To the Optimization of Quench Performance for a Large Scale REBCO Conductor

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Abstract—REBCO conductors at the level of tens kiloamperes are being developed for their application in fusion magnets. One important aspect to study is their performance in the case of a quench event happens. A conductor should survive from such an event without over design; therefore, they should be properly optimized. Using a simulation model developed based on THEA code, we studied the parameters of a REBCO conductor in a fusion magnet for their influence on the quench performance, evaluated by hot spot temperature and quench detection. According to these results, the principles to the optimization of quench performance of a REBCO conductor are discussed.

Index Terms— High temperature superconductors, quench, cable-in-conduit conductor, THEA, thermal-hydraulic

I. INTRODUCTION

THE magnet employed with high temperature superconductor (HTS) is foreseen an enabling technology for the DEMO fusion reactor, no matter this reactor is a Tokamak [1, 2], Stellarator [3] or a compact Tokamak [4, 5]. Among the practical HTS materials, the rare-earth barium copper oxide (REBCO) is yet the most attractive one, as it has the best comprehensive performance comparing with its competitors: high or moderate critical current (I_c) at relatively high magnetic field or temperature, high tolerance against strain and stress, and REBCO tapes are selling as end products demanding no more heat treatment for manufacturing a conductor. The main drawback would be the highest price valued in $\$/\text{kA}\cdot\text{m}$ [6]. Another unfavorable feature comes from its geometry: REBCO wire with the practical I_c and length can only be achieved when it is manufactured as tape with biaxial texture. As a result, the classic cable-in-conduit-conductor (CICC), which is well developed for low temperature superconductors (LTS) like NbTi and Nb₃Sn round wires, is not directly usable for REBCO tapes with large aspect ratio [6]. EPFL-SPC has developed a 50 kA REBCO conductor for the Central Solenoid (CS) of EU-DEMO. Tens of REBCO tapes are first stacked in two semicircular copper profiles with rectangular slots. Then they are twisted and soldered together,

Figure 1. Sketch of the copper cored Rutherford cable conductor being developed at EPFL-SPC, from [11]. Helium is supposed to flow through the void.

becoming the so-called strand. A certain number of strands are then twisted around a copper core and jacketed with stainless steel [2]. Figure 1 is a sketch of such a conductor.

As a rather new concept, such a conductor still needs a lot of R&D work to be fully prepared for practical use, especially in an expensive fusion reactor. One important aspect would be an optimization on its quench performance, which is regarded as a concern for all HTS conductors. Once a quench is initiated in such a conductor, the normal zone propagates rather slowly as well as the corresponding resistive voltage. As the quench might be difficult to be recognized by resistive voltage from the inductive noises, the delayed detection could eventually result into a very high hot spot temperature [7]. However, knowledge about this is relatively difficult to obtain. On one hand, quench experiments on tapes or simple coils are of limited help for understanding the behavior of a large conductor [8, 9]. On the other hand, only few test facilities can implement a meaningful quench experiment on a large conductor [10]. As a result, the main method to access the quench performance of an HTS conductors is using specifically developed numerical codes, like THEA and 4C. Over the last few years, quench simulation of HTS conductors has processed from imitating the approach of LTS CICC to respecting the features of HTS conductors and is giving more and more convincing results [11, 12]. The next step would be using these tools to find the optimized parameters of an HTS conductor, as R. Heller et al have done [13].

We have developed a simulation model based on the THEA code with 1-D analysis, which can simulate the unique features

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of REBCO conductors, for example the angular dependent I_c against magnetic field [11, 14]. With this model, some interesting questions could be answered. A representative one is: does the angle between adjacent strands (actually the tape stacks inside) have important influence on conductor's quench behavior? The answer will decide should this angle be carefully controlled during conductor manufacturing to avoid unexpected quench performance.

In this paper, we investigate the parameters of a REBCO conductor to figure out how it should be optimized in view of its quench performance. The analysis focusses on the hot spot temperature and quench detection, the latter including normal velocity (NZPV), time from quench initiation to detection (t_{dec}), the normal zone length needed for the detection voltage (Nl_d). Those parameters are roughly divided into three groups: (1) design parameters of a conductor, including: current sharing temperature (T_{cs}), copper current density (J_{Cu}), copper residual resistance ratio (RRR), twist pitch of tape stack and angle of adjacent strands' orientation (θ_s); (2) some parameters that could vary in a moderate range, including: inter-strand electrical contact resistance (ECR), n -value of REBCO tapes and magnetic field; (3) some parameters are not free to choose as they are restricted by the whole machine, including: helium mass flow rate, quench detection voltage (V_d) and time constant for current dump (t_{dump}). Although some of these parameters were also studied by R. Heller [13], here they are repeated again to form a complete conclusion.

