn

A summary of the longitudinal strain window for HTS wires and tapes is attempted in figure 5; Nb_3Sn is also added for comparison. All materials show a catastrophic reduction of I_c when the tensile critical value is exceeded. In Nb_3Sn I_c has the typical bell-like shape, characterized by a large reduction in the compressive region. In Bi2212 and Bi2223 the reduction of I_c in the compressive region is smaller than in Nb_3Sn, even if it is irreversible. In REBCO coated conductors I_c is almost constant over the widest strain range, extending at least from -1.2% to +0.45% or even +0.7%. In HTS wires and tapes a modest increase in temperature (few Kelvin) and in magnetic field (few Tesla) has negligible effect on the strain dependence of I_c. Instead in Nb_3Sn the $I_c(\varepsilon)$ curve becomes much steeper when temperature and/or field are increased.

Figure 5 gives a clear indication of the strain limits to be considered when designing cables, conductors and magnets: obviously the best operating strain is the one where the I_c is the highest, because less material will be needed (highest J_e) and the cost will be the lowest. The strain at operation should be set far enough from the irreversible tensile limit, not only to avoid the very steep decrease in I_c with strain when this limit is exceeded, but also to account for variability among samples (see for example [68]). Operation in the compressive region can be considered for Bi2212 wires and Bi2223 tapes but a moderate and irreversible reduction in I_c is the price to pay for the extended strain range. Instead in Nb_3Sn wires the operation in the compressive region brings a much larger reversible reduction in I_c and thus a big economic penalty, because 2 to 4 times more wires should be purchased.

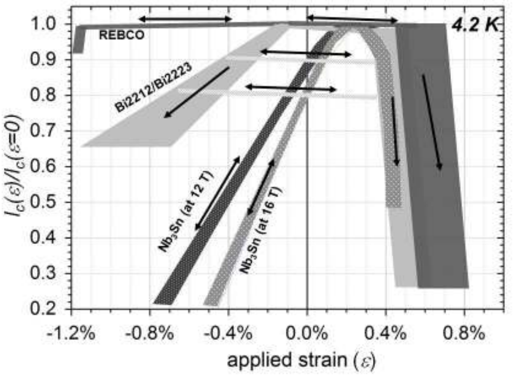


Figure 5. Reduced critical current versus strain for HTS wires and tapes (at any magnetic field) and Nb_3Sn wires (at 12 T and 16 T). The shaded areas take into account variability among manufacturers. One tip arrows for irreversible behaviour, two tips arrows for reversible behaviour.

2.5 Price and market of technical superconductors

Price overview of technical superconductors

Historically the superconducting materials that have been used in devices were not the ones with the highest T_c or critical field, but the cheapest that could be manufactured in long length and with sufficient current density. In the case of HTS (as it was the case for LTS) initial prices were very high but decreased exponentially, however the extrapolations were often to be too optimistic. For example the price of Bi2233 followed an exponential decrease, going from 1000 \$/kAm in 1997 to 200 \$/kAm in 2002 [69]; but the extrapolated price of 20 \$/kAm for 2004 (based on estimation of raw material costs), has not been reached even today. In 2006 DI-BSCCO tapes [70] were priced around 100 \$/kAm (77 K, self-field), corresponding to 20 \$/kAm at 4.5K, 5 T, but it was forecasted to reach 20 \$/kAm (77 K, s.f.) between 2011 and 2016; instead, in 2017 it was only 2 times cheaper (about 50 \$/kAm) than in 2006. Also for coated conductors the price reduction was overestimated, for example the Japanese National Project for REBCO in 2003 had a target of 12 ¥/Am (77 K, s.f.) for 2007, but in 2017 (10 years after the target date) the price is still 2 to 5 times higher, between 20 and 60 ¥/Am.

The price (in \$/kg) for technical superconductors is reported in figure 6, considering a Cu:non-Cu ratio of about one; the wide ranges reflect variability in specifications, order size and negotiating power. These values come partly from [71] and partly from private inquires and public presentations during the last 5–10 years. For comparison, silver price is now around 500 \$/kg and oscillated between 500 \$ and 2000 \$ (inflation adjusted) in the last 20 years.

Of course the actual price at operation depends on B, T, and strain (mainly for Nb_3Sn). In figure 7 the price in \$/kAm (i.e. the price to buy enough material to carry 1 kA over a length of 1 m) is plotted as a function of field. For comparison, NbTi wires are usually employed at about 1 \$/kAm (at 4.2 K, 5 T). At 4.2 K Nb_3Sn is the cheapest almost up to the practical field limit; when is operated at slightly higher temperature and/or in compressive strain (for example in some conductors for Fusion magnets) the critical current is reduced and the price increases accordingly. The values for HTS tapes are for magnetic field applied perpendicular to the wide face of the tape. In case of coated conductor the costs could be two to four times lower if the magnetic field is almost parallel to the wide face of the tape. The values for HTS are little affected by variations in temperature of few K. Bi2212 wires should cost (\$/kg) more or less like Bi2223 because the materials are similar and the fabrication process is similar; the difference (a factor 3) is presumably due to market size and negotiating power. The price of REBCO tapes is rapidly decreasing mainly because of the increase in critical current: for example the latest values from SST indicates values around 40 \$/kAm at 10 T, 4.2 K. Even such reductions do not change much the field at which the HTS becomes more competitive than Nb_3Sn; the reason is that the cost of HTS wires and tapes increase slowly with magnetic field (the curves are almost horizontal), while the cost of Nb_3Sn increases very rapidly with field; this is of course a consequence of the field dependence of I_c.

Figure 7 provides more information than figure 6, because it contains also the field and temperature dependence, but it has not a general validity, because the maximum stresses at operation are not considered (this is very important for example in high field solenoids). Unfortunately the most accurate and trustful method to evaluate the price difference between LTS and HTS for a certain device is likely to carry out the whole design process twice, once for the LTS option and once for the HTS option, of course trying to exploit the material at its maximum potential, and considering the costs of the auxiliary components (see for example [72]).

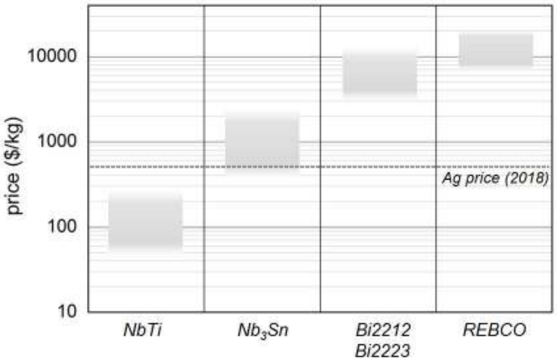


Figure 6. Price in \$/kg for technical superconductors. Values are from [71], from presentations and from inquires during the last 5 years. Weight includes matrix (bronze, Hastelloy, Ag) and copper (1 to 1 ratio).

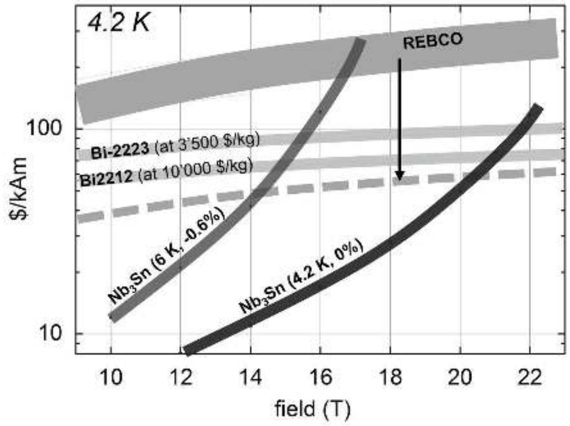


Figure 7. Price of technical superconductor as a function of field at 4.2 K; the magnetic field is perpendicular to the wide face of the tapes. For Nb_3Sn two values of operating temperatures and applied strain and reported. For HTS the temperature dependence around 5 K is negligible. The dashed line is expected for the most recent coated conductors.

The market for technical superconductors

The outstanding performance of coated conductors does not necessarily guarantee its commercial success. In fact several times during the last 40 years, superconducting materials with high current density in high field (such as V_3Ga, Nb_3Al, Chevrel phases) were expected to take over the established NbTi and Nb_3Sn, but later were abandoned because failed to find market applications justifying their costs. In the last decades the lack of commercial applications for Bi2212 wires and Bi2223 tapes has steadily reduced the number of manufactures. In fact wire and tape manufacturers cannot survive only with large but sporadic orders for accelerator, R&D tokamaks or academic projects, but need a constant and predictable flow of orders, like the one behind NbTi (MRI magnets) and Nb_3Sn (NMR magnets).

It is worth to discuss briefly how the market was established with the example of NbTi, which is by far the most successful superconductor in term of tons/year. The development of NbTi wire was carried out in the 70's mainly aiming at scientific applications, like accelerator dipoles or research magnets. At that time the annual production was few tonnes and the cost was as high as 1000 \$/kg (inflation adjusted). The development of MRI took place during the 1970 culminating with clinical trials in 1980 and followed by the development of the first commercial units by Bruker and GE at the beginning of the 80's. During the 80's and 90's the demand for medical MRI systems grow exponentially [73], reaching 3000 unit installed annually around 2014. The demand for MRI magnets pushed the manufacturers to increase the production capacity, and competition reduced the prices (about a factor 3, see [71]). During the construction of the LHC (2002-2004) about half of the world production capacity was dedicated to the wires for the accelerator (1200 t in total). One could say that the commercial market for MRI is one of the factors that made the construction of the LHC possible. Today the NbTi annual production is between 3000 t/y and 5000 t/y (weight includes copper).

In similar way, the industrial production of Nb_3Sn wires increased from < 2 t/y at the beginning of the 90's to the present 10 t/y and is economically justified by the NMR market. Often companies produces NbTi and Nb_3Sn in the same factory and on the same equipment, this is the reason why the Nb_3Sn production could be stretched to 100 t/y to accommodate the production of the ITER strands (2010–2014), i.e. using spare capacity and a small fraction of the NbTi production capacity. The FCC at CERN may require as much as 10 000 t of Nb_3Sn wire (to be procured during 5–10 years), but it is probably unrealistic for the manufacturers to expand that much the capacity without any commercial demand in view.

In terms of market value the commercial applications (MRI and NMR systems) represented over 70% of the total during the LHC wire production (1200 t in total during 2002–2004) and about 50% during the ITER wire production (about 100 t/y between 2010 and 2014). After 2013 the wire market share for MRI and NMR systems represented about 75% of the total.

