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THERMOHYDRAULIC-QUENCHING SIMULATION FOR SUPERCONDUCTING MAGNETS MADE OF YBCO HTS TAPE

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ABSTRACT

A thermohydraulic-quench code “Solxport3D-Quench” developed in MIT has been modified to simulate the thermohydraulic-quench behavior of a YBCO-made superconducting cable. The YBCO tape property subroutines are summarized in this report based on SuperPower database, they include subroutines for critical current density, critical temperature, current sharing temperature, specific heat and thermal conductivity. Several sample simulations including superconducting and quench mode are performed for demonstration.

CONTENTS

1. Introduction

More superconductor magnet designers are considering to use HTS instead of LTS for the superconducting cable. YBCO HTS is definitely the first choice of the HTS cable candidate in consideration of future price and mechanical properties.

A thermohydraulic-quench code "Solxport3D-Quench" developed in MIT [1] has been modified to simulate the thermohydraulic-quench behavior of YBCO-made superconducting cable. The YBCO tape property subroutines are summarized in this report, it includes subroutines for critical current density, critical temperature, current sharing temperature, specific heat and thermal conductivity. Several sample simulations are performed for demonstration.

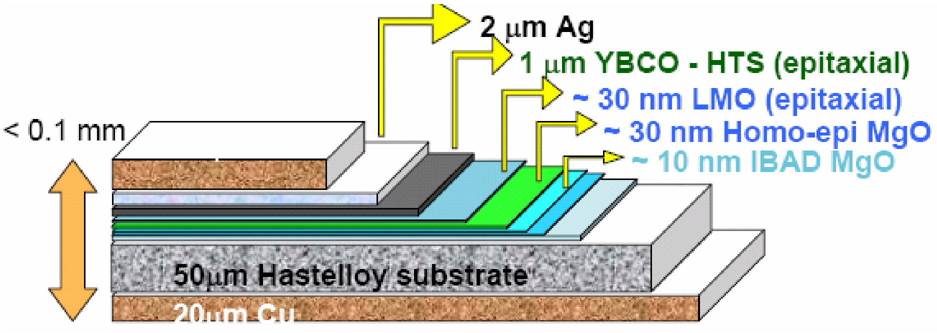


Fig. 1 Cross section of 2G YBCO tape (4mm wide and 0.1mm thick) [2]

Table 1: Component dimension of YBCO tape

	Thickness (μm)	Volume fraction f_i
YBCO layer	1	0.01075
silver overlayer	2	0.0215
copper stabilizer	40	0.43
stainless steel	50	0.5376

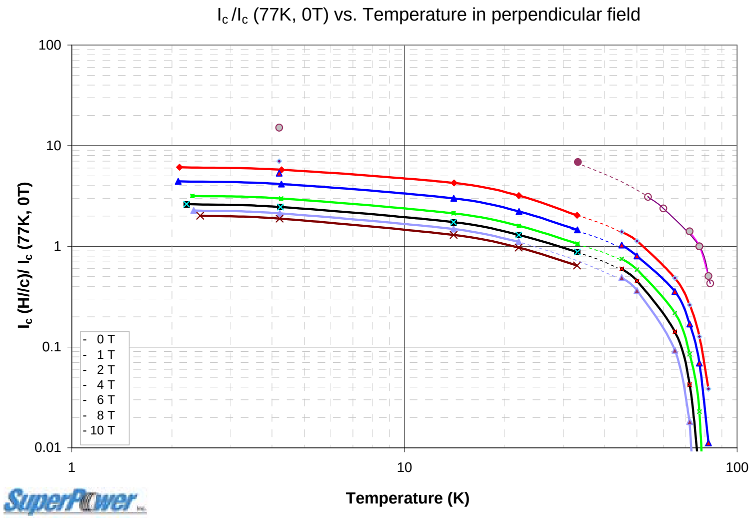


Fig. 2 Graph of the raw data for the relative critical current density of YBCO [2]

Table 2 Raw data of the relative critical current density of YBCO [2]

B (T)	T (K)	Ic /Ico (77K, 0T)	Corrected Ic /Ico
0	4.2	15.123	Same with the left
0	14	9.934	
0	33	6.689	
0	54	3.095	
0	60	2.381	
0	72	1.411	
0	77	1.0005	
0	82	0.5064	
0	83	0.4286	
1	2.107	6.112	
1	4.269	5.766	
1	14.09	4.2167	
1	22.09	3.196	
1	33.029	2.037	
1	45	1.394	
1	50	1.13157	
1	65	0.4855	
1	72	0.26195	
1	77	0.1269	
1	82	0.03843	
2	2.089	4.4299	
2	4.264	4.1589	
2	14.074	3	
2	22.097	2.224	
2	33.116	1.4579	
2	45	1.031	
2	50	0.803	
2	65	0.3568	
2	72	0.1689	
2	77	0.06919	
2	82	0.0119	
4	2.303	3.168	
4	4.256	2.99065	
4	14.056	2.13084	
4	22.093	1.598	
4	33.12	1.0654	
4	45	0.75095	
4	50	0.58736	
4	65	0.21822	
4	72	0.08512	
4	77	0.0228	
6	2.212	2.626	
6	4.238	2.4579	
6	14.06	1.738	
6	22.086	1.299	
6	33.094	0.8785	
6	45	0.59897	
6	50	0.45462	
6	65	0.1416	
6	72	0.04234	
8	2.325	2.271	