II. DESCRIPTION OF THE SIMULATION MODEL

The modelling of a quench in REBCO conductor is implemented by solving 1-D thermal, electrical, and hydraulic equation sets, as well as their coupling, with THEA code. Considering that the principles of the code were already well explained by the authors and some users [13, 15-17], meanwhile our REBCO model was also detailed introduced in our former publications [11, 14], they are only briefly recalled here.

Originated from simulating LTS cables (or conductors), 1-D analysis (as with THEA) is based on the fact that the establishment of thermal equilibrium over the cross section happens very fast. It is especially true for CICC: (1) despite that a cable is usually composed of hundreds of LTS strands, each slim strand can be directly cooled by helium filling up the void in the bundle region with a rather high convection heat transfer coefficient; (2) at the same time, helium has much higher specific heat capacity (constant volume, C_v) than the solid materials—as compared in Figure 2 (data from [18])—at temperature below 20 K, which perfectly covers the critical temperature (T_c) of LTS materials (9.5 K for NbTi and 18 K for Nb₃Sn). As a result, there is unlikely temperature difference over the cable cross section and the whole cable can be regarded as one big porous wire. A 1-D thermal-hydraulic analysis can predict well its quench behavior, as was verified by the QUELL experiment [19, 20].

In the case of REBCO conductor, there are several different conditions: (1) the diameter of strand is about ten times higher;

Figure 2. Heat capacity per unit volume of materials. The change of helium density is also given.

Figure 3. I_c of one strand at 17.5 T, with different θ and T , from [11]. Note in the conductor, if two adjacent strands (stacks) have a deflection, their I_c will be different at the same location.

(2) the number of strands is much reduced, but their local I_c could be of significant difference due to the anisotropy of REBCO tape; (3) strands could still keep considerable I_c at temperature above 20 K due to the high T_c . The first difference could make the heat transfer between helium and strands (and the tapes inside) not efficient. The second one makes that even the temperature of strands being the same, their joule heating might be different. Whereas due to the last fact, the minimum quench energy could lead to a high temperature, at which the heat capacity of solid materials starts to exceed that of helium. The last fact was also discussed by S. Hahn [21], who suggested to use “thermal runaway temperature” rather than “current sharing temperature” for the analysis of HTS quench since the difference of these two for HTS are much larger than for LTS.

Based on the above facts, we have developed a multi-monolithic-strands model, evolving thermal, electrical, and hydraulic analysis to study the quench of REBCO conductor. Instead of thinking the whole cable as one element, the assumption of uniform properties is only applied on each strand. Such assumption was numerically proved to be reasonable for a soldered strand [11]. Figure 3 gives an example of the distribution of I_c of each strand used in the simulation as function of the angle between magnet field and the normal direction of REBCO tape. The detailed scaling approach of I_c as function of temperature, magnetic field and the angle can be

Table 1. Parameters of the REBCO conductor

Parameter	Reference value	Varying range
Operating temperature (K)	4.75	No
Operating current (kA)	50.9	No
Maximum magnetic field (T)	17.5	5-17.5
Current sharing temperature (K)	~10.5	6.5-20
Ratio of operating current to (minimum) critical current	0.8	0.35-0.95
Number of strands	12	No
Strand diameter (mm)	7.2	No
Number of REBCO tapes in each strand	39	Follows
Tape width (mm)	4	No
Tape thickness (mm)	0.095	No
Fraction of tape composition: REBCO: Cu: Hastelloy: Ag	1:40:50:4	No
Copper area in each strand (mm ²)	32	32-53
Total cross section of one strand (mm ²)	40.7	Follows
Copper area in core (mm ²)	189	95-760
Copper current density (A/mm ²)	89	62-147
RRR of copper	30	30-500
Twist pitch of tape stack (m)	0.4	0.2-10
angle of adjacent strands' orientation (°)	30	0-90
Inter-strand electrical contact resistance ($\Omega \cdot m$)	2×10^{-6}	2×10^{-8} - 2×10^{-2}
Steel area (mm ²)	2588	No
Helium area (mm ²)	151	No
Hydraulic diameter (mm)	1.52	No
Helium inlet pressure (bar)	6	No
Mass flow rate of helium (g/s)	5	1-8
Critical electric field (V/m)	1×10^{-4}	No
n-value (n-index)	40	20-60
Voltage threshold for quench detection (mV)	100	10-500
Time constant for current dump (s)	20	5-35
Conductor length (m)	150	No

found in [14].

