Design Study of a 50-kA React-and-Wind Bi-2212 Cable for Fusion Magnet

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Abstract— In the last few years the current density of Bi-2212 wires has been greatly improved by filament density technologies. One further step toward applications in fusion magnets is to design a high current cable, which must overcome the drawbacks of Bi-2212 wire: brittleness and complex heat treatment process. In this paper, React-and-Wind flat cables are proposed. With react-and-wind technique, a larger choice of jacket and stabilizer materials are available including stainless steel and copper, which are widely used for superconducting cables but are not directly usable for Wind-and-React Bi-2212 cables due to their reaction during heat treatment. Two wires, representing respectively bottom and top performance of state-of-art wires, are considered. Several cable layouts are studied considering dimension, compaction rate and transverse mechanical pressure. Materials for quench protection and jacket materials are also discussed.

Index Terms—Bi-2212, React-and-Wind, Wind-and-React, Cable-in-conduit conductor, high temperature superconductor

I. INTRODUCTION

Among practical high temperature superconducting (HTS) materials, $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$ (Bi-2212) is the only one that can be manufactured into round and rectangular wires with isotropic properties. Therefore it has been attracting interests in high field application for over 30 years. However, Bi-2212 had long suffered from the unreliable performance of long length wires, whose critical current density in the superconducting ceramic (J_c) is often lower than in short samples. The interest of Bi-2212 was revived after an increase of about one order of magnitude in J_c thanks to the Over-Pressure-Heat-Treatment (OPHT) technology [1, 2].

Another drawback of Bi-2212 wire is its brittleness and low strength. Bi-2212 wires are usually made by powder-in-tube technology, with silver matrix and silver alloy sheath. Typical limits in longitudinal tensile strain are between 0.3% and 0.6%; the corresponding longitudinal stress limit is less than 100 MPa, as is reviewed in section II.C.

Considering the strain limitation, one may prefer a Wind-and-React (W&R) conductor for Bi-2212, as in the case of Nb_3Sn conductor for ITER magnet [3], which is also brittle and sensitive to strain. A W&R Bi-2212 conductor prototype was prepared by Qin et al [4] for fusion magnet. Godeke *et al* also proposed a W&R Rutherford cable for accelerator magnet about ten years ago [5]. However, in DEMO reactors the magnets are typically larger than in ITER, making the heat

treatment of the whole magnet even more challenging, not to mention with the OPHT. One more complication is that few alloys are compatible with the oxygen atmosphere during the high temperature heat treatment [4, 6, 7], limiting the choice of jacket material or requiring an extra metallic layer between the cable and the jacket. The choice of materials for quench protection is also limited for the same reason. Therefore one of the advantages of the React-and-Wind (R&W) technique is that it would allow much larger choices of structural, quench protection and insulating materials. R&W technology was already demonstrated in common coil dipoles (Bi2212 Rutherford cable) at Brookhaven [8]. Swiss Plasma Center recently tested a flat R&W Nb_3Sn cable for EU-DEMO [9, 10].

The feasibility of a flat R&W Bi-2212 cable for the central solenoid (CS) magnet of China Fusion Engineering Test Reactor (CFETR) Phase II is studied in this paper. The available strain range for bending and J_c at 4.2 K is estimated according to the published data for Bi2212 wires. On these basis, several kinds of cable layout are compared considering the cable thickness and width, compaction rate, strand diameter and transverse pressure. A scaling law of J_c as function of temperature and magnetic field was used to study stability and quench behavior. At last, jacket material options are discussed according to their thermal contraction.

