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Comparisons and analysis on the prototype EU-DEMO TF CICC with Nb_3Sn cable

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Abstract

European R&D on designing their version of a DEMO fusion tokamak has recently resulted in the testing of a prototype Nb_3Sn Cable-in-Conduit Conductor (CICC) for the DEMO TF coil. The characteristics and reported results of low temperature performance tests with the prototype CICC sample are compared with those from CICC samples incorporating other recent Nb_3Sn cable designs. The EU-DEMO TF CICC prototype shows performance characteristics similar to that of the ITER CS CICC with short twist pitch. This is a first for a CICC sample that does not have a circular cross section. Assessment of its internal magnetostatic self-field suggests that a reduction in the internal self-field due to the rectangular geometry of the EU-DEMO TF CICC prototype compared to one with a circular geometry may have contributed to the performance characteristics showing current sharing temperature (T_{cs}) initially increase then stabilize with repeated electromagnetic loading, similarly to ITER CS CICC results. However, constraints on the internal self-field are not a sufficient condition for this T_{cs} characteristic to occur.

Keywords: fusion magnet, superconducting cable, cable-in-conduit conductor, CICC, niobium-tin, conductor performance

1. INTRODUCTION

Efforts on designing so-called DEMO fusion reactors for the actual demonstration of power production by nuclear fusion are taking place in countries with active nuclear fusion programs. The European effort coordinated by the EUROfusion consortium has recently reported results on a prototype magnetic coil conductor design for their DEMO tokamak [1]. There are several parallel efforts in the EU-DEMO design, and the recent reported results are on a Cable-in-Conduit Conductor (CICC) design by ENEA for the TF coil. The design is based on Nb_3Sn superconducting cable technology, and a prototype conductor sample was fabricated and tested. Evaluation of low temperature performance took place at the EDIPO facility operated by the EPFL Swiss Plasma Center (SPC), which is located within the Paul Scherrer Institute in Villigen, Switzerland [2-6].

The reported low temperature tests on the EU-DEMO TF CICC sample follow the same types of tests performed on the superconducting coil conductors for the ITER project, the main performance criteria being the current sharing temperature (T_{cs}) [7]. The TF CICC sample is reported to have successfully satisfied the criteria for EU-DEMO performance making the design a viable option for DEMO tokamak construction [8, 9]. In addition, the reported T_{cs} test results show characteristics that have only been consistently observed for a particular CICC design, namely the ITER CS conductor with Short Twist Pitch (STP) [10]. The T_{cs} test results for ITER CS conductor show for repeated electromagnetic (EM) loading that the T_{cs} value initially increases with EM cycling then stabilizes without degradation. The EU-DEMO TF CICC is the first reported case where a CICC with rectangular cross section and different combination of cable and sub-cable twist pitches has consistently demonstrated characteristics similar to that of the circular ITER CS CICC.

Previously, a comparison between CICC designs looked into the possible relationship between CICC cable design parameters and T_{cs} performance [11]. The same analysis is repeated here on the EU-DEMO TF CICC design to provide additional insight into the relationship between cable design and T_{cs} performance.

2. THE PROTOTYPE EU-DEMO TF CICC

2.1. General Characteristics

The main characteristics of the prototype EU-DEMO TF CICC are given in Table I. All cable and sub-cable twist pitches are right-handed, and their lengths were inspired by the results of the “TFPRO2 OST2” CICC test results which showed good performance with sub-cable that is far less rigid compared to the STP design [12]. The final CICC has a rectangular shape with an aspect ratio greater than 2:1. However, the CICC cable starts out as cable with circular cross section, then after insertion into the stainless steel jacket, it is compacted to the rectangular geometry [13].

According to the manufacturing report for the CICC, the cable undergoes significant deformation during the compaction process. In particular, the twist pitch of the final stage cable increases by more than 35%, in addition to the obvious rectangular deformation. The twist pitches of the fourth and third stage sub-cables also increase significantly, both by almost 20%. This results in the average twist pitch ratio (β_λ) given by

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$$\beta_\lambda = \frac{1}{N_{max}-1}\sum_{i=1}^{N_{max}-1}\frac{\lambda_{i+1}}{\lambda_i}, \tag{1}$$

where $N_{max} = 5$ is the number of sub-cable stages in the cable, to increase from 1.59 to 1.74. The influence of the final stage twist pitch is significant as β_λ only taking into account the twist pitches up to the fourth stage sub-cable or petal is between 1.2 and 1.3. Nevertheless, neither the deformation of the CICC cable by itself nor the β_λ value should be the deciding factor that determined the T_{cs} characteristics with repeated EM loading.

Of the six petals that were assembled into the final cable, two have a smaller diameter than the other four. This is due to the different size cores of the petals; Type I petals have Cu strand based sub-cables as cores, while Type II petals have stainless steel spirals with diameter smaller than the Cu sub-cables. The Cu strands themselves have 1.5 mm diameter which is greater than the 1.0 mm diameter of the Nb_3Sn superconducting strands. The resulting difference in petal diameter is more than 1 mm. These petals are then wound around another sub-cable consisting of 84 Cu only strands. As the analysis of CICC cables with petals of differing sizes is complex, analysis is performed with one type of petal only, and conclusions are formed with consideration of the two differing results.