It is not yet clear what will be the commercial application that will sustain the coated conductor manufacturers, but few scenarios could be envisaged:

- No clear market appears and gradually most the manufacturers get out of business. Few companies will continue with little production capacity and high price to serve a sporadic demand for special magnets (this is already the case for Bi2212 and Bi2223). It will be unlikely to procure enough tape at reasonable price for huge projects like FFC or DEMO.
- Coated conductors may find commercial application in very high field NMR systems (a niche market) leading to modest production capacity of tape optimized for high field and low temperature. The production capacity may not be sufficient to satisfy the demand for large scientific projects.
- One of the electro-technical applications (for example generators for wind turbines) may find the way to market and low cost tape optimized for low field, high temperature will be mass produced at low price. This could probably be good enough for low temperature, high field applications, and large projects could be built.
- High field, compact tokamaks may prove the viability of fusion power and become the main market for HTS wires or tapes. This will guarantee a large capacity of tape optimized for high field/low temperature (<20 K) that could be used also for large scientific projects, NMR and eventually MRI magnets.

These scenarios show that in future the availability of large quantities of cheap, high performance coated conductors should not be taken for granted, even if the present status looks much more encouraging that the one of other new superconducting materials (such as Nb_3Al, Chevrel phases) in the past. In any case R&D on conductors and magnet is valuable, because the knowledge, even if not used for HTS, may be used for new class of superconducting materials that may appear in future.

3. Background on cables and magnets

3.1 Cables and conductors

In large magnets, sufficiently low inductance is needed to keep the voltage within reasonable values during charging and rapid discharges (for example in case of quenches). In large magnets, the inductance (proportional to the size and to the number of turns) is controlled by reducing the number of turns; as a consequence, the operating current must be increased. Therefore large magnets are built with large current cables instead of single wires/tapes, which usually have a low current capacity. The upper limit of the operating current is roughly determined by the cost and complexity of power supplies and HTS current leads.

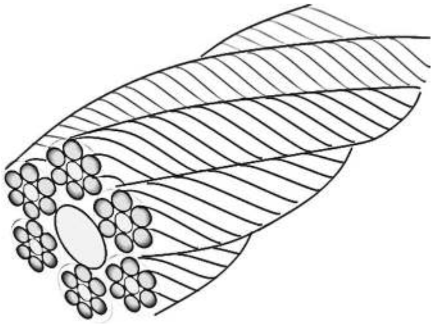
The stability considerations that justified the development of the twisted filamentary structures in LTS wires (see chapter 5 and 7 in [74] for a detailed study) were also at the origin of the transposed cable designs [2]. "Transposition" means that, when moving along the cable, each strand will occupy (sooner or later) all the positions previously occupied by all other strands. In a fully transposed cable all the strands have the same inductance, consequently the current will be equally distributed among the strands during ramping. Moreover transposition minimise AC losses. Examples of transposed cables are the braid cable (the strands are interwoven), the Litz or rope-type cable (twisted, multi stage, for example ITER cables), the Roebel bar and the Rutherford cable (a Robel cable made with round wires); see figure 8 and [74] at pag. 306–309. It should be pointed out that in Roebel bars the strands are transposed but are not twisted, i.e. the strands are not rotated during the cabling process, while in other cable designs the transposition is obtained by twisting (rotating) the strands.

In non-transposed cables (or partially transposed cables) the strands may not have all the same inductance, and the current imbalance may lead to instabilities and quenches, if the stability margin is too low. In non-transposed cables it is still possible to obtain the same inductance in all strands: for example in Bi2223 coaxial power cables all the tapes in all layers have the same inductance, if the cabling pitches of each layer are chosen correctly [75]. However non-transposed cables may still suffer from large self-field AC losses.

Typically the strands in LTS cables are not insulated, because it has been observed (see [76], pag. 438) that cables with insulated strands tend to quench before reaching the maximum performance. The reason is the low stability margin of LTS, but the details were not fully understood.

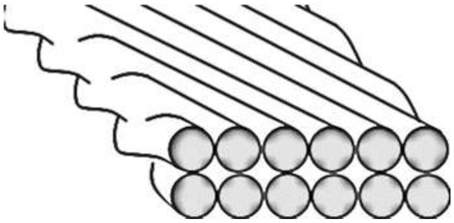
Dipoles are usually built with Rutherford cables and, like many high field solenoids, are bath cooled. Magnets for fusion and detectors are instead cooled by a forced flow of He, which provides a very high heat removal rate. The cables for this type of magnets are usually inserted in a steel conduit and the He flows in a separate channel. One type of forced flow conductor is the Cable in Conduit (CIC) conductor, in which the strands are directly in contact with the cryogenic fluid. Therefore stability is exceptional in CIC conductors; this is a very important feature for LTS but less for HTS. An exhaustive summary of LTS cables for Fusion applications developed between the 70's and the 90's can be found in [2].

In the development of HTS cables during the present decade, as reported in section 4 and 5, the strategy has often been to imitate the LTS cable designs, without verifying if the requirements for LTS were still needed in the case of HTS materials.



Litz or rope-type cable

Roebel bar



Rutherford cable

Figure 8. Top left: sketch of a Litz or rope-type cable (two stages, each six-around-one). Top right: sketch of a braided cable. Middle: photograph of a Roebel bar. Bottom: sketch of a Rutherford cable.

3.2 Large magnets

Dipoles for accelerators, very high field solenoids, fusion magnets and detector magnets are all large superconducting magnets but have very different characteristics influencing noticeably the design of cable and conductors. A cable concept can be adapted to different magnet types but it may require extensive modifications. Therefore it is useful to classify magnets and discuss their characteristic before presenting cables and conductors. The magnet types considered are dipoles, solenoids and toroidal magnets.

Dipoles and solenoids

High field dipoles (see figure 9) are characterised by a very small bore and thick winding pack; this can be expressed by saying that the ratio between the winding pack thickness and the inner radius is larger than one (for example it is about 2 for the LHC dipoles). The value of the peak magnetic field is very close to the value of the central field; these magnets are thus very efficient in generating high magnetic field. Small bore and thick winding implies that some superconductor is located very close to the central bore, thus a very large engineering current density is required. In fact, if the current density is diminished, more material should be added at the outer diameter, and this is very inefficient because it is far from the centre. High field solenoids, like laboratory magnets and NMR magnets (see figure 9), are also characterized by thick winding and small bore. Cables (or strands) for this type of magnets should have the highest possible engineering current density, thus copper should be reduced as much as possible (affecting the quench protection strategy) and any mechanical reinforcement should be moved to the outer diameter, of course if this is compatible with the accumulation of transverse pressure.

One important difference between dipoles and solenoids is in the direction of the electromagnetic loads: in high field solenoids the main loads are hoop loads, resulting in longitudinal loads (along the cable or strand). In dipoles the main forces are directed transversally to the long straight sections and require large external mechanical structure to contain the winding packs, generating large transverse compressive loads on cables and strands.

Fusion and detector magnets

In contrast with high field dipoles, toroidal fusion magnets (see figure 9) are characterised by a very large bore and a thin winding pack, i.e. the ratio between the coil thickness and the inner radius is much smaller than one. A consequence is that the magnetic field in the centre of the bore is much lower (2 to 4 times) than the peak field on the superconductor; for example in ITER the peak field on the winding is about 12 T while the central field is only 5 T. Fusion magnets are indeed high field magnets regarding the operating conditions of the superconductor, but low field magnets for the users. In a thin winding/large bore magnet large engineering current density is not a stringent requirement. The reason is that all the superconducting material is located far from the magnet centre; if the fraction of superconductor is further diluted in normal material (lowering J_e), the field can be restored by increasing marginally the winding thickness. Cables for this type of magnets can accommodate plenty of space for coolant, protection copper and reinforcement. Also large detector magnets (either solenoid or toroid) and MRI magnets belongs to this category.

Tokamak (and detector magnets) may have peak fields comparable to the ones of dipole, but the size is 1 to 2 order of magnitude larger, resulting in electromechanical loads significantly larger than in dipoles. Therefore tokamak magnets require very large steel cross section distributed inside and around the winding pack.

The size of the magnet has also an influence on the cable amperage: the larger magnet the higher the amperage, so that the inductance can be kept small. Therefore cables for high field dipoles may carry between 5 kA and 25 kA, while conductors for large tokamaks may carry between 20 kA and 80 kA.

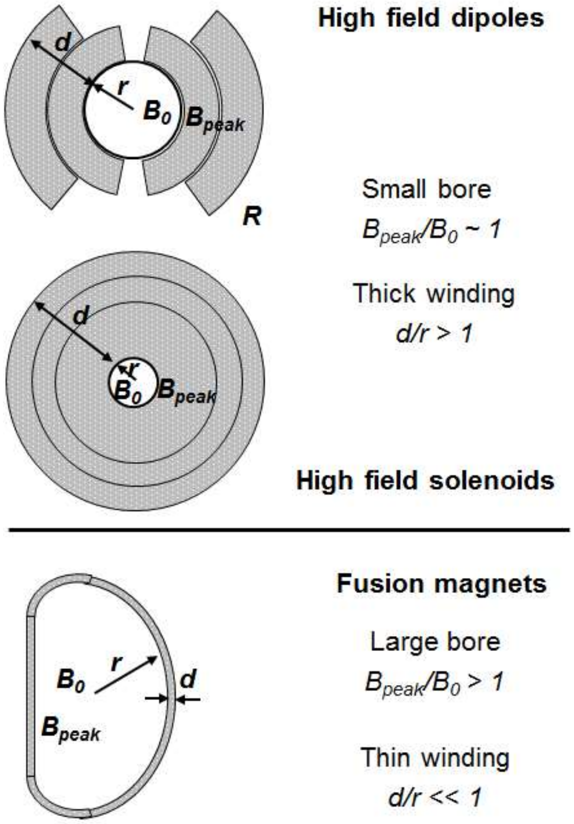


Figure 9. From top to bottom: cross sections of a high field dipole, a high field solenoid and a TF coil (for Fusion magnet). R_{in} and R_{out} are the inner and outer radii, B_0 is the central field and B_{peak} the peak field. Sketches are in scale and normalized to the outer radius.

4. Cables for accelerator dipoles

Applications of superconductivity for accelerators (see [3] and [77]) were already considered in the 60's, but at that time the construction of a full superconducting accelerator was too ambitious, thus superconductivity applications were limited to detectors. At the end of the 60's a major step towards accelerator applications was the introduction of the Rutherford cable. R&D for accelerators magnets took off during the 70's, when various designs were studied and experimental magnets tested, culminating in 1984 in the construction of the Tevatron, the first large superconducting collider. HERA, SSC (then cancelled), RHIC followed in the 90's and 2000's. At present the LHC at CERN (R&D started in 1992) is not only the largest superconducting accelerator, but also the largest superconducting machine, employing about 1'500 t of NbTi in total (accelerator and detectors). The LHC, with various upgrades, will continue the operation until the 2020's but the R&D for its successor, the Future Circular Collider (FCC), is already under way [78]. For the FCC several options are considered, from the replacement of the present NbTi dipoles with Nb_3Sn dipoles in the same tunnel, to the construction of a new 100 km tunnel to be filled with 20 T HTS dipoles. While Nb_3Sn is considered the less demanding option in term of R&D, HTS dipoles are also actively pursued. All four main dipole designs are under investigation: cos-theta, block type, common coil and canted cosine theta (CCT). The advantages and disadvantages (such as field quality and efficiency in the utilization of the superconducting material) are discussed in [79].