8	4.222	2.1308	
8	14.05	1.486	
8	22.07	1.112	
8	45	0.59897	0.4898
8	50	0.45462	0.36469
8	65	0.1416	0.09311
8	72	0.04234	0.01811
10	2.431	2.0187	Same with the left
10	4.214	1.888	
10	14.051	1.299	
10	22.05	0.97196	
10	33	0.64486	

Note: the critical current density of YBCO tape (4mm x 0.1mm) at 77K and 0T is assumed to be 250 A/mm^2 .[3]

2. Code logic [1]

The simulation starts from superconducting stage for each magnet coil. The superconducting stage switches to quench stage if anyone of the superconducting magnets quenches (i.e., exceeding the current sharing temperature.) It is followed by the dumping stage after a given quench detection time. The recovery of the superconducting stage is allowed at any time step before dumping. The currents of each magnetic coil are calculated by a time-difference method. The thermohydraulic parameters during superconducting and quench/dumping stage are obtained by a finite element method. The size and location of each finite element are dynamically defined at each time step during quench and dumping.

The general logic flow chart is shown in Fig. 3, in which the definitions are followed: $Tst<Tcs$ for superconducting mode, $Tst>Tcs$ for quench mode; Superconducting stage if all channels are in superconducting mode, quench stage if at least one of channels are in quench mode, dumping stage if $Vnmax \geq Vq$ for $time \geq dtimeq$ in quench stage; "nquenchflag" is a flag parameter to define different modes, nquenchflag=1 for superconducting mode, nquenchflag=2 for quench mode; nquenchflag=3 if the whole coil recovers back to superconducting mode from quench mode.

The simulation enters the quench stage if $Tst>Tcs$ at any location within the coil. During quench stage, at the beginning of each time cycle, the code calculates the critical lengths of each channel. The critical lengths are defined as: current sharing length "cslength' in which all the strand temperatures Tst are greater than the current sharing temperature Tcs, i.e., $Tst>Tcs$; normal length 'crlength' in which all the strand temperatures Tst are higher than the critical temperature Tcr, i.e., $Tst>Tcr$. If cslength =0, the code would calculate this channel in superconducting mode by using the basic mesh defined at the beginning of the simulation. However, if cslength>0, the code would first remesh the channel, and then calculate the thermohydraulic data based on the new mesh. Finally all thermohydraulic results would be converted back into those based on the basic mesh before the next round time cycle. The remesh is carried out by dividing the simulated channel into 3 zones: normal zone with strand temperature greater than the critical temperature, i.e., $Tst>Tcr$, quench front zone (i.e., transition zone) with large temperature gradient from the normal zone, and the superconducting zone which are those regions beyond the quench front zone.

The meshes in both the normal zone and the quench front zone are refined at given divisions while the mesh in the superconducting zone still uses the basic mesh. The time step in the quench stage is adopted either based on given energy change rate or based on the input from the users. If the maximum voltage “Vnmax” for each double pancake exceeds a given value “Vq” (i.e., quench starts) continuously for a given time window “dtimeq” (i.e., quench detection time), the simulation would enter dumping stage, in which all the superconducting coils are switched into “resistance” mode.

At the beginning of the dumping stage, all the control modes are switched into “resistance”, i.e., all coils are no longer in current control mode, and the dumping circuits are included into the model. The current scenarios must be re-calculated in each coil at each time step during dumping. The recovery of the superconducting stage is not allowed. However, some coils could be in a superconducting mode and therefore be simulated using the basic mesh if their critical length remains at zero.