TABLE I
MAIN CHARACTERISTICS OF THE PROTOTYPE EU-DEMO TF CICC CABLE.

Parameter	Value
Nominal Current (kA)	81.7
Cable Shape	
geometry	rectangle
dimensions (mm×mm)	73.7×31.9
edge radius (mm)	~4
Cable Layout	EU-DEMO TF WR1
No. of Nb_3Sn strands	
1st stage	3
2nd stage	9
3rd stage	36
4th stage	180
5th stage	1080
No. of Cu strands	
4th stage core	12
Total	132
Strand Radius (mm)	
Nb_3Sn strand, r_s	0.50
Cu strand, r_c	0.75
Cooling Spiral Radius, r_{cs} (mm)	3.3
r_i/r_s factors	(see Table II)
Twist Pitch, λ_i (mm)	
1st stage	103
2nd stage	135
3rd stage	175
4th stage	227
5th stage	690
Twist Pitch Ratio, β_λ	1.74
Strand Current, j_s (A)	75.6
Void Fraction (%)	24.6

2.2. Estimation of the Internal Magnetostatic Self-field

The internal magnetostatic self-field of the prototype EU-DEMO TF CICC cable is estimated using the cable model of [11], which also permits relative comparisons to be performed with the CICC cables analyzed in [11]. The cable model assumes a circular cross section, and so the field calculations are not entirely valid for the rectangular EU-DEMO TF CICC. But given the crude nature of the zeroth order estimations of the field, the calculations still provide relevant comparisons to be made. The topic of CICC geometry shall be treated in later sections.

The calculations of the terms resulting in the zeroth order estimation of the internal longitudinal self-field $B_\parallel$ along the length of the CICC cable are given in Table III for each sub-cable stage. The maximum magnitude of the internal azimuthal field B_Φ around the center of the cable, assuming a circular cross section is given by

$$B_{\Phi\,\max} = 1080\mu_0 j_s/2\pi r_5 \tag{2}$$

where 1080 corresponds to the total number of Nb_3Sn superconducting strands in the EU-DEMO TF CICC cable, and r_5 corresponding to the radius of the cable if it had a circular cross section is calculated from the information in Tables I and II.

There are differences in the calculated $B_\parallel$ and $B_{\Phi\,\max}$ values between CICCs with Type I and Type II petals, as seen in Table III. These are on the order of 4% with the ratio $B_\parallel/B_{\Phi\,\max}$ differing by about 8%. The differences are a direct consequence of the difference in cable radius, as the larger radius induces larger transverse orientation of the sub-cable for the same twist pitch while decreasing B_Φ inside the cable.

Conversely, it is also the case that twist pitch elongation due to the deformation of the cable during CICC compaction results in the decrease of $B_\parallel/B_{\Phi\,\max}$. This effect which has to take into account the cable layout, arises from the decrease in $B_\parallel$ due to the smaller transverse orientation of the sub-cable for the same cable radius.

Further discussion on the results of calculations estimating internal magnetostatic self-field is presented in subsequent sections.

2.3. Other Cable Characteristics and their Possible Effects

Though the total number of Nb_3Sn strands is greater than any other recently tested fusion magnet CICC that has been reported, the average nominal superconducting current per strand j_s for the prototype EU-DEMO TF CICC is 75.6 A, same as that for the ITER TF CICC. However, EU-DEMO TF CICC is expected to operate under a background magnetic field of 13 T compared to 11.8 T for ITER TF CICC. The larger magnetic field and greater strand number would exert a larger cumulative Lorentz force inside the EU-DEMO TF CICC cable, possibly increasing inter-strand contact stress and consequently damaging strand. However, this effect seems to have been offset by the rectangular geometry and orientation of the CICC with respect to external field, as has been observed before [14-17].

TABLE II
CABLE LAYOUTS AND r_i/r_s FACTORS OF THE PROTOTYPE EU-DEMO TF CICC AND PROTOTYPE EDIPO CICC CABLES.

Design Name		EU-DEMO TF WR1 layout	SUBSAM layout
Cable Layout[†]		(3SC×3×4×5+(3Cu×4))×4+(3SC×3×4×5+CS)×2+(3Cu×4×(6+1))	3SC×3×4×4
r_i/r_s factors			
Common	1st stage	$\frac{2}{\sqrt{3}} \approx 1.15$	$\frac{2}{\sqrt{3}} \approx 1.15$
	2nd stage	$\frac{4}{3}+\frac{2}{\sqrt{3}} \approx 2.49$	$\frac{4}{3}+\frac{2}{\sqrt{3}} \approx 2.49$
	3rd stage	$(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right) \approx 6.01$	$(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right) \approx 6.01$
Type I	4th stage[‡]	$2(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right)+\kappa(1+\sqrt{2})\left(1+\frac{2}{\sqrt{3}}\right) \approx 19.82$	$(3+2\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right) \approx 14.50$
	5th stage[‡]	$4(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right)+5\kappa(1+\sqrt{2})\left(1+\frac{2}{\sqrt{3}}\right) \approx 63.04$	
Type II	4th stage	$2(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right)+\frac{r_{cs}}{r_s} \approx 18.61$	
	5th stage[‡]	$4(1+\sqrt{2})\left(\frac{4}{3}+\frac{2}{\sqrt{3}}\right)+3\kappa(1+\sqrt{2})\left(1+\frac{2}{\sqrt{3}}\right)+2\frac{r_{cs}}{r_s} \approx 60.64$	