Dipoles are very long magnet with a relatively small transverse cross section, resulting in tight bending radius for the cable, i.e. from < 0.3 m for common coil to <0.1 m for cos theta. Considering four coil designs, three material options (Bi2212, Bi2223, and REBCO) and various cable designs, tens of combinations are possible. In general the laboratories which have expertise in the fabrication of one specific coil design (for example the common coil at Brookhaven) focus their investigation on how the different cable types can be adapted to that specific dipole design.

In addition to dipoles for high energy colliders, HTS materials are also considered for undulators and low field bending magnets, for example for medical accelerators. In the latter applications the main advantage against LTS is the possibility to operate by conduction cooling (i.e. without a cryogenic fluid) using a cryocooler. All these magnets are not discussed in this paper because they are relatively small and do not require high current cables.

4.1 Roebel cable (REBCO)

As it was pointed out by Wilson [3], the Rutherford cable was developed in 1971 as a modification of the well-known (at that time) Roebel cable (also called Roebel bar) in order to use round wires—the manufacturing process of NbTi is better suited for round wires. The success of NbTi Rutherford cables in the 70's and 80's has imposed the round wire as a standard, probably forcing the development of superconducting materials towards round wires, even if, for example for Bi2212, much large current density could be obtained in tapes than in wires. With the emergence of HTS tapes, in 1999 Wilson [3] proposed to revive Roebel cables for accelerator magnets.

Copper Roebel cables were developed over 100 years ago to be used in the windings of AC machines. Therefore, it is not surprising that the first HTS superconducting Roebel bars (from 1996 to 1999) were manufactured for transformers [80] and SMES [81] by Sumitomo. The cables were composed of few insulated Bi2223 tapes, the transposition taking place over a relatively long distance to accommodate the long in-plane bending radius of the tape. Few years later also Siemens [82] set up a machine for cabling Bi2223 Roebel bars (piece length of about 100 m), the application being superconducting transformers.

The Roebel concept was adapted to coated conductors around 2006 at the Karlsruhe Institute of Technology (KIT) [83]. Instead of bending the tape in-plane, meandered strand tapes were manufactured by punching a wide tape (see figure 10). The initial limitations were: 1) punched tapes could easily delaminate, because the copper around the tape edges is removed 2) cables could withstand only a modest transverse compression, 3) the maximum production length was short because of the accumulation of periodic errors in the cabling process. Today all these limitations have been overcome: Cu electroplating is applied after punching and it efficiently reduces the delamination; an optimization of the cable layout made the cable tolerant to large transverse pressure [84] and impregnation further increases the resilience to transverse compression [85]; there is virtually no length limitation thanks to a computer controlled feedback system for punching and cabling.

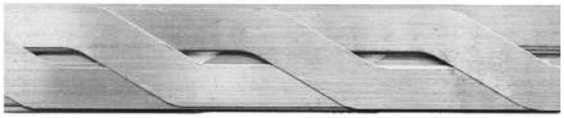


Figure 10. Top view of a coated conductor Roebel bar (or cable).

Aligned block dipole (CERN)

CERN has chosen Roebel cables [86] because this design is the most compact (very high filling factor), provides current capacity of the order of tens of kA, and is fully transposed (even if it may not be necessary in HTS cables). The choice of using an anisotropic cable design is particularly meaningful for the block type dipole, because in this combination of cable and magnet, the field will be almost parallel to the wide face of the tape (less than 5° misalignment), resulting in a much higher critical current. In addition the electromagnetic forces will be applied mainly perpendicular to the wide face of the tape, exploiting the very high pressure tolerance of this type of cable [87,88]. One more advantage is that the magnetization currents and the AC losses (hysteretic and coupling) are strongly reduced when the field is oriented parallel to the wide face of the cable, as shown in recent measurements [89]; this is of great importance for accelerator magnets which have strict requirements in term of field quality.

Regarding the winding process, it has been observed [90] that, at the coil ends, the tapes in the cable shift relative to each other during winding; in order to avoid buckling the following measures were introduced: optimisation of the cable pitch, enlargement of gaps between meanders and introduction of spacers at the coil ends.

A coil prototype (feather M2) with realistic geometry (tilted ends) has been manufactured recently [91] with a relatively low current density tape supplied by SuNAM. One more magnet will be prepared with a high current density tape supplied by Bruker EAS. The magnet was impregnated with epoxy resin and the cable insulated with glass fibre, taking care that the epoxy/glass composite had a thermal contraction comparable to the one of the tapes, in order to avoid delamination. During impregnation about 5 MPa of pressure are applied to the cable to avoid the resin to penetrate in between the strands, thus ensuring good electrical contact between strands. An additional enamelled copper wire (for quench detection) is incorporated in the cable and it is used to compensate completely the inductive signal. The dipole was tested in gas flow down to about 5 K and protected with a dump resistor. The measured critical current is close to the value obtained from short samples.

Quench simulations [92] have shown that, after one strand in the cable becomes normal, the current should redistribute to the remaining tapes at relatively small voltages (few mV), which may be difficult to be detected in the noisy environment of large magnets. Large voltage should appear only when all the tape in the cable cross section are normal, but the temperature would rise very quickly, leaving little time to protect the magnet. Instead pick-up coils should be effective to detect the current redistribution at the early stage of quench development. In contrast with the simulations, during the quench tests it was observed that the detection with pickup coils was not effective, while the non-inductive voltage (from the enamelled copper wires) was drifting already at the onset of the quench, thus being a very reliable method for quench detection. It was also found that the current sharing regime extends from the critical current up to 1.6 times the critical current, when thermal runaway occurs. This result is in contrast with what is observed in coils wound with a single tape, where extremely rapid thermal runaway (as soon as I_c is reached) leads to catastrophic burning. This is a further the benefit of using cables instead of a single tape. The Feather 2 magnet was quenched several times without reduction of the performance and without training: it is very likely that cracks in the resin and other small energy releases are not sufficient to drive a quench, as is the case for LTS dipoles. Even charging at high current rates does not affect the quench current, demonstrating that HTS magnets, in contrast with LTS, can sustain large AC losses (coupling and hysteretic) without quenching, mainly because of the very large temperature margin (HTS are exceptionally stable).

In this initial development the HTS dipoles are intended to be used as high field inserts for LTS dipoles, but the option of a full HTS dipole magnet is also explored [92]. The main motivation is that, because of the very different transverse stress limits in the HTS and LTS coils, the mechanical integration may pose significant challenges; solutions may require large volumes thus penalizing the magnetic field generation. In the same publication an alternative, "old" design of the dipoles ends, the so called "clover ends" have also been proposed: the advantage of this design is that the in-plane bending of the cable is reduced.

Cos-theta dipole (CEA)

In the EUCARD 2 program, a cos-theta magnet—the same magnet design used for the NbTi dipoles in the LHC—is under development at CEA. The cable is the same that is being used at CERN for the aligned block type. Mechanical analysis on a preliminary dipole design [93] has shown peak transverse stresses as high as 600 MPa. This value was considered too high for the Roebel cable [94] and it was reduced to 250 MPa by means of a larger external structure, thus increasing the gap between the outer LTS magnet and the HTS insert. A problem in common with the block type design is that at the coil ends the relative slippage between tapes in the Roebel cable generates either a local increase of the cable thickness (leading to stress concentration under transverse pressure) or even bulging, when the slippage exceeds the length of the longitudinal gap between strands. To mitigate these effects the transposition pitch was increased and the number of tapes in the cable was reduced.

It was also observed [94] that Roebel cables can not follow the same trajectories of Rutherford cables (composed of ductile round wires): this specific Roebel cable was limited to bending radius of 11 mm in easy bending and 2 m in hard bending. Therefore the spacers at the coil ends had to be designed to respect these constrains. In the initial winding trials the coil ends consisted of several spacers (one for each turn), but they were too complex to manufacture; a simplified design (one spacer every two turns) gave also satisfactory results.

One could expect that the field quality of a cos-theta dipole wound with a REBCO Roebel cable should be worse than the one of a block type, because in the cos-theta dipole large field components perpendicular to the wide face of the tape will generate large screening currents. However recent simulations [95] have shown that the cos-theta design should have better field quality than the block type, because the magnetizations in the tapes cancel each other. One disadvantage of the cos-theta design is that it would require a larger amount of tapes because the critical current will be lower, as the tapes are exposed to a larger perpendicular component of the magnetic field.

From Roebel to Rutherford

In the coated conductor Roebel bar proposed by KIT [83] the tapes are stacked in two stacks (see figure 11 top). Recently it was proposed by A. Ballarino [96] to arrange the tapes in several stacks of two tapes (see figure 11 bottom), i.e. both cable and tape cross sections are rotated by 90°. In contrast with the original configuration, the new design has a much larger aspect ratio (see figure 11). One disadvantage of the new configuration is that the meandered tapes should be punched out from very wide tapes, losing a lot of material. The yield could be greatly improved if the substrate is punched before the deposition of the buffer and ceramic layers, which is possible only for some deposition techniques. A possible advantage is a much smaller tendency to buckle when the cable is bent along the easy bending direction. It should be noted that if the strand has 90° symmetry (i.e. round or square wire instead of rectangular wire or tape), the two configurations have similar cross-sections.

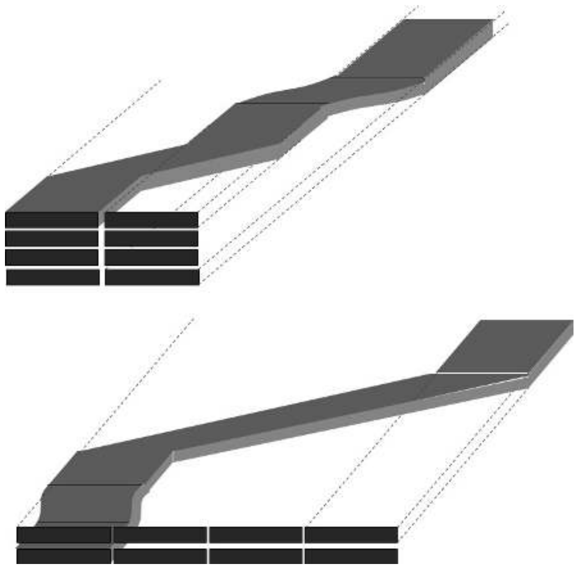


Figure 11. Sketch of a coated conductor Roebel cable as proposed by KIT (top) and A. Ballarino (bottom).