II. Review of $J_c(B, T, \epsilon)$ in Bi2212 wires

A. Current density

The formation of gas bubbles in the ceramic during heat treatment is the reason of the poor performance of long Bi-2212 wires. If the gas bubble formation is prevented by densifying the superconducting filaments, J_c can be increased by almost one order of magnitude [2, 11]. Several densifications methods have been developed. Cold isostatic pressure (CIP) and swaging are applied after drawing but prior to heat treatment [11]. Densification can be applied before heat treatment by groove-rolling, and was later developed as GDG (groove-rolling/drawing/groove-rolling) process [12-14]. OPHT is used alone or in combination with the previous methods. A very high J_c of 6860 A/mm² at 4.2 K and 15 T was reported [15]. New purer precursor powders are also contributing to the improvement in critical current density, because the reduction in the amount of volatile impurities limit the gas bubbles formation [15].

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TABLE I
WIRE CONFIGURATION FOR DATA IN FIG. 1

Reference	Powder Supplier	$\varnothing$ (mm)	Fill factor	Densify method
2001, Hasegawa [16]	\	0.81	25%	No
2009, Rey [17]	Nexans	0.8	10.5%	No
2011, Lombardo [18]	Nexans	0.8	26%	No
2014, Huang [11]	Nexans	1.2	23%	No
2014, Huang [11]	Nexans	1.2	23%	CIP at 690 MPa
2014, Huang [11]	Nexans	1.2	23%	CIP + 10bar OP
2014, Larbalestier [1]	Nexans	0.8	23.4%	100 bar OP
2016, Zhang [19]	nGimat	0.81	12%	100 bar OP
2016, Leveratto [13]	Nexans	0.7×0.7 (square)	18%	GDG
2017, Jiang [15]	nGimat	0.78	20%	50 bar OP
2017, Jiang [15]	Nexans	0.8-1.0	19.6%	50 bar OP
2018, Liu [20]	NIN	1.0	24.3%	50 bar OP

B. Dependence of J_c on magnetic field and temperature

The improvement in critical current density of Bi-2212 wires with the employment of filaments-densify technologies is almost one order of magnitude. Fig. 1 shows some published data of magnetic field dependence of J_c at 4.2 K [2, 11, 13, 15-20] (data in [14] was first presented in EUCAS 2017). The characteristics of the Bi-2212 wires used in these experiments are summarized in Table I. Some of the original data are given in the form of critical current or critical current density of wire, but the corresponding J_c (current density in the superconducting ceramic) have been calculated and compared here. For all of these wires, the field dependence of J_c at 4.2 K appears very similar, despite the differences in the manufacturing processes.

The scaling law of J_c for Bi-2212 is obtained by fitting the data reported by Lombardo et al [18] with the scaling relation shown in Eq. (1-3). The fitting parameters are shown in Table II. It should be stressed that B_{sc0} and T_{sc} are constants for all wires and only the parameter A changes with different wires; in this paper two values of A are considered representing two

Fig. 1 Relation of J_c and B at 4.2 K from published data. Open symbols are for measurement data of non-densified wires, filled symbols are for data of densified wires. Lines are for fitting data using the scaling law shown in Eq. 1-3 (only the parameter A is changed for different wires.) The hypothetical A-wire and M-wire used in the later sections are also shown. The fitting lines are shown up to 25 T.

hypothetical wires as later explained in section III.A. Although the temperature dependence varies among samples, especially at higher temperature [17, 18, 21, 22], the scaling law above with the same set of parameters (see table II) is still valid for all samples at least at temperatures < 30 K, which is of interest for the cable design. Due to the lack of data at high temperature or at low temperature and high field (> 25 T), this scaling law should be cautiously used in those conditions.

C. J_c -Strain Relation

The model for J_c -strain behavior has been proposed by tenHaken et al, which was further improved by Cheggour et al [23-33]. According to this model, J_c will immediately degrade irreversibly in longitudinal compression at almost constant rate. In longitudinal tension, there is a range of slight reversible decrease of J_c ; after that, J_c will degrade irreversibly very fast. This reversible limit, according to various published data, is between 0.3% and 0.6% for the state-of-art wires.