[†] SC is Nb_3Sn superconducting strand; CS is cooling spiral
[‡] $\kappa \equiv r_c/r_s = 1.5$

TABLE III
ZEROTH ORDER ESTIMATION OF THE INTERNAL MAGNETOSTATIC SELF-FIELD FOR THE PROTOTYPE EU-DEMO TF CICC CABLE.

Petal Type	Type I	Type II
No. of elements, N_i		
1st stage	3	
2nd stage	3	
3rd stage	4	
4th stage	5	
5th stage	6	
Twist Pitch, λ_i (mm)		
1st stage	103	
2nd stage	135	
3rd stage	175	
4th stage	227	
5th stage	690	
$\prod_{m=0}^{i-1} N_m$		
1st stage	1	
2nd stage	3	
3rd stage	9	
4th stage	36	
5th stage	180	
r_i/λ_i		
1st stage	0.00561	0.00561
2nd stage	0.00921	0.00921
3rd stage	0.01716	0.01716
4th stage	0.04365	0.04100
5th stage	0.04568	0.04394
$\frac{N_i}{\lambda_i}\frac{2\pi r_i/\lambda_i}{\sqrt{(2\pi r_i/\lambda_i)^2+1}}\prod_{m=0}^{i-1} N_m$ (mm^{-1})		
1st stage	0.00103	0.00103
2nd stage	0.00385	0.00385
3rd stage	0.02205	0.02205
4th stage	0.20972	0.19781
5th stage	0.43182	0.41653
Sum	0.66848	0.64127
$B_\parallel$ (T)	0.064	0.061
$B_{\Phi\,\max}$ (T)	0.518	0.539
$B_\parallel/B_{\Phi\,\max}$	0.123	0.113

On the other hand, the void fraction of the CICC cable at 24.6% is among the smallest of recently reported fusion magnet CICCs. The smaller the void fraction, the more tightly compacted and constrained is the cable. However, this does not seem to have prohibited the cable strands from relaxing as observed by the increase in T_{cs} at the start of EM cycling. Although the strain relaxation could be an artifact of a short conductor sample whose cable ends were not sufficiently constricted, the calculations of the internal magnetostatic self-field for the CICC cable also present the possibility of the cable strands relaxing with T_{cs} increase in line with observations of some CICC cable designs studied in [11].

2.4. Treatment of the Central Cu Core

It is assumed in the CICC cable model of [11] that Cu strands do not carry current. So similarly to ITER TF and CS conductor designs with their central cooling spirals, there would be no current near the center of the prototype EU-DEMO TF CICC [18]. The consequent and equivalent hole is more significant because the Cu sub-cable core is wider than the cooling spirals of the ITER CICCs. In any case, the lack of current in the middle of the circular cable was ignored in prior calculations and in the estimates of $B_\parallel$. There is some justification for this which is as follows.

Consider the construction of the fifth stage cable from the fourth stage sub-cables. The combining and simplification process using the cable model results in the uniform circular transverse surface current on the outer surface and also a uniform circular transverse current closer to the center of the cable. This inner circular transverse surface current flows in the opposite direction to the circular current over the outer cable surface but with the same current magnitude. The field $B_\parallel$ due to the inner transverse current cancels the field due to the outer transverse current in the region inside the inner circular surface current where there is no superconducting strand.

For the region in between the two surface currents, the inner circular transverse surface current increases $B_\parallel$, but this tends to zero as the length of the cable goes to infinity, which is the assumption of the cable model. Consequently, only the effect of the outer circular transverse surface current remains. The twist pitch of the fifth stage cable adds to the outer circular transverse current and increases $B_\parallel$ to the final value across the cross section of the cable for regions with superconducting strand.

3. COMPARISON BETWEEN CIRCULAR AND RECTANGULAR CICC CABLE

3.1. Results of the Magnetostatic Self-field Calculations

As seen in Table III, the estimated value of $B_\parallel$ for the EU-DEMO TF CICC cable with nominal current is around 0.06 T, and the estimate for $B_{\Phi\,\max}$ is around 0.52 T or 0.54 T depending on whether the cable is Type I or Type II. For comparisons between CICC cable, the ratio $B_\parallel/B_{\Phi\,\max}$ is calculated and is determined to be 0.123 and 0.113 respectively for Type I and Type II cable. These values are close to but slightly larger than the values for Nb_3Sn CICC cable that with EM cycling showed either definite initial increases in T_{cs} followed by stabilization or just a high and stable T_{cs} with no degradation, the value being $B_\parallel/B_{\Phi\,\max} \approx 0.11$.