4.2 Twisted stack (REBCO)

The "twisted stack" concept was introduced by MIT (see section 5.2): several tapes are simply stacked and periodically twisted to obtain a partial transposition, in fact the tape inductances in the centre of the stack are different from the ones at top and bottom. In contrast with the Roebel cable, which requires punching and assembling of strands, a twisted stacked cable can be manufactured with "standard" tapes.

The application of the twisted staked cable to a block type dipole is being studied, for the moment only theoretically, by the Laboratoire de Génie Electrique (G2Lab) in Grenoble. A preliminary design [97] considered a stack of 20 tapes (4 mm wide) resulting in a 4x4 mm square cross section. In the straight part of the dipole the tapes in the stacks are oriented almost parallel to the magnetic field, the forces being perpendicular to the wide face of the tapes. The stack is twisted only at the coil ends, where the magnetic field is lower. Even if the magnet ends must be long enough to accommodate the hard bending of the tapes, their length has not a big impact on the overall length of the dipole; however complicate structures should be designed to support the 3D trajectory of the twisted stack at coil ends.

In a successive work [98] three options have been studied by numerical analysis in a full size magnet (about 15 m long): insulated tapes, non-insulated tapes and partial insulation (the tapes are insulated in straight part but in electrical contact at the twisted section in the coil ends). In both insulated and non-insulated cases the requirements for uniform current distribution and low magnetisation could not be achieved. In the partially insulated case, the simulations show no coupling currents or current imbalances. These results need to be confirmed by measurements on model coils, and is not excluded that coupling currents and current imbalance between non transposed tapes could be less severe than expect, as discussed in the next section.

4.3 Non-twisted soldered stack (REBCO)

CEA (Paris) in collaboration with LNCMI (Grenoble) is investigating an even simpler (and less transposed) cable concept to be used in block type dipoles. In a preliminary proposition [99] the stack was composed of two wide (12 mm) tapes soldered to a central copper tape; two more copper tapes were stacked above and below the superconducting tapes. The inductance is balanced between the two tapes by inverting their position in the stack at the pancake transition. In contrast with the G2Elab option, in this stack the tapes are transposed without twisting and thus maintain a high level of alignment with the magnet fields, even at the coil ends.

Before the fabrication of a coil prototype the design of the cable was revised [100]: CuBe tapes (see figure 12) have been used to increase the mechanical safety margin and two-in-hands winding method (two insulated cables electrically powered in parallel) has been introduced in order to reduce the inductance.

The two cables are transposed at the pancake transition, but the pair of tapes in each cable is not transposed: this should be sufficient to guarantee the same inductance and thus uniform current distribution. The fabrication of a dummy coil validated the winding procedure; small saddle spacers have been introduced to facilitate the transitions from one pancake to the adjacent one without introducing in-plane bending in the cable. The prototype dipole [100] consists of three double-pancakes: a long central one (about 0.7 m long, 30 turns per pancake) and two shorter (0.3 m long) above and below the central one. The magnet generated about 4.4 T at 2600 A (power supply limit) at 4.2 K in self-field [101]; tests at higher currents in background field are in preparation.

A dedicated study [102] was carried out comparing measurements of the screening current with numerical simulations. This was motivated by the low grade of transposition; in fact the two ceramic layers in the cable run parallels for about 100 m in the central, long pancake. At 77 K the drift in the magnetic field (after ramping) is due only to the screening current in the superconducting layer while the coupling currents between the superconducting layers decay very fast and have no significant influence on the magnetic field. Instead at 4.2 K the time constant of the coupling currents is increased because the copper resistance between the two tapes is strongly reduced. Nevertheless the disturbance to the total magnetic field caused by the coupling current is less important than the one caused by the screening current in the superconducting layers.

These results indicate that coated conductor cables may not need a high degree of transposition. One more experimental evidence comes from Bi2223 tapes, which are composed of non-twisted filaments. Such tapes have been employed to build a large (0.5 m diameter), 3 T MRI magnet at Kobe Steel [103] and at Robinson Research Institute [104]; neither coupling current nor screening current have prevented the operation. A Bi2223 tape is qualitatively similar to a non-twisted soldered stack of REBCO tapes, in the sense that both are composed of parallel (non-transposed) superconducting paths in good electrical contact (metal matrix); also the size of the cross section is comparable. Dedicated R&D should be devoted to understand how much transposition and how much mismatch in the inductance can be tolerated in cables made with HTS tapes and wires, which, in contrast with LTS, have an extremely large stability margin.

An even further simplification would be simply to wind a coil with a single tape instead of a cable. This option was already investigated at Brookhaven National Laboratory with the construction and tests of various common coils dipoles [105] wound with tapes (Bi2223 and Nb_3Sn). Recently [106,107] a coil was manufactured and tested using a single 12 mm wide REBCO tape: the operating current was only about 600 A in background field, which may be too low for high field dipoles. Nevertheless it can be speculated that, if the ceramic layer can be made thicker and thicker, it would be possible to fabricate thick and wide tapes capable of few kA.

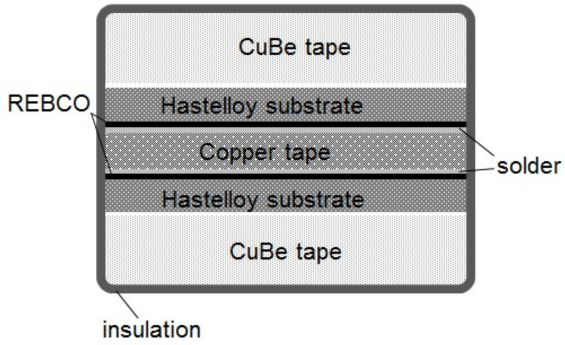


Figure 12. Cross section of the CEA cable. The coated conductor tapes are soldered to a central copper tape, then sandwiched (not soldered) between two CuBe tapes.

4.4 Rutherford cable (Bi2212)

The Rutherford cable is a natural choice for Bi2212, which can be manufactured in round wires like NbTi. However, in contrast with NbTi, Bi2212 requires a heat treatment at over 650°C in oxygen atmosphere; therefore materials for coil formers and electrical insulation should be selected accordingly. Between 1997 and 2001 Rutherford cables were investigate in a large collaboration program involving Showa Electric Wire & Cable, IGC, LBNL and various academic partners. Rutherford cables were manufactured [108] with a thick core (0.5 to 2 times the strand diameter) of Nichrome 80 (see figure 13a). The core had three functions: 1) reducing the bending and deformation of the strand at the cable edges, 2) increasing the rigidity of the cable, 3) reducing coupling currents and the associated losses. Additional measures (such as Al_2O_3 coating on the core) were tested to further reduce the coupling losses; however measurements showed that sufficiently high transverse resistance are obtained even in the case of a bare core. The cabling tension and the compaction rate were set at lower values than the ones usually used for cabling NbTi wires: for example the compaction rate was 0.85, while values between 0.88 and 0.92 are used for NbTi cables (corresponding void fractions are 12% and 8%).

Nichrome 80 was selected for the cable core because does not react with oxygen during the heat treatment and thus does not degrade the I_c of wires; MgO coating on the core has also a beneficial effect.

In a further study [109], the thick core was replaced by thin MgO paper to avoid sintering between the wires; a two stages flat cable composed of 6-around-1 sub-cables was also manufactured and tested (see figure 13b). The production of long cables (up to 70 m) without loss of critical current was demonstrated. The critical transverse pressure for impregnated Rutherford cables [110] was about 60 MPa when loaded on the broad side and 100 MPa for edge loading.

R&D on "react and wind" technology was carried out on large cables (30 strands) [111]: after the heat treatment the strands do not stick to each other, hence the critical bending radius is not very different from the one of a single wire.

At the Texas A&M University, an alternative mechanical reinforcement for cables [112] consists in cabling six strands around an Inconel X 750 perforated tube and inserting the cable in an external armoured tube (see figure 13c). It was also found that the strands were still able to slide when the cable is bent. In 2010 the spring armoured cable was considered for the design of a 20 T dipole [113].

Reinforced cables similar to the ones of figure 13a and 13c have been prepared recently [23] at Fermilab, choosing NiCrAl and Inconel X 705 as reinforcement (see also section 2.1). The round design allows a straightforward grading of the strength and critical current, as shown in figure 13d.

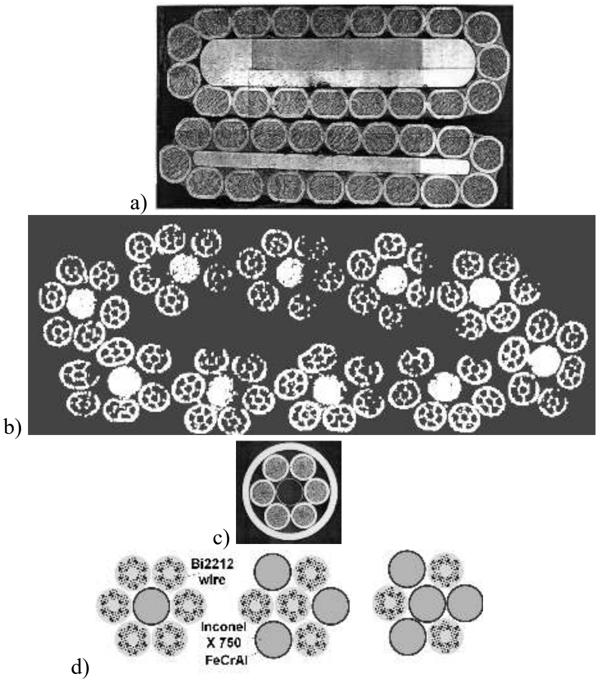


Figure 13. From top to bottom: a) photograph of the cross sections of Bi2212 Rutherford cable (with core), reproduced with permission from [108]. b) Photograph of the cross sections a Bi2212 Rutherford cable composed of 6 around 1 sub cables, reproduced with permission from [109]. c) Photograph of the cross sections of the armoured Bi2212 cable, reproduced with permission from [112]. d) Sketch of the cross sections of three Bi2212 round cables, reproduced with permission from [23].

In 2011 Fermilab [114] manufactured coreless Rutherford cables. The critical current of the cabled strands was about 20% lower than the one of the control wires and it was found that the reduction correlates with the amount of deformation during manufacturing. The I_c reduction could be attributed to the absence of core and the substantial higher compaction that in earlier cables, as mentioned in the first paragraph of this section (see also [108]).