To design an R&W Bi-2212 conductor, the first step is to identify the strain range which can be tolerated without resulting in too much J_c degradation. Although for a free standing Bi-2212 wire there is only very narrow strain range in which there is no irreversible J_c degradation, several

Table II
SCALING PARAMETERS FOR J_c

p	q	α	μ	B_{sc0} [T]	β	ν	A [N·T $^\nu$]	T_{sc} [K]
0.885	4	1.02	10	307	1.59	1.24	408/1836	95

$$B_{sc}(T) = B_{sc0} \left(1 - \left(\frac{T}{T_{sc}}\right)^\alpha\right)^\mu \quad (1)$$

$$F_{p0}(T) = A \left(1 - \left(\frac{T}{T_{sc}}\right)^\beta\right) B_{sc}(T)^\nu \quad (2)$$

$$J_c(B, T) = \frac{F_{p0}(T)}{B} \left(\frac{B}{B_{sc}(T)}\right)^p \left(1 - \left(\frac{B}{B_{sc}(T)}\right)\right)^q \quad (3)$$

experiments have verified that for both tension and compression, after J_c irreversibly decreased, a new longer reversible range is established. In addition, the J_c -strain relation is independent on magnetic field [29, 30, 33]. A sufficient large strain range (and thus corresponding bending radius) is then available if some J_c is sacrificed. In fact, according to tenHaken [25], the reversible plateau in tension is no other than a result of thermal induced compression owing to the different thermal contraction of Bi-2212 ceramic and Ag alloy during cooling down from heat treatment temperature: this means that the J_c of a virgin wire after heat treatment is already degraded irreversibly, as shown in Fig. 2 (see also Fig. 2 in [25]). J_c of a strain free wire (if the matrix has exactly the same thermal contraction with Bi-2212 ceramic) will immediately degrade irreversibly once it is put under tension or compression (dashed line in fig. 2 left).

Fig. 2 (left) shows the strain dependence of J_c in both tension and compression. The data are from [27-30, 33] and the characteristics of the Bi-2212 wires used in these experiments are summarized in Table III. It should be noted that in the measurements of Dai *et al* and Godeke *et al*, the Ti-6Al-4V spring brings about 0.3% pre-tension to the test sample when cooling down from soldering temperature to 4.2 K. This pre-tension has been accounted for in Fig 2. J_c starts to decreases rapidly at strain higher than 0.4%. Thus 0.4% of tension should be the ultimate limit to be considered in the cable design.

In compression the critical strain is basically 0%, but it can be extended if some degradation of J_c is accepted. As shown in Fig. 2, with a compression of -0.4%, the degradation of J_c is between 10% and 20%. Thus, even a conservative estimation of 20% degradation at -0.4% compression would result in a 0.8% strain range (from -0.4% to 0.4%), which should be sufficient for R&W conductor design. As comparison, Fig. 2 (left) also shows the J_c -strain relation for Nb_3Sn (intrinsic) (data from [34]). Unlike HTS materials, $J_c(\epsilon)$ of Nb_3Sn strongly depends on magnetic field, so the relation at 15 T, which is in the field range of interest (15 T - 20 T) is plotted. Bi-2212 wire shows less J_c degradation than Nb_3Sn in the strain range of interest, but the difference is that in Nb_3Sn the

Fig. 2 The left figure shows J_c -strain relation for Bi-2212 wires from published data. Typical relation for Nb_3Sn is also given as comparison. All data are measured at low temperature (4.2 K or 6 K). The right figure is a sketch of the variation of J_c and strain during an R&W coil fabrication. Dash lines connect C', D' and E.

reduction of J_c is reversible, while in Bi-2212 is not. On the other hand, in both cases the reduction is permanent when the wires are used in magnets.