Furthermore, given that there are twice as many Type I petals as there are Type II petals in the CICC cable, the actual value of $B_\parallel/B_{\Phi\,\max}$ may be closer to the upper value, for which T_{cs} degradation in CICC has been observed with EM cycling.

Finally, it is noted that applying the original twist pitch values of the EU-DEMO TF CICC cable when it had circular cross section before deformation from compaction, $B_\parallel/B_{\Phi\,\max}$ would be larger at 0.205 and 0.190 for Type I and Type II cables respectively. Therefore, it would be worthwhile to test and measure the T_{cs} of the EU-DEMO TF CICC using original circular cross section cable and observe whether the same behavior in T_{cs} occurs with EM cycling.

3.2. Effect of Rectangular Geometry

It has been observed that a rectangular shape in CICC cable can improve T_{cs} performance. The “EU-AltTF” CICC which has the same cable as an option 2 ITER TF CICC with the central cooling spiral removed is a case in point [14]. For the ITER TF CICC, $B_\parallel/B_{\Phi\,\max} = 0.127$, and its T_{cs} measurements showed degradation with EM cycling. Though the published data is a little ambiguous, the EU-AltTF CICC with its rectangular geometry of aspect ratio around 1.8:1 did not show much degradation while achieving higher T_{cs} than ITER TF CICC, especially when the CICC was oriented along an external magnetic field. Authors della Corte, Turtù, *et al.* attributed the different behavior and higher T_{cs} of the EU-AltTF CICC to reduced accumulated pressure and bending strain arising from Lorentz forces that are experienced internally by the cable strands [14, 15]. In this case, the rectangular geometry alone could give rise to better performance of Nb_3Sn CICC in general.

On the other hand, possible changes in the cabling due to the additional processing before jacket insertion and then compaction, as was found in the prototype EU-DEMO TF CICC sample, had not been accounted for. In particular, no measurements of the cable and sub-cable twist pitches were performed after compaction, which would have verified whether they remained the same in the EU-AltTF CICC cable [12].

Regardless, if the hypothesis is correct that the internal magnetic self-field of the CICC cable has a significant effect on relaxing strain in the Nb_3Sn cable strands in line with the observations on recent CICCs in [11], a consistent explanation for the increase in T_{cs} of the EU-DEMO TF CICC is that $B_\parallel$ is reduced with respect to B_Φ for cases of rectangular CICC compared to the circular CICC case. An argument supporting this conjecture is provided in the following section.

3.3. Change in Internal Self-field due to Geometry

From any standard text book on classical electromagnetics, the expression for the magnetostatic field $\boldsymbol{B}$ due to a current density $\boldsymbol{J}$ is given by the formula

$$\boldsymbol{B}(\boldsymbol{x}) = \frac{\mu_0}{4\pi}\int_V \boldsymbol{J}(\boldsymbol{x}') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} d^3x' \qquad (3)$$

where V is the volume over the superconducting cable [19]. Consider as in the CICC cable model of [11] that the cable is infinitely long and that $\boldsymbol{J}$ being the same all along the cable has translational symmetry along its length. With the cable length being along the z-axis, this means that $\boldsymbol{J}$ and $\boldsymbol{B}$ are both independent of the z coordinate. So,

$$\boldsymbol{B}(x,y) = \frac{\mu_0}{4\pi}\int_A dx'dy' \int_{-\infty}^{\infty} \boldsymbol{J}(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz' \qquad (4)$$

where A is over any cross section of the cable in the $x'y'$ plane. Then, we can do a coordinate translation along z' such that $z = 0$.

Now, if we decompose $\boldsymbol{J}$ as the sum of the transverse current density $\boldsymbol{J}_\perp$ and the longitudinal current density $\boldsymbol{J}_\parallel$, such that

$$\boldsymbol{J}(x,y) = \boldsymbol{J}_\perp(x,y) + \boldsymbol{J}_\parallel(x,y), \qquad (5)$$

then (4) can be split into the following two equations.

$$\boldsymbol{B}_\parallel(x,y) = \frac{\mu_0}{4\pi}\int_A dx'dy' \int_{-\infty}^{\infty} \boldsymbol{J}_\perp(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz' \qquad (6)$$

$$\boldsymbol{B}_\perp(x,y) = \frac{\mu_0}{4\pi}\int_A dx'dy' \int_{-\infty}^{\infty} \boldsymbol{J}_\parallel(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz' \qquad (7)$$