Berkeley National Laboratory has studied the construction of racetrack coils for common coil dipoles using Bi2212 Rutherford cables [115]. Al_2O_3/SiO_2 fibres were used for insulation because pure SiO_2 reacts with Ag. The insulation sizing was removed before winding to avoid the reaction with oxygen during the heat treatment; the insulation could be handled without breakage even if the sizing was removed. Sandvik Zr-702 alloy or Inconel Alloy 600 were used as structural materials. The best combination was Inconel 600 with Al_2O_3/SiO_2, even if limited reaction with Ag was observed [116]. Few test coils were reacted: leakage from cable edges was detected and attributed to lack of integrity of the Ag sheath, (to be addressed by the wire manufacturer, see [116]) and exacerbated by the change in volume and different thermal expansion during heat treatment. In 2015 the magnet design was changed to Canted Cosine Theta (CCT) [117] because this design prevents the accumulation of transverse forces (at the expenses of a lower engineering current density), and is thus well suited for Bi2212 Rutherford cables which cannot withstand more than 60 MPa of transverse pressure. The fabrication of the CCT coil former requires extensive machining; therefore to shorten machining time Inconel 600 was replaced by aluminium bronze (alloy 954).

Brookhaven has been developing common coil dipoles wound with Rutherford cables [118]. The advantages of this design affecting the cable are: 1) planar (2D) geometry, which make easier to design the mechanical containment of the loads 2) large bending radius (thus low bending strain) at the coil ends. Therefore it is possible to consider a “react&wind” technique also for brittle conductors like Nb_3Sn and Bi2212 (the cables were manufactured at Berkeley National Lab). The advantage of R&W is that insulation materials and coil structural components do not need to withstand high temperature heat treatments: various alloys (such as aluminium, low carbon steel, bronze and stainless steel) [119] were tested. The cables were insulated with glass fibre and impregnated with epoxy.

4.5 CORC (REBCO)

The Conductor on Round Core (CORC) design for coated conductor tapes has been introduced recently [120] (fig.14), but it is very similar to the power cables that have been built with Bi2223 and REBCO tapes since the 90’s. The CORC concept relies on the asymmetric cross section of coated conductors and on the very high longitudinal compressive limit (down to about -1.5%, see 2.3): when the tape is wound around a core—the ceramic layer is kept facing the core—only compressive strain is applied to the ceramic; therefore the diameter of the core can be very small, resulting in compact, high current density cable.

Instead Bi2223 tapes, which are symmetric and can tolerate much smaller longitudinal compressive strain than coated conductors, can be cabled in CORC cables only using very large formers (as in power cables), resulting in modest current density.

If coated conductors are prepared with the copper on the ceramic side thicker than the copper on the Hastelloy side, the ceramic layer will be located close to (or at) the neutral plane, and the core diameter could be further reduced, as demonstrated in [121].

CORC cables have been proposed for accelerator magnets [122] because of the very high current density and flexibility. Lawrence Berkeley National Lab has built and tested a proof of concept of a CCT dipole coil using a CORC cable [123]. Two coils (each of them of only three turns) were prepared with two different types of cables, the largest one having 29 tapes (3.6 mm Ø cable). The coils were hand-wound with no tension and not impregnated. The critical current of the coils at 4.2 K in self-field was about 12.5 kA, not far from the value expected from short sample. It was not possible to estimate precisely the expected I_c because there were no data on $I_c(B)$ at 4.2 K and low field (<1 T).

The critical transverse pressure was measured in CORC cables (steel former) [124] and can be estimated to be between 30 MPa and 120 MPa on the mid-plane, depending on the cable parameters. The main advantage of the CCT against other designs (preventing the accumulation of transverse mechanical loads) is effective for CORC cables, but it is less interesting for Roebel cables, that can withstand much larger transverse pressure.

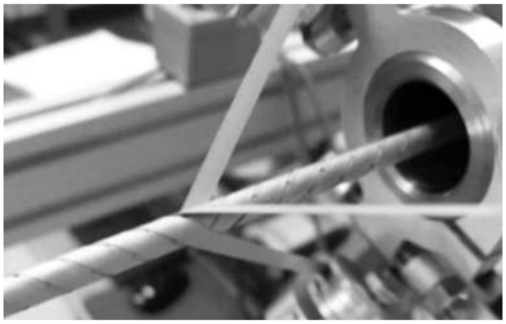


Figure 14. Cabling of a CORC cable at Advanced Conductor Technologies (USA).

5. Conductors for fusion and detectors

The first large scale superconducting magnets for Fusion research were manufactured around 1968–1971 and the first tokamak, the T-7, was built in 1977 (see [2] for a review). In the 80's and 90's more machines and tokamak were designed and built. The use of HTS for high field generation in tokamaks was considered already in the 90's, but the designs remained on paper because of low demand for higher magnetic field from plasma physicists and the technological immaturity. Recent tokamaks like KSTAR and ITER still have relatively modest peak field, less than 12 T.

Demountable coils were first proposed in the 70's, but have been used only in the copper coils of Alcator C-Mod. In Japan, demountable coils are considered for large helical reactors, because they would simplify the magnet construction. To contain the ohmic losses at the joints the operating temperature should be at least 20 K (see section 5.5).

In the present decade the concept of very high field, compact tokamak has gained traction based on two motivations: 1) It is expected that compact tokamaks could be built in factory on assembly lines, thus avoiding the delay and cost overrun which are common in large tokamaks built on site, like ITER and future DEMO reactors; 2) The expectation of cheap and abundant coated conductors. MIT has pioneered this approach with the design of the Vulcan demountable magnet in 2012 and with the ARC design in 2015 [125]. Tokamak Energy, a private company in UK, has also introduced the concept of a compact, high field spherical tokamak [126]. In these designs the operating conditions are >20 T and >20 K. In high field compact tokamaks the nuclear heat load is supposed to be more intense than in traditional low field, large tokamaks; therefore the operation at high temperature is a significant advantage because it would be possible to remove a much larger power. One more reason to opt for the high temperature operation is, at least for the MIT tokamak, the present of demountable coils, which would include thousands of joints generating ohmic losses. For the operation at >20 T and >20 K aligning the tapes to the magnetic field is a substantial advantage, in order to obtain the highest current density and contain costs. At present Commonwealth Fusion Systems (a MIT start-up) is working on a cable prototype.

5.1 Bi2212 conductors and early REBCO concepts

The use of Bi2212 for high field tokamaks (24 T of peak field) was first mentioned in 1991 [127]; at that time Nb_3Al was also considered to replace Nb_3Sn for generating higher field (a decade later Nb_3Al would have been available on km length from Hitachi). In [128] it was estimated that the operation at higher temperature (even at 77 K) would have modest effect on the total cost of the reactor, but it may simplify the quench protection; in addition the plasma stability would improve at higher magnetic field. In 1998 a concept for a 16.5 T tokamak working at 20 K was proposed [129] based on the Bi2223 tapes available at that time. Bi2212 was considered for the design of the large A-SSTR2 tokamak [130] (operating at 23 T and 20 K); the J_c values considered in the design were much higher than the ones available at that time, assuming future improvements. This paper presents for the first time a conceptual design of the conductor (see figure 15): it is a forced flow conductor composed of a rectangular cable (six sub-cables, 1200 strands in total) assembled with a copper cable in a steel jacket. The stability at 20 K is improved by filling the cable with Pb (very high thermal capacity at low temperatures); the conductor is cooled by He gas flowing in a separate channel.

In 2003 a sub-size sample [131] of a three stage rope-type cable was designed, built and tested by the Japan Atomic Energy Research Institute (JAERI). The cable was made with 729 Bi2212 wires (0.8 mm diameter) and the critical current was about 10 kA at 12 T and 20 K.

In the same period bi-axially textured REBCO was getting more and more attention. Already in 2001 MIT considered REBCO thick films in the construction of TF magnets [132]. It was suggested to exploit the anisotropy of coated conductors by orienting the ceramic plane as parallel as possible to the magnetic field. It was assumed that the very large thermal capacity at >20 K and the huge temperature margin would radically change the quench management. The quench protection system and the copper protection could be omitted because the magnet could be designed so that it will never quench, but this bold statement has not yet been seriously investigated. It was also proposed to radically change the way magnets are built: instead of winding large coil with conductors, a process which was deemed expensive, the TF coils could be manufactured by stacking structural plates coated with thick HTS films (see figure 16). This idea was inspired by industrial rapid prototyping and printed circuit manufacturing in the electronic industry; it also resemble to the construction method of Bitter magnets. In addition, such magnets could be “demountable”, it means they could be disassembled to make it easier the replacement of the plasma facing components, which require periodic maintenance.

Also in Japan Bi2212 was dropped in favour of REBCO [133] in the conceptual design of the VECTOR commercial power reactor (operating at 20 T, 33 K). The TF conductors were composed of three grades: the highest grade (40 kA at 20 T and 30 K) is composed of a stack of only four tapes, each tape having a ceramic layer 100 mm wide and 10 micron thick. The tapes are transposed (without twisting) at the pancake joint; this is basically what has been done recently by CEA in a prototype dipole (see 4.3); a similar technique (transposition without twisting) is also presently studied for winding large solenoids for MRI applications [134]. In [133] it is mentioned that wide tapes will have lower hysteretic losses than a narrow 2 mm wide tape. Commercial tapes were not yet available, hence the authors speculated about future ceramic cross section; later the first commercial tape were much thinner and narrower, but today THEVA has successfully produced tape of over 8 micron in thickness and AMSC can produce 40 mm wide tape, not too far from the expectations in 2005.

Activities on Bi2212 wires were revived after 2013, when the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) considered a Bi2212 CIC conductor [135] for the Chinese Fusion Experimental Tokamak Reactor (CFETR): both TF and CS magnet systems should be graded with NbTi, Nb_3Sn and Bi2212. In this design the advantage of HTS is not only to generate higher field but also to reduce the size of the winding pack, leaving more space for other components. Specific R&D activities have been carried out by ASIPP: it was found [136] that the I_c of Bi2212 wires is much more sensitive to local indentation occurring during cabling than the one of Nb_3Sn and NbTi wires; therefore high compaction, short twist pitches and large deformation should be avoided during cabling. In 2017 [137] a sub-size, 3 stage rope-type cable containing 42 strands was manufactured (see figure 17); the cable is inspired by the ITER conductors. A silver tube was placed around the cable to avoid direct contact between the strand and the 316L jacket during the heat treatment. The I_c in self-field was about 13 kA, about 10% lower than the value for short samples, but the reason is unknown; it may be related to a chemical reaction with the 316L jacket. The choice of a round, rope-type cable may be impractical and inefficient because Bi2212 wires may have very low critical transverse stress, while the transverse load accumulation in large round conductors is substantial.