The quench process in this study is divided into four steps. First it is initiated by the minimum quench energy (MQE), which is determined by a try-and-error approach, corresponding to a disturbance with 1 cm and 1 ms. The energy is deposited into one strand at the region with lowest J_c (74 m of the total 150 m in this case). Then the quench is developed freely until the resistive voltage exceeds the detection threshold value (V_d). After detection, 1.1 s is waited for quench validation and quench protection system operation. Finally, dump the current in conductor exponentially with a time constant t_{dump} and the magnetic field follows. A detailed description of the quench process is presented in [11]. In this paper, to evaluate the quench performance, the maximum hot spot temperatures (T_{max}) of strands (the highest of the 12, in most cases they are very close, also see [11]), copper core, helium and jacket are presented in next section for comparison. NZPV, t_{dec} , and NL_d are also presented to better understand the quench

behavior. MQE is only given for reference. As this paper focus on quench performance, only T_{max} , NZPV, t_{dec} and NL_d are discussed. MQE, which is a measurement of conductor's stability, is only given as an input parameter, but not discussed. The parameters concerning quench modelling of the REBCO conductor are listed in Table 1. For the parameters to study, both reference values and the varying ranges are given. Some parameters will follow others when the latter change. In the below results, any parameter takes the reference value unless it is the one for study.

III. RESULTS AND DISCUSSION

A. Design parameters of conductor

1) Current sharing temperature

T_{cs} at the region with highest magnetic field, or temperature margin, is an important design parameter, at least for LTS conductors [22]. In the case of LTS conductors, the motivation for a sufficiently high T_{cs} is to ensure the stability. On the other hand, the higher T_{cs} is, the more inefficient usage of the superconductor, since T_{cs} is directly related to the amount of superconducting wires in the conductor. For HTS, stability would not be an issue, but the quench behavior might also be influenced by T_{cs} .

Figure 4 shows the T_{max} of the four components of the HTS conductor. The notable difference among them was discussed in [14] and ascribed to the relatively poor transverse heat transfer. Apparently, higher T_{cs} is not beneficial to the quench

Figure 4 Quench behavior of the conductor as function of T_{cs} .

behavior of HTS conductor at all. Although higher T_{cs} brings more available I_c and postpones the heat generation, it also slows down the normal zone propagation and quench detection. Increasing T_{cs} from 10 K to 20 K, the latter effect becomes dominant and T_{max} is increased by about 30 K.

There is another thing could be noted from NL_d . For higher T_{cs} , the normal zone length needed for detection is also shorter. This is because the electrical resistance of copper is increasing with temperature significantly above 20 K. Such situation is quite different with LTS conductor, in which NZPV is much faster, so a quench can be detected more earlier. Consequently, temperature is usually much lower when a quench is detected. Therefore, the length of normal zone is the major contribution to the resistive voltage.

From these results, high T_{cs} would not be preferred concerning quench protection of HTS conductors.

2) Copper current density

Initially, copper was introduced to LTS wires as stabilizer: without it LTS couldn't work [23]. In CICC, additional copper wires are also cabled together with superconducting wires for quench protection, which further reduces the quench current density and heat generation. For HTS conductors, the latter function is more likely why copper should be employed since HTS conductors are very stable. In this sense, copper in HTS conductors shouldn't be called "stabilizer". Instead, "quench protection material", or "quench protector" would be better names.

Whatever the name, it can be foreseen the importance of copper on quench behavior, which is however a contradiction. On one hand, as mentioned above, more copper in a conductor would release the heat generation during a quench. On the other hand, with same current and normal zone length, the voltage is lower due to the lower resistance, which means a slower quench detection.

Figure 5 shows the quench behavior of the HTS conductor with different J_{Cu} . From the results of T_{max} , one can conclude that, at least for this HTS conductor, more copper is preferred for quench protection. The effect of heat generation dominates the quench behavior instead of normal zone propagation. Twice the copper cross section from the reference case, hot spot temperature can be reduced by more than 70 K, though quench would be detected later for more than 10 s. Although more copper reduces the current density of the whole conductor, for conductors in CS coils in Tokamaks, it would be less a problem. The main negative factor for conductor current density comes from the large amount of steel needed to protect the conductor from hoop stress. Double copper cross section from the reference value only decrease the current density for about 16%.