Since in the R&W Nb_3Sn conductor [35], the strain range during transportation, winding, operation is between -0.4% and +0.1%, it is reasonable to consider R&W also for a Bi-2212 conductor which shows better performance against strain than Nb_3Sn . The strain evolution during a hypothetical fabrication process of a CS coil is reported in Fig. 2 (right):

- 1) A→B: React the cable on the same diameter of the final coil and then cool down to room temperature (RT). Part of J_c is lost as a result of the different thermal contraction of Bi-2212 ceramic and Ag alloy. The strain state at RT is then set as 0%.
- 2) B→C/C': Straighten the cable, and jacketing. Now the strain in the cable is between $-\epsilon_b$ (point C) and $+\epsilon_b$ (point C') and J_c is reduced for the strands in the compressive region.

TABLE III
WIRE CONFIGURATION AND TEST CONDITION FOR DATA IN FIG. 2

Reference	2006, Sugano [27]	2011, Lu [28]	2015, Godeke [30]	2015, Godeke [30]	2018, Dai [33]
Filament Configuration	61×7	85×7	61×7	37×18	19×18
Matrix & Sheath	Ag/Ag-Mg-Cu	Ag/Ag-Mg	Ag-Mg-Sb	Ag/Ag-Mg	Ag/Ag-Mg
Wire Supplier	Showa	OST	Showa	OST	NIN
Diameter (mm)	0.8	0.8-1.0	0.8	0.8	1
Fill Factor	21%	25-30%	33%	25%	24.30%
Densify Method	None	None	OPHT	OPHT	None
Test Condition	6 K, 8 K and 10 K; 20 and 30 T	4 K; 5 T to 15 T	4.2 K; 5 T and 15 T	4.2 K; 5 T and 15 T	4.22 K; 14 T
Sample Holder Material	Cu-2wt%Be	Cu-2wt%Be	Ti-6Al-4V	Ti-6Al-4V	Ti-6Al-4V
(Thermal Contraction mismatch)	(<0.01%)	(<0.01%)	(+0.3%)	(+0.3%)	(+0.3%)

- 3) C/C'→D/D': coil winding. The strain state at RT is now the initial one (about 0%), but J_c is lower at the compression side in step 2.
- 4) D/D'→E: Cool down to operating temperature. The strain state is now usually compressive due to the difference of thermal contraction between cable and jacket, assuming $-\epsilon_{th}$. J_c could be further reduced because of the additional thermal compression. And if $-\epsilon_{th} < -\epsilon_b$, all the wires in the cable will have same degraded J_c .
- 5) E→F: Energize the magnet, which introducing tensile strain ϵ_e (hoop strain). The strain state is eventually $-\epsilon_{th} + \epsilon_e$.

In Fig. 2 (right), as an example, ϵ_b is set at 0.2%, $-\epsilon_{th}$ is set at -0.4%, ϵ_e is set at 0.2%. In such case, the maximum compressive strain controls the final critical current (I_c) of the cable. On the other hand, since J_c degrade very fast once tension exceeds the tensile critical limit, any additional tension could lead to considerable J_c degradation. Therefore, it's better to keep a sufficient margin from the tensile limit.

The limitation on the cable width from in-plane bending at vertical turn-turn cross over are discussed in III. D.

III. OVERVIEW OF CABLE CONFIGURATIONS

With the above background, it is possible to start the design study of an R&W conductor for the central solenoid of CFETR Phase II, whose design objective is to generate a large magnetic flux in the plasma while keeping the magnet volume as small as possible. A cable that could achieve this goal should have the following characteristics [36]: operating current $I_{op} = 50$ kA; operating temperature $T_{op}=4.5$ K (temperature margin > 2 K) and peak magnetic field $B_{max}=17$ T.; inner radius (R_{in}) is set at 1 m.