In the case of (6), we can note that the x and y components of the integrand are odd with respect to z', thus making the x and y components of $\boldsymbol{B}_\parallel$ zero upon integration, leaving only a z component. For (7), the integrand has no z component. We finally recognize that $\boldsymbol{B}_\parallel$ and $\boldsymbol{B}_\perp$ are respectively the longitudinal and transverse magnetic flux densities along the CICC cable. Due to the even symmetry of the integrands with respect to z' in (6) and (7), the equations can finally be expressed as

$$\boldsymbol{B}_{\parallel}(x,y) = \frac{\mu_0}{2\pi}\int_A dx'dy' \int_0^\infty \boldsymbol{J}_{\perp}(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz' \quad (8)$$

$$\boldsymbol{B}_{\perp}(x,y) = \frac{\mu_0}{2\pi}\int_A dx'dy' \int_0^\infty \boldsymbol{J}_{\parallel}(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz'. \quad (9)$$

Let us consider the magnitude of the integrand in (9) with θ being the angle between $\boldsymbol{J}_{\parallel}$ and the vector $\boldsymbol{x}-\boldsymbol{x}'$. For the self-field of the CICC, we are only interested in (x, y) that lie within A. Additionally, $|\boldsymbol{J}_{\parallel}|$ as well as $|\boldsymbol{J}_{\perp}|$ are finite within A. So, as $z' \to \infty$, the integrand tends to zero due to the factor $\sin\theta$ with $\theta \to 0$. This is compounded by the $1/|\boldsymbol{x}-\boldsymbol{x}'|^2$ factor in the integrand. We can conclude that for a given (x, y) in A, $|\boldsymbol{B}_{\perp}|$ is mostly determined by the integration up to some finite value R with respect to z' for the integral in (9). Explicitly,

$$\boldsymbol{B}_{\perp}(x,y) \backsimeq \frac{\mu_0}{2\pi}\int_A dx'dy' \int_0^R \boldsymbol{J}_{\parallel}(x',y') \times \frac{\boldsymbol{x}-\boldsymbol{x}'}{|\boldsymbol{x}-\boldsymbol{x}'|^3} dz'. \quad (10)$$

For a given cable cross section, R should be proportional to some factor of the characteristic length of the cross section. For a circular cross section, this would be the diameter (d). For a rectangular cross section, this would be the larger of either the width (a) or the height (b). If $\boldsymbol{J}_{\parallel}$ is considered to be incompressible, which should be the case for fixed void fraction, the shape or geometry of A may change but its area will not. And, the effect of altering A from circular to rectangular geometry with large aspect ratio (κ) will be to increase the value of R as the range of θ will be larger for the same z' in the integrand of (10). This should result in the increase of $|\boldsymbol{B}_{\perp}|$ as $|\boldsymbol{J}_{\parallel}|$ is assumed to be constant within A for the cable model. This argument does not apply to (8) given that the factor $\sin\theta \to 1$ with $\theta \to \pi/2$ as $z' \to \infty$, where in this case θ is the angle between $\boldsymbol{J}_{\perp}$ and the vector $\boldsymbol{x}-\boldsymbol{x}'$. Despite the change in geometry of A, the range of θ in (8) will not vary much for z' near R and deviations of $\sin\theta$ near $\theta = \pi/2$ are of second order.

Let us now consider (8) and (9) as $z' \to 0$. For a given z', $\boldsymbol{x}-\boldsymbol{x}'$ is such that $z' \leq |\boldsymbol{x}-\boldsymbol{x}'| \leq R'$, where R' is the largest distance between any point $\boldsymbol{x}$ and $\boldsymbol{x}'$. Altering A from circular to rectangular geometry still preserves the area of the cross section, as mentioned earlier. However, for rectangular A with $\kappa \equiv b/a \geq 1$, R' would be larger than for circular A. In fact, a fraction

$$\frac{|A_\Delta|}{|A|} = \frac{2}{\pi}\left(\cos^{-1}\sqrt{\frac{\pi}{4\kappa}} - \sqrt{\frac{\pi}{4\kappa}}\sqrt{1-\frac{\pi}{4\kappa}}\right) \quad (11)$$

of the circular area of A gets transposed outside the original domain of A after altering to rectangular A. If $\kappa \leq 4/\pi$, there are additional terms to (11) such that

$$\frac{|A_\Delta|}{|A|} = \frac{2}{\pi}\left(\cos^{-1}\sqrt{\frac{\pi}{4\kappa}} + \cos^{-1}\sqrt{\frac{\pi\kappa}{4}} - \sqrt{\frac{\pi}{4\kappa}}\sqrt{1-\frac{\pi}{4\kappa}} - \sqrt{\frac{\pi\kappa}{4}}\sqrt{1-\frac{\pi\kappa}{4}}\right) \quad (12)$$

becomes the fraction of A that gets transposed outside circular A.