It should be noted that, in the HTS conductor studied in this paper, there are basically two types of copper, which is similar as in the case of LTS CICC. One is the copper in the strand, i.e. from the tape and profile. The other type is the copper core. Their difference is the ease of current sharing: current must go through higher resistance in the latter case. With the reference parameters, these two types of copper play very similar roles. Therefore, if more copper is needed, it could be added wherever

is convenient.

Figure 5. Quench behavior of the conductor as function of J_{Cu} . Solids symbols are for varying copper in strand, open symbols are for varying copper in core.

Figure 6. Quench behavior of the conductor as function of RRR .

3) Residual Resistance Ratio

The resistivity of copper at low temperature also depends on its RRR, so RRR could also influence the quench behavior, as figure 6 shows. $T_{\max}$ decreases with RRR increasing, but the effect is limited, NZPV, t_{dec} and NL_d as well. When RRR is higher than 300, increase it further doesn't help a lot. Changing RRR from 30, which is the reference value, to 300 (or 500, nearly the same), $T_{\max}$ decreases by about 30 K. Anyway, RRR must be considered together with the copper amount, as well as the total expense.

4) Twist pitch and θ_s

These two parameters are unique for REBCO conductors with twisted stacked tapes, as shown in Figure 7. The orientation of one strand is actually the one of the REBCO stack inside, as explained above. REBCO tapes have anisotropic I_c with respect to magnetic field. Twisting it results into non-uniform I_c along longitudinal direction, which is also a function of the twist pitch. The tapes in each strand have the same orientation, i.e. the same I_c , but those in different ones could not. Therefore, a question is, does θ_s have important influence on quench behavior of the conductor? A series combination of twist pitch and θ_s are considered to answer it. Note that in a real conductor, twisting happens both at the stack and cable level. In this simulation, the twist pitch is regarded as the total effect of these two. Although in the flat part twist of cable is not really happening, it is regarded a minor effect and is not discussed in this simulation for simplicity.

Figure 8 shows the quench behavior of the HTS conductor with respect to twist pitch, considering θ_s is 30° , with which the orientation of 12 strands composes 360° . Increasing the twist pitch from 0.2 m to 1 m, $T_{\max}$ reduces by about 10 K. If the twist pitch is longer, $T_{\max}$ starts to increase. The maximum, which is about 40 K higher than the minimum, is achieved with a twist pitch of 7.5 m. Such results indicate that there would be a twist pitch, with which a minimum $T_{\max}$ can be achieved. Figure 8(b) shows the parameters concerning quench propagation.

The fundamental reason why twist pitch plays a role on quench performance is, it decides the length of the I_c peak in one strand. The longitudinal heat transfer in the conductor mainly depends on the thermal conductance of materials and mass flow rate of forced helium, which doesn't change with twist pitch. Taking one strand for example, when twist pitch is rather short (<1 m), heat flux can pass through the I_c peak very easily, so normal zone propagation velocity is hardly blocked by this peak. On the contrary, if twist pitch is very long (>5 m, almost equivalent to a non-twisted cable), the normal zone will stay in $1/4$ twist pitch almost for the whole quench process. If twist pitch is in a moderate range, the normal zone will have to go across one wide I_c peak. When other strands are also taken into account, the situation is more complicated. While one strand is at the I_c valley, others are either on the hillside or the peak, as is shown in Figure 9. The ultimate result is what presented in Figure 8.

Figure 10 shows the quench behavior of the HTS conductor with different θ_s . The twist pitch is fixed as 0.4 m. It can be seen that $T_{\max}$ hardly changes with different θ_s in the range of $0-90^\circ$:

the variation is less than 2 K and the change of t_{dec} is also less

Figure 7. Sketch of the twist pitch of a strand and the angle of adjacent strands' orientation.

Figure 8. Quench behavior of the conductor as function of twist pitch.

Figure 9. The change of I_c in half twist pitch of strands. Twist pitch is 0.4 m, and θ_s is 30° . I_c of the other 6 strands duplicate with these 6. The average I_c of one strand also shows a periodic peak.

Figure 10. Quench behavior of the conductor as function of θ_s .

Figure 11. Quench behavior of the conductor as function of θ_s at different twist pitch.

news for cable manufacturing.