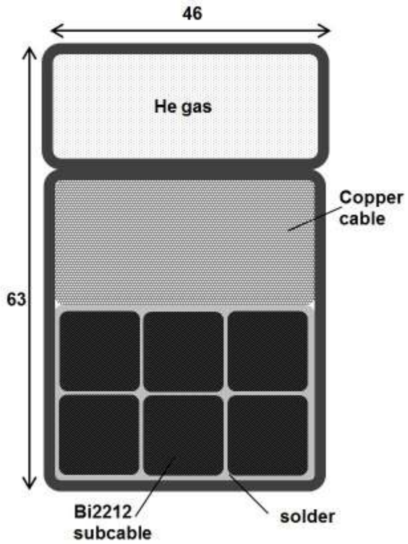


Figure 15. Schematic cross section of a Bi2212 forced flow conductor. Reproduced with permission from [130].

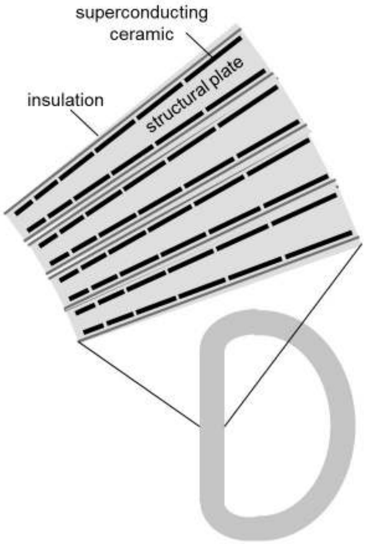


Figure 16. Sketch of the winding pack cross section proposed in [132].

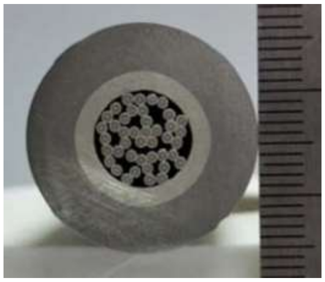


Figure 17. Photo of the cross Section of the Bi2212 cable in conduit manufactured at ASIPP. Reproduced with permission from [137].

5.2 Twisted stack (REBCO)

MIT was the first to considered REBCO for fusion magnets, but when coated conductors become commercially available the same institute introduced a new concept, the so-called “twisted stack” [138]. The idea is to simply prepare a stack of tapes and then apply twisting to obtain a partial transposition. The stack should be inserted in a containing structure, for example in a helical slot machined in a copper round bar (see figure 18); these round elements can be assembled in triplets, 6-around-one or other cable configurations. The partial transposition leads to a difference in inductance among the tapes, which has been estimated to be less 7%: this value is considered acceptable in large, slow charging magnets. The hysteretic losses for a twisted stack were estimated to be about 10 times larger than the one of Nb_3Sn wires (per unit length and unit of transport current).

Few strands (without copper structure) [139] have been manufactured and tested with positive results; when long samples have to be tested they are wound over polygonal formers. In fact, even if the strand is twisted (and encased in a round structure), the mechanical and transport properties are not isotropic: the stack will have very different critical bending radius in the hard and easy bending directions, especially if the stack is not soldered. Therefore it has been proposed [140] to wound a “D” shaped TF coil by keeping the stack non-twisted over the straight leg (better orientation for large transverse loads); the stack is twisted (and thus transposed) only in the lower part of the bent section, where the electromagnetic forces are the lowest; this concept is similar to the one used for the dipole at Grenoble (see section 4.2).

The twisted stack concept has been further developed and modified by four other Institutes: ENEA, SPC, KIT and the North China Electric Power University.

Figure 18. Twisted stack of coated conductor tapes in a grooved copper profile. Reproduced with permission from [138].

ENEA twisted-stack conductor

At ENEA the stacks are placed in a slotted aluminium core which is extruded continuously [141]; see figure 19 for an example with five slots, but other configurations have been considered. This conductor can be manufactured in one cabling stage. The peculiarity of the concept is that the prototype conductor was fully developed and manufactured industrially (Tratos Cavi, the manufacturer of some of the ITER cables). Instead, when cable concepts are developed in laboratory, the scaling up to industrial level may require extensive modifications. The test of first prototypes [142] showed low values of the electrical resistance between the tape in the stack but relatively high values between the stacks and the aluminium core. Very recent measurements [143] have shown that the resistance is reduced when the conductor is bent.

The cooling flow repartition in the different conductor channels has been studied in [144]; in addition the cooling capability at 77 K was measured in a dummy cable and compared with finite element model. Bending test of short samples [145] confirmed that the I_c versus bending strain behaviour can be described by a perfect slip model, in which the tapes are free to slide independently, but the strain is not uniform among the tapes (see [143,145]; therefore this type of cables could be wound over shorter radii than in the case of soldered stacks on the same cross section size.

SPC twisted-stack conductor

SPC has chosen to prepare a strand by stacking the tapes, inserting the stack between two copper profiles, twisting and finally soldering all the elements together. The strands can be cabled around a flat copper core (Rutherford cable with core). Two sections of such conductors (each made of 20 strands, see figure 20) were manufactured and tested in 2015 [146]: SuperPower tapes were used for one conductor and SuperOx for the other one. In both conductors the initial current sharing temperature (T_{cs}) was about 100% of the values expected from short tape measurements. Nonetheless a reduction of T_{cs} was observed during electromagnetic cycling [147]: about 10% in the SuperPower conductor and 20% in the SuperOx one. The latter was disassembled and the strand critical currents were measured: it was found that the degradation occurred mainly at the cable edges [148]. Further tests on strands at 77 K [149] have not clarified the origin of the degradation. Various types of copper profiles and tape arrangements have been tested [150]: in general a square stack of relatively narrow tapes (see figure 20 bottom) is the most convenient option because it provides the highest current density and lowest strain. New conductors are in preparation.

KIT twisted-stack conductor

The SPC twisted stack has been modified by KIT [151] in order to increase the current density: the stack is composed of tapes with two different widths (see figure 21), resulting in almost 25% more current density than in a square stack. The tapes are stacked, twisted and soldered in one single manufacturing step; the cylindrical solder matrix (surrounding the twisted stack) is then inserted into a thin a copper tube which is swaged to close the insertion gap; the tube is carefully compacted to avoid applying excessive transverse pressure on the stack. A triplet has been prepared [152] and the critical current has been measured as a function of the twist pitch, which in turns generate a bending strain on the strands. The strands could be assembled in a Rutherford cable [153], as it was proposed by SPC.

North China Electric Power University twisted-stack conductor

The group at North China Electric Power University has modified the twisted stack concept to obtain higher current density and isotropic behaviour [154]. Four stacks (each with square cross sections) of narrow tapes are assembled; each stack is rotated by 90° with respect the others (see figure 22). The disposition of the tapes in the stack is very similar to the filament dispositions in ROSAT Bi2212 wires [155] that were manufactured at the end of the 90's. Around the stacks there are four circular sectors, which can be made of copper or aluminium. Then a metal sheet (Al, Cu or steel) is continuously formed around the core and welded. This technique has no length limitation, in contrast with tube insertion (as used by KIT). The conductor is manufactured on an industrial production line. The prototype cable was not meant for a specific application, but it could be adapted and assembled in large conductors for Fusion or detector magnets.

The ENEA and North China Electric Power University concepts are not soldered (lower coupling losses, less strain under bending, but eventual strain non-uniformity and higher voltage during current redistribution). The SPC and KIT ones the tapes are soldered together and to the surrounding structure (higher coupling currents, higher strain under bending, but homogeneous strain and low voltage during current redistribution).

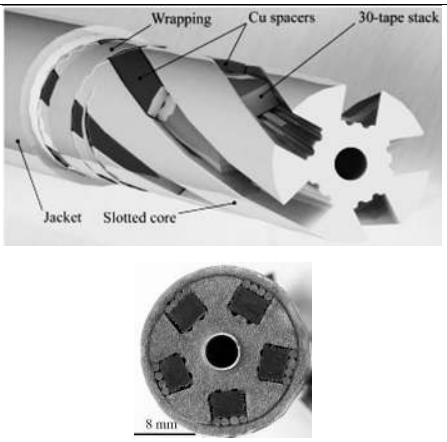


Figure 19. Top: 3D sketch of the ENEA twisted stacked conductor. Bottom: photo of the cross section of the same conductor. Reproduced with permission from [141].

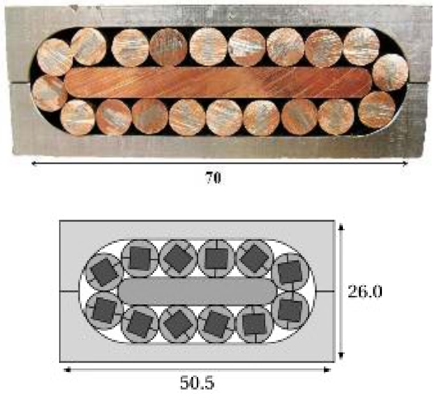


Figure 20. Top: photo of the cross section of the prototype conductor manufactured at SPC, from [146]. Bottom: sketch of the cross section for the new SPC conductor. Reproduced with permission from [149].

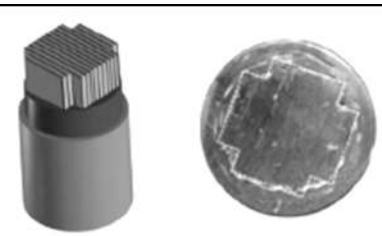


Figure 21. 3D sketch (left) and photograph of the cross section (right) of the soldered twisted stack manufactured at KIT. Reproduced with permission from [153].

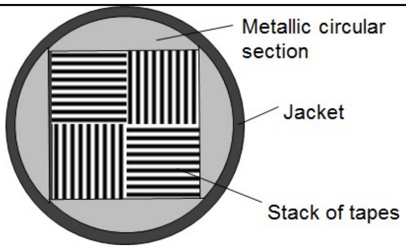


Figure 22. Sketch of the quasi-isotropic conductor manufactured by the North China Electric Power University, [154].

5.3 CORC

The CORC concept, discussed for accelerators (see section 4.6), has also been proposed [156] for large fusion and detector conductors, arranging six CORC around a central former (see figure 23). The Fusion conductor is a CIC conductor (He flows in contact with the strand), for large heat removal; the jacket is made of steel in order to withstand large electromagnetic forces. Assuming an operating current in each sub-cable of about 10 kA, and a background field at least 15 T, the resulting transverse force would be 150 kN. This value should be further multiplied by a factor 2 or 3 because of transverse load accumulation. According to the transverse pressure measurements in [124], the I_c degradation at >300 kN would be already substantial.

The conductor for detectors has a copper jacket and is conduction cooled via two additional channels in the jacket. In large detectors high purity aluminium is used for protection of LTS superconducting cables because it is transparent to particles; the choice of high conductive material is also justified by thermal and electrical stability in LTS, but it may not be need for the very stable HTS materials. In this prototype copper was preferred because it is easy to solder. The test in the SULTAN facility is planned in autumn 2017.