The larger range of $|\boldsymbol{x}-\boldsymbol{x}'|$ for rectangular A reduces the integrands of (8) and (9) for the points $\boldsymbol{x}'$ that corresponded to the fraction $|A_\Delta|/|A|$ in circular A, due to the $1/|\boldsymbol{x}-\boldsymbol{x}'|^2$ factor. This results in a smaller integral after integrating over x' and y' compared to the case for circular A assuming uniform $|\boldsymbol{J}_{\perp}|$ and $|\boldsymbol{J}_{\parallel}|$. This effect is more pronounced as $z' \to 0$. Then, $|\boldsymbol{B}_{\parallel}|$ and $|\boldsymbol{B}_{\perp}|$ both decrease when altering A from circular to rectangular geometry with large κ. However, this effect is less pronounced for (9) as $\theta \to \pi/2$ and $\sin\theta \to 1$ for small z' and points $\boldsymbol{x}'$ that correspond to the fraction $|A_\Delta|/|A|$ in rectangular A. Therefore, the altering from circular to rectangular A with large κ decreases $|\boldsymbol{B}_{\parallel}|$ more compared to $|\boldsymbol{B}_{\perp}|$.

In conclusion, the change in $\boldsymbol{B}_{\parallel}$ relative to $\boldsymbol{B}_{\perp}$ is such that $|\boldsymbol{B}_{\parallel}|$ decreases with respect to $|\boldsymbol{B}_{\perp}|$ as A changes from circular to rectangular geometry, especially when $\kappa > 4/\pi$. Assuming that most of the contribution to $\boldsymbol{B}_{\perp}$ is the azimuthal component $\boldsymbol{B}_{\Phi}$, then the value of $B_{\parallel}/B_{\Phi\,\max}$ can also be expected to decrease with the change in the geometry of A.

4. DISCUSSION

4.1. EU-AltTF CICC vs. TFPRO2 OST2 CICC

As mentioned earlier, a rectangular CICC geometry with large aspect ratio alone could explain elevated T_{cs} measurements. However, the EU-AltTF CICC did not show initial increases in T_{cs} measurements with EM cycling. If the internal magnetic self-field has an effect on increasing T_{cs}, then to be consistent with prior observations and conjecture, it could be concluded that the change in CICC geometry was not sufficient to result in the change of $B_{\parallel}/B_{\Phi\,\max}$ so that $B_{\parallel}/B_{\Phi\,\max} \approx 0.11$.

Of course, the significance of $B_{\parallel}/B_{\Phi\,\max} \approx 0.11$ came about from the observation that the TFPRO2 OST2 CICC sample which to date showed the best T_{cs} performance amongst circular CICC designs has $B_{\parallel}/B_{\Phi\,\max} = 0.108$ as does the ITER CS CICC with STP cable, along with some other CICC samples with $B_{\parallel}/B_{\Phi\,\max} \approx 0.11$ showing less T_{cs} degradation than in ITER TF CICC and original ITER CS CICC designs [11, 20, 21]. So, the cable model for TFPRO2 OST2 was reexamined to see how sensitive the value of $B_{\parallel}/B_{\Phi\,\max}$ was to small changes in the parameters.

For the TFPRO2 OST2 CICC design, there was a simplification in the cable model in which both Cu and Nb_3Sn strands in the first stage sub-cable were assumed to be of same diameter, when in reality Cu strand was larger by 0.01 mm. If all strands in the first stage sub-cable were increased to 0.82 mm, $B_{\parallel}/B_{\Phi\,\max}$ would only increase to 0.109. In the case of TFPRO2 OST1 which showed degradation, there is a discrepancy in the literature regarding its final stage twist pitch. However, increasing this twist pitch from 460 mm to 470 mm, which is the range of the discrepancy, only decreases $B_{\|}/B_{\Phi\,\max}$ from 0.116 to 0.112. Taking both twist pitch and strand diameter into account, $B_{\|}/B_{\Phi\,\max}$ would only increase up to 0.118. As such, minor changes reflecting simplifications of the model or parameter discrepancies do not vastly affect the value of $B_{\|}/B_{\Phi\,\max}$, though an accumulative effect with multiple variations could possibly be significant.

What these results seem to point at is that the average internal magnetostatic self-field is fairly stable with respect to cable parameters, that the conditions for T_{cs} performance increase is not determined by the internal self-field alone and that though T_{cs} increase may not be highly sensitive to cable parameter values, the right combination of parameters is needed for this to occur. Further investigation with experiments on new or altered CICC samples should provide definitive answers.

4.2. Comparisons between Rectangular CICCs

The EU-AltTF CICC is not the only example of a Nb_3Sn CICC that has the same cable in a different jacket geometry. During development of the dipole magnet for EDIPO, a number of CICC designs were developed and tested. The first of a series of CICCs was “Subsam1” followed by “Pitsam1” [5, 22]. Information in published papers describe the two CICC designs to be different in only the rectangular dimensions, the thickness of the jacket and the cable void fraction, as detailed in Table IV.

TABLE IV
MAIN CHARACTERISTICS OF THE PROTOTYPE EU-DEMO TF CICC CABLE.