A. Operating current of Bi-2212 wire

It is premature to choose one value for the current density of Bi-2212, since J_c of Bi-2212 can vary a lot depending on the fabrication method, as shown in Fig. 1. Consequently, two hypothetical wires with different levels of J_c at 4.5 K and 17 T are considered: one (called M-wire, M for moderate) with J_c of 1317 A/mm² which is achieved by all the densification methods; one (called A-wire, A for ambitious) with J_c of 5927 A/mm², representing the uppermost boundary. The superconducting fraction is conservatively set at 20% for both wires, resulting in engineering current densities (J_e) at 4.5 K and 17 T of 263 A/mm² and 1185 A/mm² respectively. It is

Table IV
CONFIGURATIONS FOR Bi-2212 REACT-AND-WIND FLAT CABLE

Cable Configuration	Void fraction before compaction	Reduction of Cable envelope with compaction rate of 85%	Sketch of cross section before compaction
Rutherford cable	~22%	~8%
2-layers Rutherford cable	~22%	~8%
Roebel bar (strand aspect ratio =2)	< 5% (without compaction)	< 5% (without compaction)
Roebel bar (strand aspect ratio =3)
2-layers Roebel bar (strand aspect ratio =2)
Rutherford cable (pair sub-cable)	~61%	~54%
Rutherford cable (triplet sub-cable)	~49%	~40%
Rutherford cable (3x3 sub-cable)	~67%	~61%
Rutherford cable (6-around-1 sub-cable)	~48%	~39%

Fig. 3 Cable width (dash lines) and thickness (solid lines) for different configurations as function of wire cross section (a is aspect ratio of rectangular wires) for a 50 kA cable at 17 T. The left figures are with A-wires and right figures are with M-wires. The cable configurations are sorted into 4 groups according to the void fraction. The color of the label is corresponding to the line. The translucent-yellow region shows the typical range of wire cross section (corresponding to 0.8 to 1.5 mm round wires). The magenta dot line shows the upper limit for both cable width (40 mm) and thickness (8 mm) for a winding with radius of 1 m.

assumed that J_c of Bi-2212 is first reduced by 20% because of the -0.4% strain; then another 20% is taken as margin for operating current (J_{op}), resulting in a current sharing temperature of about 7.4 K. Consequently the J_{op} is 64% of the J_c of a free standing wire. For a conductor with 50 kA I_c at 17 T and 4.5 K, the ceramic cross section is about 60 mm² for the moderate strands, corresponding to a total strand cross section of 300 mm². For the A-wire, the total strand cross section is about 67 mm².

B. Cable layouts

In R&W cables the strands should be located as close as possible to the cable mid-plane, in order to keep the bending strain during winding as small as possible. Therefore all the considered cables are flat and have a large aspect ratio (see Table IV). In addition to the common Rutherford cable, other types of flat cables, composed of twisted pairs and triplets have been studied. In the cable name, the first number indicates the number of twist stages and the second one (or two) indicates the sub-cable pattern.

A Roebel bar made of rectangular wires (two different aspect ratio were considered) is also discussed; the main

advantage of this configuration is that low void fraction can be obtained without compaction; for this reason the Roebel bar is particularly suitable for Bi-2212 wires, which are very sensitive to deformation during compaction [37].

To evaluate these cables, the following criteria are considered during the selection process.

- Compaction rate: the cable should be compacted as much as possible to avoid degradation with cycling load [38].
- Cable thickness: the cable should be thin enough to limit the bending strain during winding
- Cable width: the cable should be narrow enough to limit the in-plane bending strain during turn-to-turn transitions (orthocyclic winding method).

C. Compaction rate and void fraction

In Rutherford cables the compaction rate (or packing factor) is the sum of the cross-sectional area of all the strands divided by the area of the die used for compaction. A rate of 0.78 is the minimum achievable, corresponding to no deformation on the strands; the void fraction is then 22%. In NbTi Rutherford cables the compaction rate is between 0.88 and 0.92. For Bi2212 Rutherford cables, it has been reported [38] that the

Table V
PARAMETERS OF SELECTED CABLES

Cable configuration	Wire type	Wire ϕ (mm)	No. of strands	Cable thickness (mm)	Cable width (mm)	Nominal maximum transverse pressure (MPa)
2-layer Roebel bar ($a=2$)	M-wire	1x2	148	8	37	23.0
Rutherford cable ($T_{cs}=7.4$ K)	A-wire	1.5	37	3	28.5	29.8
Rutherford cable ($T_{cs}=10$ K)	A-wire	1.5	49	3	37.5	22.4

compaction rate should be <0.85 . The reason is that, as measured in [37], J_c in Bi2212 wires is very sensitive to indentation.