CORC cables are not fully transposed but so far experiments have shown [157] that the partial transposition is not affecting the operation of the cable at high current ramp rates: no instabilities were observed despite differences in inductance, and thus in current distribution, among the layers.

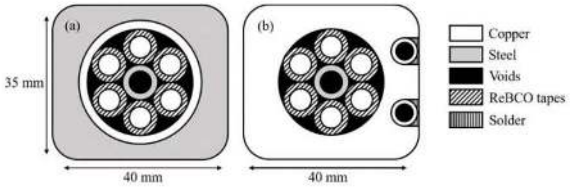


Figure 23. Cross section of the two CORC conductors manufactured at CERN. The left one is for fusion applications and the right one for particle detectors. Reproduced with permission from [156].

5.4 Roebel (REBCO)

One of the disadvantages of the Roebel design is the limitation in the number of tapes that can be assembled together, thus limiting the maximum current. KIT proposed [158] to overcome the limit on current by wrapping several Roebel cables around a central flat core, the so called Coated Conductor Rutherford Cable (CCRC), (see figure 1 in [158]). The edged bending test [159] of a CCRC model cable have shown that relatively thick core (25 mm) and small winding angle (i.e. long twist pitches) should be used to guarantee a negligible reduction in the critical current. At present KIT has stopped developing this concept. It should be pointed out that the possibility to orient the broad face of the tapes parallel to the magnetic field, a major advantage of Roebel cables, is lost in the CCRC arrangement.

Considering the advancements in critical current density and in the thickness of the ceramic layer, it is not excluded that in future it could be possible to manufacture a single Roebel cable with a capacity of several tens of kA.

5.5 Segmented coil (non-transposed stack of Bi2223 and REBCO)

A variation of the Roebel concept was initially investigated at NIFS [160]: the meander tapes were fabricated by joining (by soldering) pieces of tapes instead of punching them out from wider tapes. This method will of course introduce a large number of resistive joints and the magnet should be operated at high temperature (probably >20 K).

A modification of this concept is to suppress completely the transposition and simply stacking the tapes in short, large current conductors (see figure 24) which are joined together to form the magnet [161]. This concept is viable because the coil is composed of short conductor pieces connected by many resistive joints, where the current can redistribute between tapes: the joint resistances will dominate over the inductance ensuring the same current in all the tapes. This concept is particularly suited for helical magnet because the construction by jointing short elements (winding sections) is supposed to be simpler and thus cheaper than winding a long conductor (see figure 25). Clearly the operating temperature should be as high as possible, in order to remove efficiently the heat generated at the joints. In fact it has been estimated [161] that even if the full magnet would contain about 8000 joints the power dissipation at 20 K would be only 10% of the power required to keep a conventional magnet (with few joints) cold at 4 K. One possible disadvantage is that the charging rate should be relatively slow to contain AC losses but this is not a major drawback for helical reactors that can be charged slowly [162]. Further studies [163] regarded the quench protection and the cooling by He gas, which should not pose big challenges.

The concept was first demonstrated in a short sub-size samples [162], by stacking 46 Bi2223 tapes in two stacks. The conductor carried 12 kA in 8 T background field (parallel to the wide face of the tape) at 20 K. Later a coated conductor version was designed [161], aiming at an operating current of about 100 kA at 20 K and 13 T. A full size prototype cable [163 Yanagi 2016] was manufactured and tested; the sample included a joint, which is a critical component for this concept. The sample was tested up to 100 kA at 5 T, 4.2 K and the joint resistance was less than 2 nΩ. The joint [Ito2014] was a bridge, lap type: the surfaces were polished with sand paper, cleaned with ethanol and an Indium foil was inserted between the surfaces to be jointed. Measurements [165 Ito2017] of joint resistance as a function of bending radius showed that such joint can be manufactured straight and later bent to follow the magnet curvature. The joint resistance can be reduced [166] if the joint components are baked at about 150°C: the reason is that baking removes moisture and other gases adsorbed at the surfaces, thus decreasing voids at the interface between the Indium foil and the coated conductors. During joint fabrication the temperature is set at 90°C to soften the In layer.

In the initial proposition the joints were permanent (assembled during construction and never demounted). Now demountable joints [167] are also considered, in order to allow the disassembling of the magnet system for easier and faster maintenance, especially in case of prototype reactors.

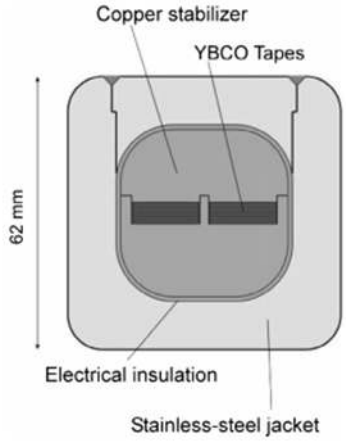


Figure 24. Schematic cross section of the conductor designed at NIFS. Reproduced with permission from [163].

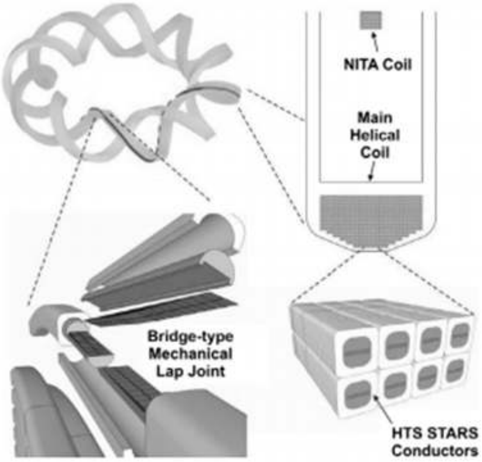


Figure 25. Illustration of the coil and winding pack for the Heliotron. Reproduced with permission from [163].

6. High field solenoids

High field magnets are used to carry out fundamental research in condensed matter physics, and, in much less extend, engineering, chemistry and biophysics. DC resistive and hybrid magnets (resistive insert + LTS outsert) generates fields up to 45 T; Cu pulsed magnet [168] can generate up to 100 T (during milliseconds), which is more or less the field limit dictated by the strength of present structural materials; electromagnetic flux compression systems can generate fields exceeding 600 T (during µs in few mm^3) and have been used to measure the upper critical fields in YBCO [169]; recently laser-driven, capacitor-coil assemblies are also approaching the 1 kT range [170]; the frontier of high field generation lies over 20 000 T [171] by explosive flux compression (available only in Los Alamos, USA and Sarov, Russia), which are unique events due to the complexity and costs.

Many experiments cannot be done in the very short time of pulsed fields (<1 ms) and require DC field. At present the maximum field available in LTS magnets is around 23 T or 24 T. A water cooled resistive magnet could generate such magnetic field, because the engineering current density in a copper Bitter magnet can be as high as 650 A/mm^2 [172] (comparable to superconducting magnet), and can operate at 600 MPa [173] of hoop stress, much higher than Nb_3Sn. However such resistive magnet would need a much larger capital cost for the infrastructure (power supply and cooling water system) and will also have much larger operating costs than a superconducting magnet. For example a 15 T Bitter magnet would require a multi MW power supply and cooling water system (costing together >10 million $), at least one order of magnitude more expensive than a superconducting magnet (including the power supply). The electricity cost would be at least 1000 $/h (assuming 0.1 $/kWh), while for the superconducting magnet about 1 l/h of liquid He would be sufficient (< 10 $/h). Therefore superconducting magnets are preferred for DC fields up to the practical limit of 23–24 T.

To generate higher fields hybrid magnets are used. They are composed of an LTS outsert magnet and a resistive copper alloy insert; the reason is that the LTS outsert reduces the capital and operating costs compared to the ones of a fully resistive magnet. The accessible bore diameter of high field DC magnets (superconducting, hybrid or resistive) is between 25 mm a 50 mm. Full superconducting LTS magnets are usually built with single wires, while the large LTS outserts of hybrid magnets are built with cables. Planning, design and construction of large hybrid magnets can take over 10 years [174] and it happens that such magnets could be not operated at the design field, probably because of the very narrow margins on the operational limits. Because of the cost and complexity, DC high field magnets are available in very few laboratories worldwide:

- NHMFL in Tallahassee, USA: 41 T resistive (33 MW), 45 T hybrid, 32 T superconducting (in construction)
- CHFML in Hefei, China: 38 T resistive (25 MW), 45 T hybrid (in construction)
- HFML in Nijmegen, the Netherlands: 37 T resistive (21 MW), 45 T hybrid (in construction)
- TML, NIMS in Tsukuba, Japan: 35 T hybrid
- LNCMI in Grenoble, France: 35 T resistive (24 MW), 43 T hybrid (in construction)
- HFLSM, Tohoku University in Sendai, Japan: 31 T hybrid, 25 T superconducting

HTS high field solenoids

In the 90's and 2000's Bi2223 and Bi2212 have not been able to push the field limit much higher above the one of LTS because of the low tensile strength (in non-reinforced wires and tapes). Instead coated conductors can be operated at much higher hoop stresses (see section 2.3); this opportunity was taken by the NHMFL in Tallahassee, which started the design and construction of a 32 T all superconducting solenoid (intended to be a user magnet) in 2012 [175] and is now almost completed [176]. The magnet is composed of a LTS outsert (built with Nb_3Sn CIC conductor) and a REBCO insert which is wound with single tape.

At the HFLSM in Sendai it was chosen to build a cryogen free magnet; the reason is the much lower operating costs compared to a liquid He cooled superconducting magnet [177], at least in Japan when purchasing liquid He from companies can be very expensive. The magnet [178] consists of an LTS outsert wound with "react&wind" Nb_3Sn Rutherford cables and an HTS insert. Two different HTS inserts were built (with single tape) and tested: one with the recently available high strength Bi2223 tape from Sumitomo, the other with coated conductor. Both inserts generated >7 T (> 24 T of combined field) but the one built with coated conductor burnt during a quench at peak field.

One of the very first superconducting magnets (in 1960, see [179]) was wound without electrical insulation. This technique was rediscover in 1987 [180] and again in 1999 [181] for a large NbTi detector magnet. In 2010 it was proposed to wind HTS superconducting magnets (mainly double pancakes) with non-insulated tapes [182]. Non-insulated magnet cannot be ramped as fast as insulated ones (depending on the inductance and equivalent turn to turn resistance), but they have two major advantages: 1) Quench self-protection and high tolerance against overcurrent; therefore it is possible to operate very close to I_c, while REBCO insulated magnet are often operated far from I_c to avoid thermal runaway, fearing that the quench will burn the magnet; 2) High engineering current density, because the electrical insulation is removed from the winding pack. A first demonstration of the potential of this technique was the construction of a 26 T, 37 mm bore magnet at MIT, tested in collaboration with the NHMFL and SuNAM [183]. Encouraged by the results, the design for a 35 T, 40 mm bore magnet was recently presented [184]. Both magnets have been designed with radial grading, i.e. wider tapes at the coil ends, a location where the critical current density is lower due to the largest perpendicular component of the magnetic field. These two magnets are clearly much smaller than hybrid or LTS magnets, as shown in figure 26.