On the other hand, the influence of θ_s on quench behavior of the conductor is related to the twist pitch, as is shown in Figure 11. In Figure 11, the quench behavior as function of θ_s , is shown with three different twist pitches, representing respectively short (0.4 m), moderate (1 m) and long (5 m) twist pitch. With short twist pitch, as already discussed above, θ_s has little influence on quench behavior. When twist pitch goes to moderate, the maximum difference is up to about 15 K. Such difference increases to above 20 K when twist pitch is longer. Summarizing the above results, there are two ways to deal with twist pitch and θ_s . One is to choose certain values for them, 1 m and 30° respectively in this case, to have a minimum T_{max} . Another one is to keep a short twist pitch, for example 0.4 m, to avoid uncertainty of quench behavior due to the θ_s , which can release the conductor manufacture.

The reason why twist pitch and θ_s can affect the quench behavior, is because they decide the I_c variation along the conductor length. In view of this, the electrical contact resistance (ECR) between strands, as well as between strand and the copper core, would also be especially important for the twisted REBCO conductor, since it decides the ease of current bypass among strands. If ECR is too high, current in the quenched strand will be difficult to transfer to the neighbor strands, who could still have spare I_c .

B. Varying parameters

1) Inter-strand electrical contact resistance

Although there are some methods to change the inter-strand ECR, as in the case of LTS conductors, it is difficult to precisely control it, since it depends on too many parameters: temperature, contact pressure, roughness and so on. In view of this, a wide range of ECR is considered for the influence on quench behavior, with the reference twist pitch and θ_s , as shown in Figure 12. When ECR is varying within $2 \times 10^{-8} - 2 \times 10^{-5} \Omega \cdot m$, T_{max} hardly changes, despite lower ECR delays quench detection. That is, when ECR is increasing in this range, on one hand, current is easier to transfer from the normal part of one strand to the neighbors which can offer more space for superconducting current, so heat generation is reduced in the quench process. On the other hand, as quench detection is delayed, heat generation happens in a longer time. According to the measurement of N. Bykovsky [24], ECR in such REBCO conductor is around $2 \times 10^{-5} \Omega \cdot m$. If similar manufacture process is adopted as that sample, un-predictable quench behavior is unlikely to happen because of ECR. On the other hand, if ECR is intentionally enhanced to reduce the coupling loss, T_{max} will significantly increase averagely 35 K for ECR increasing for one order of magnitude. Besides, the maximum temperature gradually moves from copper core to strands, which indicates that current is locked in each strand and the copper core doesn't help reduce heat generation anymore. Therefore, if the strands are plated with high resistance layer to reduce coupling loss, it would be better to increase the copper cross section in each strand, instead of using a thick copper core.

2) n-value

Another parameter that is rather random is the n-value of the

than 1 s. This means that θ_s can be left it be, which are good

tapes, which could differ with the manufacturer, cabling process, temperature, magnetic field and so on. As for quench behavior, n -value will decide both quench detection and heat generation. A very high n -value means the HTS tapes, as well as the total cable, will have neglectable resistance/voltage so long as the temperature is lower than T_{cs} . However, once T_{cs} is exceed, higher n -value results into both higher resistance and voltage signals. Such complex phenomenon can also only be studied by simulation.

Figure 13 shows the quench behavior with different n -values. The relations of T_{max} , NZPV and n -value are quite simple. The higher is the n -value, the faster is normal zone propagation and the lower is the T_{max} , but the influence on T_{max} is very small (less than 5 K changing n -value from 20 to 60). Therefore, n -

Figure 12. Quench behavior of the conductor as function of ECR.

Figure 13. Quench behavior of the conductor as function of n -value.

Figure 14. Quench behavior of the conductor as function of magnetic field.

Figure 15. Quench behavior of the conductor as function of I_{op}/I_c . Solids symbols are for varying T_{cs} , open symbols are for varying field.

value is eventually of little importance concerning quench performance for REBCO conductors.

3) Magnetic field

One more parameter that potentially has large influence on quench behavior, but is less a design parameter for the conductor, is the magnetic field, which could change in the coil winding. Figure 14 shows the quench behavior as function of magnetic field. Clearly, when quench is initiated at low field region, slower quench propagation and higher hot spot temperature would be expected, despite that much higher energy is needed to quench the conductor at low field region. In this sense, when using REBCO conductor, a graded layer winding, as is designed for Euro-DEMO CS [2], is better than pancake winding, since the former has less field variation along the conductor.