For the last four conductors in Table. IV, the void fraction after compaction of 0.85 is still very large, and they might suffer from J_c degradation by cycling load, because the strands would have plenty of space to move under transverse electromagnetic forces. If much larger compaction rate is applied in order to reduce the void fraction, they might suffer from J_c degradation by wire indentation due to compaction. Therefore these conductors are unlikely to be selected.

D. Width and thickness of cable

For CS coil with inner radius of 1 m, the maximum strain range of $\pm 0.4\%$ results in a maximum allowable cable thickness of 8 mm, assuming the strands are fully bonded. This is a conservative assumption, because it was found that in Bi-2212 Rutherford cables the strands were free to move one with respect to the others [39] under bending.

Regarding the cable width, the limit comes from the in-plane bending at the turn-to-turn cross over. For a winding radius of 1 m and a turn-to-turn transition length of $1/5$ of the circumference, the width should be less than 40 mm in order to keep the strain below 0.4%.

E. Cable selection

A first selection is carried out based on the cable dimensions and available strand diameters. Fig. 3 shows the nominal width and thickness (before compaction) of the cables as function of the strand diameter. The yellow rectangle shows the region with strand diameter between 0.8 mm and 1.5 mm (currently available) and with cable thickness <8 mm, and cable width <40 mm. A cable design should be discarded if the corresponding cable width (dashed line) and cable thickness (solid line) versus strand diameter are not present in the yellow rectangle at the same time.

For A-wires (Fig. 3 left), because of the high J_c , almost all the layouts can be selected. For example a Rutherford cable (the thinnest of all options) with a wire of 1.2 mm diameter, would have a cross section of $3.0 \text{ mm} \times 28.5 \text{ mm}$.

For cables with M-wires, the width become a critical problem since the number of wires increase a lot. Only the 2-layer Roebel bar can be selected, with a wire slightly bigger than the common ones (2 mm^2).

To summarize: the remarkable improvement of the J_c in Bi-2212 wires makes it possible to design an R&W cable. In the most favorable case (J_c of 5927 A/mm^2 at 4.5 K and 17 T;

Fig. 4 Selected cable configurations (the left two figures) and schemes of the conductors with both jacket (not in real scale) and additional copper protection (see section IV). Additional cooling channel might be needed for some conductors like the Roebel bar, since the void in cable region is too small. The right figure is a round Bi-2212 CICC.

corresponding to J_c of 1185 A/mm^2), a very simple and compact Rutherford is a possible option. Considering a very modest wire with J_c of 1317 A/mm^2 at 4.5 K and 17 T (achieved by all densified wires), only the Roebel bars are possible options. If the performance of the wires is in between the two, some of the other options would be also feasible, like the 2-layer coaxial Rutherford, which consist simply in wrapping the Rutherford cable with another layer of wires. The twist pitches of the two layers should be chosen to minimize the inductance mismatch between the two layers, and thus uniform current distribution during current ramps [40]. Other cable configurations with high initial void fraction are not as appealing as the former ones.

IV. OPERATING ISSUES IN CENTRAL SOLENOID

Two cable designs are selected for further discussion because of their dimensions, the low void fraction and the low compaction rate: Roebel bar with M-wire and Rutherford cable with A-wire. One more cable with higher T_{cs} (10 K instead of 7.4 K) is also designed with A-wire. Table V lists the selected design parameters and sketches of the cross section are shown in Fig. 4. In Fig. 4, a round Bi-2212 CICC is also shown for comparison [36].

A. Transverse stress

When the Central Solenoid is charged, the magnetic field in vertical direction and the current in circumferential direction result into radial outward force on the cable. The outermost wires in the cable will withstand the maximum force by accumulating the force from all the other wires.