REBCO magnets (at least up to 35 T or 40 T) can have a small size (because of the large current density and high tensile strength) and thus do not need to be wound with cables. To generate even higher fields, huge reinforcement cross sections are needed also for coated conductors, as it was presented in a conceptual design of 60 T hybrid magnet [185] at the NHFML. This magnet is composed of a very thick HTS (REBCO) middle section which is wound with a cable in conduit (see figure 26): the conductor is composed of a Robel cable (favourable alignment between tapes and magnetic field), a cooling channel, protection copper and a thick steel jacket to withstand the hoop loads. An even more futuristic design was proposed in [186], where it was shown that a 100 T DC magnet (made only with coated conductor) could be technically feasible. The magnet has an outer diameter of about 6 m and a height of about 17 m. Over 90% of the weight is steel reinforcement. This conceptual design utilises single tapes and not cables, despite the very large size (and thus inductance): the reason is that non-insulated coils cannot (and do not need) to be discharged fast.

In figure 26 the quarter coil cross sections of various superconducting and hybrid magnets are reported in scale, and in figure 27 the total winding pack volume (superconducting strands plus eventual reinforcement) is plotted a function of field. Non-insulated REBCO magnets need noticeable smaller winding pack volume than hybrid magnet. The very small volume has a considerable economic effect: despite coated conductors are more expensive than Nb_3Sn (about one order of magnitude in \$/kg), the smaller volume (one order of magnitude) makes them a viable alternative. The concomitant high current density in high field and the very high tensile strength contribute to the drastic reduction in volume compared to LTS, thus containing the costs.

To summarise, if the wire or tape can be operated without additional reinforcement (relying on self-supporting strength), the magnet is relatively compact and inexpensive. If the loads exceed the limit of the wire/tape then extra reinforcement is needed, the magnet outer diameter starts to grow, demanding even more material and leading to a catastrophic increase in volume (and thus in cost) despite the modest increase in magnetic field (see figure 27). The relationship between magnet costs, field and volume is discussed in [187] for several type of large magnets.

Clearly the main issue regarding high magnetic field generation is about developing stronger structural materials, rather than increasing the current density in the superconductors; for example it has been mentioned [185] that in the 60 T hybrid, the coil volume could be significantly reduced if the thick Hastelloy jacket is replaced by Zylon (high strength polymer). Nonetheless on challenge is the mismatch between the thermal contraction of the superconducting cable and the one of the structural material, which is usually very low or even positive for high strength material (Zylon or carbon fibre).

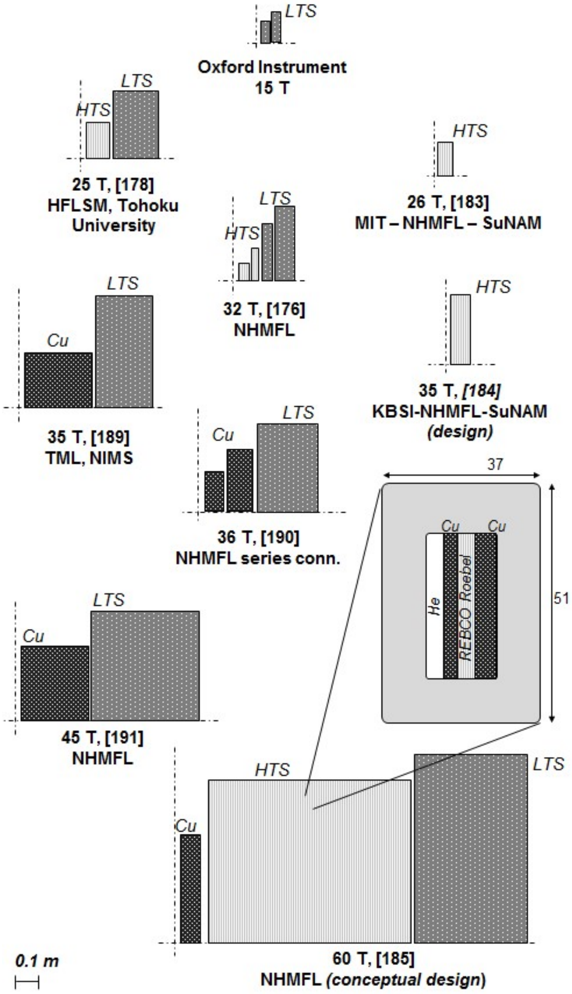


Figure 26. Cross sections of a quarter of winding packs of various superconducting and hybrid solenoid magnets. Resistive sections

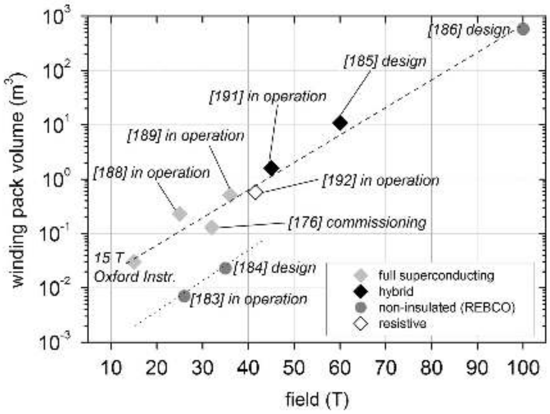


Figure 27. Winding pack volume for various high field solenoids. Lines are guide for the eye.

are in dark grey, LTS sections in grey and HTS sections in light grey. In scale.

7. Conclusions and perspectives

At present the engineering current densities in Bi2212 wires, Bi2223 tapes and REBCO coated conductors are in the same range, but coated conductors can tolerate the highest values of strain and stresses, even compared to reinforced Bi based wires and tapes. Coated conductors have probably the largest margin of improvement because have been available commercially for about 10 years, while Bi based for already 25 years. This justifies why most of the activities on materials, cables and magnets are focused on coated conductors. Nevertheless, before giving up completely Bi2212, it may be worth to revive Bi2212 coated tapes because of the easy fabrication process, also considering the experience gained during the last 15 years.

A serious concern about coated conductors is the weakness against peeling and shearing forces, to be carefully considered during the design of cables and magnets. The main present disadvantages of coated conductors are the short piece length and the long and unreliable procurement time. Price is also an issue, even if coated conductors are getting cheaper and cheaper (mainly by increasing I_c) and are already cost competitive with Nb_3Sn in some operating conditions; of course a further price reduction is welcome and would enlarge the application opportunities. Considering the present advancements in coated conductor, it is conceivable that thicker ceramic layers and wider tapes could be produced, pushing the I_c in tapes to few kA (at low temperature, in field). In Fusion magnets, a drastic reduction in the number of tapes would allow a simplification of the cable design: for example it would be possible to wind a TF or CS magnet with a Roebel cable. In dipole magnets it may be possible to wind coils with a single tape, but a disadvantage could be the quench protection, which is in general more forgiving in tape assemblies (two or more tapes). In some cable design the REBCO tapes are soldered together, while in others the tapes are non-soldered. It is not yet clear what are the mechanical and electrical benefits (and drawbacks, i.e. AC losses) of these options.

Bi2212 wires can be cabled in Rutherford cables but require less compaction and longer twist pitches than NbTi wires. During the last two decades there have been several studies on the most appropriate structural material to be used with Bi2212 (wind and react): ferritic iron-chromium-aluminium and Nichrome 80 seems to be the best choices, while Inconel alloys (even when coated) have sometimes caused a reduction in I_c. Aluminium bronze has the advantage of short machining time.

Bi2223 tapes have been little considered for cables and conductors in large magnets. At present they are cheaper, but marginally less strong than coated conductors. Bi2223 tapes have been used successfully in over twenty power cable projects around the world and in NMR and MRI magnets.

The cable designs presented in this review could be ranked in term of filling factor. The highest value is found of course in non-twisted stacks. Roebel cables have slightly smaller values because of the empty space in between the two stacks of meandered tapes. CORC can provide high values if a very small core is selected. Round twisted stacks have the lowest filling factor because the section occupied by normal material around the stack is relatively large. In terms of engineering current density the difference among the designs can be greatly enhanced by the anisotropic behaviour of the tapes (especially for coated conductors): non-twisted (but transposed) designs could provide over three times higher engineering current density than twisted ones.

Cables with the highest engineering current density are preferred in dipole magnets; in fusion magnets all the designs could be used, however a more compact cable would provide extra freedom in the magnet design.

Matching the characteristics of strands, cables and magnets may be the most effective strategy. For example CCT dipoles are a good choice for cables that cannot tolerate large transverse compressive loads.

Isotropic behaviour of cables and conductors is often set as a goal. Actually preserving the anisotropy in the cable could be an advantage, because, if it is possible to orient the cable properly, coated conductors could perform at their best (both electrically and mechanically). Instead if the tapes are twisted the performance will be determined by the lowest values.

Coated conductors (as single tape) could be used to manufacture high field solenoid magnets approaching 40 T; cables would not provide any major advantage. To generate even higher fields, progresses in structural materials will be of much greater importance than improving the critical current density or developing new cable types.

HTS non-twisted filamentary or monofilament tapes have been used to manufacture MRI and NMR magnets; superconducting tapes have been used for several prototype cables and conductors with encouraging results. Even in commercial high field NMR magnets, some coil sections are wound with rectangular NbTi and Nb_3Sn wires; the reason is that rectangular wires perform better than round ones in those specific conditions (high field, high mechanical loads). NbTi wires are usually round and composed of twisted filaments because NbTi is isotropic and has very low stability margin. HTS are anisotropic and have very large stability margin, thus non-twisted filaments and tapes could be acceptable. In addition tapes (Bi2212, Bi2223, REBCO) can be reacted before winding (one of the advantages is the much wider choice in structural and insulating materials), while wires (Bi2212) usually has to be cabled and wound before reaction, because of the much larger critical bending radius (wires are thicker than tapes); in tapes the superconducting layer could be even located at the neutral plane, further reducing the critical bending radius. For all these reasons it is time to acknowledge that round, twisted, filamentary wires are not, in general, the preferred strand for manufacturing magnets.

HTS have unique features with respect to LTS: extremely high stability margin, higher operating temperature, higher mechanical limits. These features have not yet been fully considered in the design of cables; in fact HTS cables often imitate the LTS designs and borrow the same requirements, without investigating if different choices would be applicable. Requirements for HTS cables, for example regarding transposition, remain partially unstudied and need to be clarified by analysis and experiments. The benefits could be simpler, more efficient and more cost effective designs.

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