4) I_{op}/I_c

The major influence of magnetic field is the I_c . Lower field means higher I_c , that is lower I_{op}/I_c , which is similar as the influence of T_{cs} . Converting the x-axis of figure 4 and 14 into I_{op}/I_c for these cases and put the data together, a plot of T_{max} as function of I_{op}/I_c is shown in figure 15. Interestingly, no matter how the change of I_{op}/I_c happens, the relation between T_{max} and I_{op}/I_c appears a similar trend, especially at lower I_{op}/I_c . The same for NZPV, t_{dec} and NL_d . Such result indicates that for HTS conductors, it is better to operate them without very large current margin, especially considering their good stability.

C. Global parameters

1) helium flow rate

Helium flow, which depends on the power of cryogenic system, friction in conductor and conductor length, is not totally free to choose, but is also an important parameter for quench behavior of REBCO conductor, as shown in figure 16. The relation between T_{max} and mass flow rate is very simple: T_{max} decreases as mass flow rate increases, significantly. NZPV also increases monotonically with mass flow rate. On the other hand, there is still a little trick about the effect of mass flow rate, which can be seen from the detection time and the normal zone length. With higher mass flow rate, quench is detected later with the resistive voltage, although NZPV is faster. An explanation to this interesting result is, in the case of high mass flow rate, better cooling capability lower the temperature of the cable and so does the resistance, therefore longer length is needed to reach the same resistive voltage. Although helium flow with higher speed also helps heat transfer in longitudinal direction, so higher NZPV is achieved, NL_d increases more significantly. Finally, quench is detected later. Anyway, as the price to enhance mass flow rate is increasing, it must be considered comprehensively together with many other aspects.

2) Detection voltage

In CS coil, the resistive voltage for quench detection must be distinguished from all the inductive noises. Therefore, the threshold voltage for quench detection could be limited. In the above cases, a threshold of 100 mV is assumed. It is important to know if the real threshold is higher, how much would the T_{max} increase and if it is worthy to achieve much lower

Figure 16. Quench behavior of the conductor as function of helium mass flow rate.

Figure 17. T_{max} of strand components as function of detection voltage.

Figure 18. T_{max} of strand components as function of t_{dump} .

threshold. Figure 17 answers these questions. Increase the threshold from 100 mV to 500 mV, T_{max} will increase for more than 100 K. In such case, other means must be adopted to inhibit T_{max} , like adding more copper into the conductor. On the other hand, if the threshold could be achieved as only 10 mV, T_{max} could also be greatly reduced by about 75 K, which leaves a lot of spaces for other design aspects, including helium flow.

3) Time constant for current dump

In above simulation, the t_{dump} is chosen as 20 s. This parameter is limited by the inductive voltage and the safety operation of other components, like vacuum vessel, and it also has a big influence on the quench behavior of the conductor, as shown in figure 18. The t_{dump} also has significant influence on T_{max} . If due to whatever reason, t_{dump} is set as 35 s, then again large amount of copper in the conductor or high mass flow rate of helium would be needed.

IV. CONCLUSION

For a REBCO conductor, fast normal zone propagation doesn't always result into fast quench detection and low hot spot temperature. Therefore, when optimizing it, it is better to discuss a parameter for the influence on T_{max} , which is the ultimate target.

Among the design parameters for REBCO conductor, copper current density or copper cross section, as well as its RRR, has the most important influence on quench behavior. In the CS coil where hoop stress is very high and large amount of steel is needed, double copper cross section from the reference value would reduce T_{max} for about 70 K, whereas the conductor current density only decreases for about 16%. Increasing RRR from 30 to 300, T_{max} decreases for about 30 K, but higher RRR hardly changes T_{max} . For REBCO conductor, too high T_{cs} not only wastes the expensive HTS tape, but also worsen the quench behavior: quench detection is delayed, and hot spot temperature is raised. Although a moderate twist pitch around 1 m results into a lowest T_{max} , keep it as low as possible can avoid the influence of the angle between each two strands on quench behavior, therefore releases the cabling process.

ECR has little influence on T_{max} so long as it stays in the range of $2 \times 10^{-8} - 2 \times 10^{-5} \Omega \cdot m$. Further decreasing it results into an increase of T_{max} for 35 K per orders of magnitude. The effect of the magnetic field where a quench happens, supports the degraded layer winding, since in low field region, quench detection is strongly delayed and T_{max} is increased. The n -value has very little influence. Varying from 20 to 60, T_{max} only changes for about 5 K.

Helium mass flow rate, detection voltage and t_{dump} all have significant influence on quench behavior but are not free to choose. The available values (or at least ranges) of these parameters must be considered during conductor design.

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