Table V shows the estimation of average transverse stress for the optimized cable configurations. Katagiri et al [26] reported an experiment on Bi-2212 wire, which shows a transverse stress limit for irreversible J_c degradation ranging from 9 MPa to 20 MPa; similar low values were measured also in Bi-2212 with AgZr matrix [41]. This could be a harsh restriction for both R&W and W&R cable. It should be noted that in these two papers, Bi-2212 also shows poor property against tension. Whereas as mentioned above, modern Bi-2212 wires are made with strong Ag-Mg alloy as sheath and filaments are densified. As a consequence, the transverse stress limit could also increase. However, there are no published values for critical transverse stress on state-of-art wires. It would be very valuable to measure the critical current retention under transverse pressure in the state-of-art Bi-2212 wires.

On the other hand, Dietderich et al [42] has measured a much higher stress limit of 60 MPa on a Rutherford cable in a fiberglass-reinforced epoxy matrix. Bi-2223 tapes, which have similar tension behavior of Bi-2212 wires, can withstands transverse pressure of about 70 MPa [43]. In round Nb_3Sn wires it was found that the degradation of J_c happens already at few MPa, while in hydrostatic conditions, for example if the wire is surrounded by resin, as is the case of impregnated cables, the critical stress is much higher (40 MPa) [44]. This makes the Roebel bar with rectangular shape more attractive.

In the Bi-2212 round conductor (which used a low current wire, comparable to M-wire) for CFETR the stress can be estimated at about 45 MPa [36]. Therefore in flat cables the transverse stress would be about two times lower than in round conductors. For comparison the accumulated transverse stress in ITER Nb_3Sn conductors (900 strands, 68 kA, 11.8 T) is about 37 MPa [45].

B. Stability

The stability of the conductor against various types of perturbations was of particular importance in the development of LTS cables, because LTS materials have low stability (the reason is that J_c decreases very rapidly with temperature). In HTS J_c decreases slowly with temperature, thus are expected to be more stable against any type of perturbation.

A simple thermal-hydraulic model analysis with CryoSoft THEA [46] is used to calculate the energy margin and hot spot temperature in the case of quench for Bi-2212 conductor. The model consists of the Bi-2212 cable (all the wires are considered homogeneous in thermal and electrical), a stainless steel jacket (similar amount of steel is assumed as ITER CS conductor [47], although for a DEMO reactor in which HTS is most likely to be employed, it would be much more [48]) and forced flow critical helium (operating pressure is 6 bar, with pressure drop 1 bar/km [49]) in the void. The cable is composed of Bi-2212 ceramic (n value=30), silver (RRR=220), AgMg (RRR=5) [50, 51] and copper (RRR=100). Based on a recent thermal-hydraulic test on Nb_3Sn cable-in-conduit

conductor (CICC) at SPC, the cable-jacket thermal resistance is assumed to be 0.01 Km/W for conductor with M-wires and 0.02 Km/W for conductor with A-wire, since in the former the contact area is about twice. For quench simulation, 0.1 V is assumed as the detection voltage, 1.1 s is assumed for quench protection system (QPS) reaction and 20 s is assumed as the discharge time constant [52, 53]. A heat disturbance is deposited into the cable along 0.1 m and during 0.1 s.

Fig. 5 shows the calculated stability margin of the conductors (in mJ/cm³) as function of copper cross section. The conductor's stability is already comparable or larger than the one of ITER Nb_3Sn CICC (> 200 mJ/cm³) even without using any additional copper [54]; for comparison, in ITER the energy for mechanical disturbances was estimated at 15 mJ/cm³ and the energy from AC losses between 80 and 120 mJ/cm³ [54]. Therefore a Bi2212 cable could withstand higher transient thermal loads than an Nb_3Sn cable.