CICC Sample	Subsam1	Pitsam1
Nominal Current (kA)	20	21.2
Cable Dimensions (mm×mm)	12.5×9.9	17.9×6.3
Cable Layout	SUBSAM	
No. of Nb_3Sn strands		
1st stage	3	
2nd stage	9	
3rd stage	36	
4th stage	144	
No. of Cu strands	0	
Strand Radius, r_s (mm)	0.405	
r_i/r_s factors	(see Table II)	
Twist Pitch, λ_i (mm)		
1st stage	58	
2nd stage	95	
3rd stage	139	
4th stage	213	
Twist Pitch Ratio, β_λ	1.54	
Strand Current, j_s (A)	138.9	147.2
Void Fraction (%)	36	30

The calculated values of $B_{\|}/B_{\Phi\,\max}$ based on cable parameters alone for Subsam1 and Pitsam1 are both 0.039 because they have the same cable design. However, their cable aspect ratios are about 1.3:1 and 2.8:1 respectively. In addition, it is interesting to note that the calculated cross section area using the cable model of [11] is smaller than the actually measured areas of both cables, not taking into account the rounding of the inner corners. Of the two, Subsam1 has a larger cross section area than Pitsam1. The cable model always over estimates the cable size, so the larger actual cross section area would suggest large void fraction. This is the case for Subsam1 at 36%, but not so much for Pitsam1 whose void fraction of 30% is at about the level for ITER CICCs. For reference, the cable model predicts a theoretical void fraction of 32% with a circular cross section.

The T_{cs} measurements for each CICC sample were performed at different currents than at the expected operating current of EDIPO, which is 17 kA. This was so as to simulate the same Lorentz force load on the cables while testing them using the SULTAN test facility. The results of the tests are dramatically different with Subsam1 showing severe degradation and Pitsam1 showing very little at higher T_{cs} than that of Subsam1, despite the fact that Pitsam1 was tested at higher current. Explanation for this is attributed to the large void fraction of Subsam1, which allows larger transverse bending strain to occur in the cable strands during EM loading.

The significantly better performance of Pitsam1 is also attributed to its void fraction. However, CICCs with similar or smaller void fraction have also shown significant T_{cs} degradation including all CICCs recently studied with $B_{\|}/B_{\Phi\,\max} \approx 0.03$ [16]. What may be in play other than the reduction in accumulated pressure resulting from the rectangular cross section is the possible elongation of the cable and sub-cable twist pitches arising from the deformations during the CICC compaction process. Reaffirmation of the cable twist pitches before and after jacket compaction has not been reported for Pitsam1, nor for Subsam1. Moreover, the estimated diameter of the third stage sub-cable in Pitsam1 using the cable model is 4.9 mm which is more than 3/4 the height of the final cable. Thus, it is more than likely that the CICC cable was deformed with some elongation of the cable twist pitches prior to testing. The corresponding value of $B_{\|}/B_{\Phi\,\max}$ for Pitsam1 would be decreased by this, especially relative to Subsam1. Though this range of $B_{\|}/B_{\Phi\,\max}$ values will still not correspond to CICCs with observed increases in T_{cs} performance, it would be of interest with respect to CICCs with $B_{\|}/B_{\Phi\,\max} \approx 0.03$.

The CICC design “Pitsam3” is a rectangular CICC with the same cable design as “Pitsam2” which was studied previously along with “Pitsam5S” and “Pitsam5L” [11]. The only difference between Pitsam3 and Pitsam2 is that Pitsam3 is rectangular with a cable aspect ratio of 1.7:1 and Pitsam2 is square, as are Pitsam5S and Pitsam5L, with a cross section area that is slightly smaller than that of Pitsam3. $B_{\|}/B_{\Phi\,\max} = 0.032$ for both designs, based on cable parameters. The void fractions are also similar with Pitsam2 being reported to be 30.3% and Pitsam3 to be 30.8%.

The T_{cs} performance of both CICC samples degrade but to a lesser degree for Pitsam3 and with better overall performance than Pitsam2. The level of T_{cs} degradation in Pitsam3 matches that of Pitsam1, both CICCs being of rectangular geometry. So, it seems that for values of $B_{\|}/B_{\Phi\,\max} \approx 0.03$, the T_{cs} performance of CICCs is affected more by the cross section geometry, which may also have decreased the actual value of $B_{\|}/B_{\Phi\,\max}$ from the parameter based value for the CICC.

Considering only the square CICCs, T_{cs} performance is seen to improve with decreasing values of $B_{\|}/B_{\Phi\,\max}$. But, the performance level may be a consequence of β_{λ} which also decreases with higher performance. With this in consideration, comparison between all PITSAM layout CICC samples would place Pitsam3 between Pitsam2 and Pitsam5L or even perhaps after Pitsam5L, with the value of $B_{\|}/B_{\Phi\,\max}$ for Pitsam3 having been decreased due to its rectangular geometry and twist pitch elongation. On the other hand, the value of β_{λ} for Pitsam3 would lie between those for Pitsam5S and Pitsam2 in accordance with the same level of elongation in later stage sub-cable twist pitches as observed in the EU-DEMO TF CICC due to the compaction process to rectangular geometry. T_{cs} test results show that performance follows the sequence in $B_{\|}/B_{\Phi\,\max}$ and not β_{λ} [16]. In fact, looking at the initial T_{cs} values of the CICCs, the difference in T_{cs} between Pitsam5S and Pitsam2 is smaller than that between Pitsam2 and Pitsam5L, which is also the case for the values of $B_{\|}/B_{\Phi\,\max}$.