C. Quench protection material

Regarding quench protection, the cross section and the electrical conductivity of the metal in parallel with the superconductor should be large enough to keep the hot spot temperature below a reasonable value. Using the model described in the previous section, the hot spot temperature is plotted as a function of the copper cross section in Fig. 5. It is found that 200 mm² copper are enough to reduce the hot spot temperature to a reasonable level in M-wire cables. In A-wire cables, the copper cross section should be at least 400 mm², because the amount of silver matrix is now lower. A higher T_{cs} ,

Fig. 5 Energy margin evaluating stability (filled symbols and solids lines) and hot spot temperature evaluating quench (open symbols and dash lines) as function of copper cross section.

Table VI
THERMAL CONTRACTION OF BI-2212 WIRE AND POSSIBLE JACKET
MATERIALS FROM ROOM TEMPERATURE TO 4 K

Material	$\Delta L/L$ (%)
Bi-2212 wire [54]	-0.284
Stainless steel 316 [55]	-0.297
Ni80Cr [56]	-0.229
Inconel X750 [57]	-0.218

i.e. more superconducting strands, is of little use for controlling hot spot temperature. Large amount of high conductivity metal is always needed: copper can be introduced as a flat-highly-compacted cable; to reduce losses in the copper, thin wire with Cr or Ni coating should be used. Another option is to use a solid mixed 95% Cu and 5% Cu-Ni matrix [10]. One advantage of the R&W Bi-2212 conductor is that copper can be included in the cable, while in W&R conductor the copper should not get in contact with oxygen during the heat treatment.

D. Cable Jacket

The CS magnet is composed of several solenoid modules; at operation the hoop loads and vertical loads are very large and are supported by a thick jacket. For an R&W Bi-2212 conductor, the jacket is added after the heat treatment, thus the choice of materials is wide. On the other hand, the different thermal contraction of jacket and strands during cooling will bring additional thermal strain in the strands. Therefore, the best jacket material should have thermal expansion close to the one of Bi-2212. Table VI shows the thermal contraction of some materials as well as Bi-2212 wire from room temperature to 4.2 K [55-58]. Stainless steel 316 is a very good choice because the thermal contraction is very close to the one of Bi-2212 wire. The other two alloys Inconel X750 and Ni80Cr are considered as structural material for W&R Bi-2212 conductor but will result in tension of about 0.06%. Indeed, in the case of W&R conductor, although bending strain is eliminated, cooling down from the heat treatment temperature (~ 1100 K) to operating temperature (~ 4 K) might introduce higher thermal strain, as in the case of ITER conductor [59]. The dimensioning of the jacket cross section should be studied during the magnet and winding pack design, therefore will not be further discussed here.

V. SUMMARY

Various 50-kA R&W flat cables with round or rectangular wires have been studied. Two hypothetical strands were considered with conservative J_c (M-wire, modest J_c) and ambitious J_c (A-wire). With 20% J_c degradation, a sufficient axial strain range from -0.4% to 0.4% is available for bending. With M-wire (modest current density achieved by all state-of-art wires), Roebel bar cable. With A-wire (very high current density), even Rutherford cable becomes available. Roebel bar cable has the highest filling factor and is free from compaction, therefore decreases the risk to degrade I_c of cable by indentation during compaction.

R&W flat conductor can be wound after reaction, allowing many choices of jacket and insulation materials. A proper jacket material should be strong and have comparable thermal contraction with Bi-2212 wire to reduce the thermal strain during cooling down, for example stainless steel 316.

Bi-2212 conductor is quite stable, but for quench protection additional low resistance material should be added; copper can be used in R&W Bi-2212 conductor; the cross section should be at least 200 mm².

The transverse load in flat cable is much smaller than in the

round CICC. But for cable with A-wire, the transverse stress may still be above the limit. The critical transverse pressure should be measured on state-of-art Bi-2212 wires with better mechanical properties.

Prototypes of these R&W Bi-2212 conductor concepts should be manufactured in future to verify the engineering feasibility and measure the properties, especially for relatively new concepts, i.e. 2-layer Rutherford and Roebel bar conductors.

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