Using the above result and applying them to the SUBSAM layout CICCs, it can be seen that the initial T_{cs} values of Subsam1 and Pitsam1 CICC samples are also consistent with the order in $B_{\|}/B_{\Phi\,\max}$. Pitsam1 is deduced to have lower $B_{\|}/B_{\Phi\,\max}$ than Subsam1, and the initial T_{cs} of the Pitsam1 sample is about 6.9 K at 21.2 kA current with 11 T background field. The initial T_{cs} of the Subsam1 sample is about 6.1 K for 20 kA current and 11 T background field [22].

Any further detailed comparison directly between PITSAM and SUBSAM layout CICC samples is difficult due to the different cable layouts including different Nb_3Sn strand number and different testing conditions. Such comparisons would be similar to comparing ITER TF CICC with ITER CS CICC, and an overall comparison of all examined CICC designs has already been performed at a basic level in [11].

4.3. The MF SCH Layout CICC Cables

A final set of CICC cable designs that were also previously studied for their internal magnetostatic self-field characteristic is the set of cable designs that follow the Series-Connected Hybrid (SCH) magnet design of the hybrid magnet at the National High Magnetic Field Laboratory (NHMFL) in Tallahassee, Florida, particularly the mid-field (MF) CICC design [23, 24]. Short and long twist pitch cable versions of this design were fabricated for the 45 T hybrid magnet system at the High Field Magnet Laboratory (HFML) in Radboud University Nijmegen [25]. T_{cs} performance of these CICCs was evaluated at the SULTAN facility [26-28].

The $B_{\|}/B_{\Phi\,\max}$ value of the short twist pitch version of the "MF SCH" CICC cable was calculated to be around the 0.11 range for which increases in T_{cs} were observed for some CICC designs. However, this assumed a circular cross section, and the MF SCH layout design is rectangular with an aspect ratio of 2.0:1. From previous discussions, $B_{\|}/B_{\Phi\,\max}$ would be expected to decrease as a result of the rectangular geometry and twist pitch elongation. For example, a 20% elongation of the final stage cable twist pitch alone would lead to $B_{\|}/B_{\Phi\,\max} \approx 0.09$. This may explain the lack of definitive and consistent T_{cs} improvement with EM cycling for the CICC design.

Similarly to the EU-DEMO TF CICC, the void fractions of samples from both short and long twist pitch versions of the MF SCH CICC design are relatively small at 26.7% and 26.3% respectively. The predicted theoretical void fraction using the cable model of [11] with circular cross section gives 27%. However, the void fraction does not seem to be a major factor in performance as long as it is below some critical value which should be equal to or smaller than the value obtained from the cable model.

Besides different cable twist pitch, CICCs using the MF SCH CICC design were made with different strand and testing of them was performed under different conditions. Specifically, there is the first and original MF SCH CICC sample for the hybrid magnet at NHMFL, and there is the CICC sample for the 45 T magnet system at HFML whose results were studied [23, 25]. The samples are very similar and have the same cable design including twist pitch and cable layout. The difference in strand and testing conditions could be compared to the performance results, and this may lead to understanding of the average cable strain and in turn to the internal Lorentz forces of the cable. Sieving out the effects of the external field would give indication of the internal self-field which can be compared to prediction. This should be possible as the strands in both samples have been assumed to possess the same scaling parameters for the critical current density [29]. This is left for further study.

5. CONCLUSIONS

The T_{cs} performance test results of the EU-DEMO TF CICC sample demonstrate that T_{cs} increase with EM cycling can occur with rectangular Nb_3Sn CICC and with long twist pitch cabling. These results have been analyzed and found to be consistent with the possibility that the internal magnetic self-field of the CICC affects T_{cs} performance and may be partly responsible for T_{cs} increase to occur. However, other factors such as CICC geometry and void fraction have been shown to affect performance and may be more significant under various circumstances. Further tests on CICC samples as suggested throughout the paper should provide definitive answers.

Nevertheless, what has been established so far is guidance on what can be altered about a Nb_3Sn CICC cable to improve its T_{cs} performance given its design. Excluding the possibility of improving the Nb_3Sn strand performance, these are

- Altering the CICC cross section to a rectangular geometry with large κ;
- Reducing the cable void fraction, though reduction below a certain limit results in diminishing improvement;
- Adjusting the cable and sub-cable twist pitches such that $B_{\parallel}/B_{\Phi\,\max}$ either decreases or increases depending on the value of $B_{\parallel}/B_{\Phi\,\max}$ the cable initially possesses.

On the first and last points, the deformation of the CICC cable from circular to rectangular geometry may also significantly decrease $B_{\parallel}/B_{\Phi\,\max}$.

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