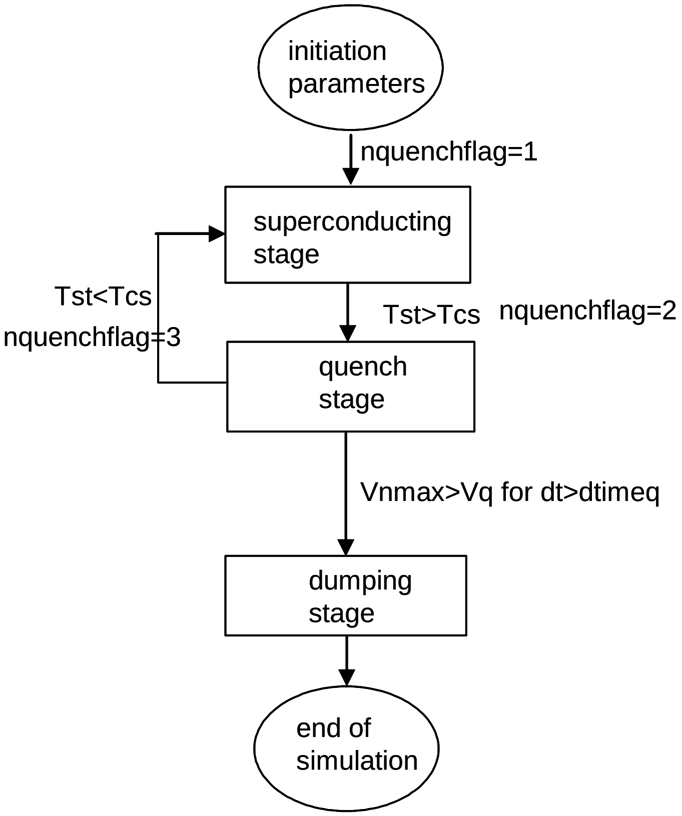


Fig. 3 General flow chart of the thermohydraulic-quench code.

3. YBCO property subroutines

3.1 Critical current density

The subroutine is written based on the updated SuperPower data base [2] to cover B field up to 15T. The updated database is listed in Table 3, and the graphs are shown in Figs. 4 and 5.

Table 3 Updated data base of the relative critical current density of YBCO

B (T)	T (K)	Ic /Ico (77K, 0T)
0.00E+00	2	15.8
0.00E+00	4.2	15.123
0.00E+00	14	9.934
0.00E+00	33	6.689
0.00E+00	54	3.095
0.00E+00	60	2.381
0.00E+00	72	1.411
0.00E+00	77	1.0005
0.00E+00	82	0.5064
0.00E+00	83	0.4286
0.00E+00	88	0.00E+00
1	2	6.2
1	2.107	6.112
1	4.269	5.766
1	14.09	4.2617
1	22.09	3.196
1	33.029	2.037
1	45	1.394
1	50	1.13157
1	65	0.4855
1	72	0.26195
1	77	0.1269
1	82	3.84E-02
1	85	0.00E+00
2	2	4.5
2	2.089	4.4299
2	4.264	4.1589
2	14.074	3
2	22.097	2.224
2	33.116	1.4579
2	45	1.031
2	50	0.803
2	65	0.3568
2	72	0.1689
2	77	6.92E-02
2	82	1.19E-02
2	83	0.00E+00
4	2	3.2
4	2.303	3.168
4	4.256	2.99065
4	14.056	2.13084
4	22.093	1.598
4	33.12	1.0654
4	45	0.75095
4	50	0.58736
4	65	0.21822
4	72	8.51E-02
4	77	2.28E-02
4	81	0.00E+00
6	2	2.7
6	2.212	2.626
6	4.238	2.4579

6	14.06	1.738
6	22.086	1.299
6	33.094	0.8785
6	45	0.59897
6	50	0.45462
6	65	0.1416
6	72	4.23E-02
6	78	0.00E+00
8	2	2.3
8	2.325	2.271
8	4.222	2.1308
8	14.05	1.486
8	22.07	1.112
8	33	0.73
8	45	0.4898
8	50	0.36469
8	65	9.31E-02
8	72	1.81E-02
8	75	0.00E+00
10	2	2.1
10	2.431	2.0187
10	4.214	1.888
10	14.051	1.299
10	22.05	0.97196
10	33	0.64486
10	45	0.4
10	50	0.292
10	65	5.67E-02
10	71	0.00E+00
11	2	1.92
11	4.2	1.794
11	14	1.238
11	22	0.917
11	33	0.608
11	45	0.35
11	50	0.2582
11	65	4.48E-02
11	70	0.00E+00
12	2	1.82
12	4.2	1.7009
12	14	1.1776
12	22	0.8598
12	33	0.57
12	45	0.32
12	50	0.2276
12	65	3.10E-02
12	68.8	0.00E+00
14	2	1.67
14	4.2	1.5607
14	14	1.0561
14	22	0.7664
14	33	0.495
14	45	0.24
14	50	0.1769

14	65	1.40E-02
14	67	0.00E+00
15	2	1.62
15	4.2	1.5047
15	14	1
15	22	0.729
15	33	0.4579
15	45	0.22
15	50	0.157
15	65	9.00E-03
15	66.2	0.00E+00

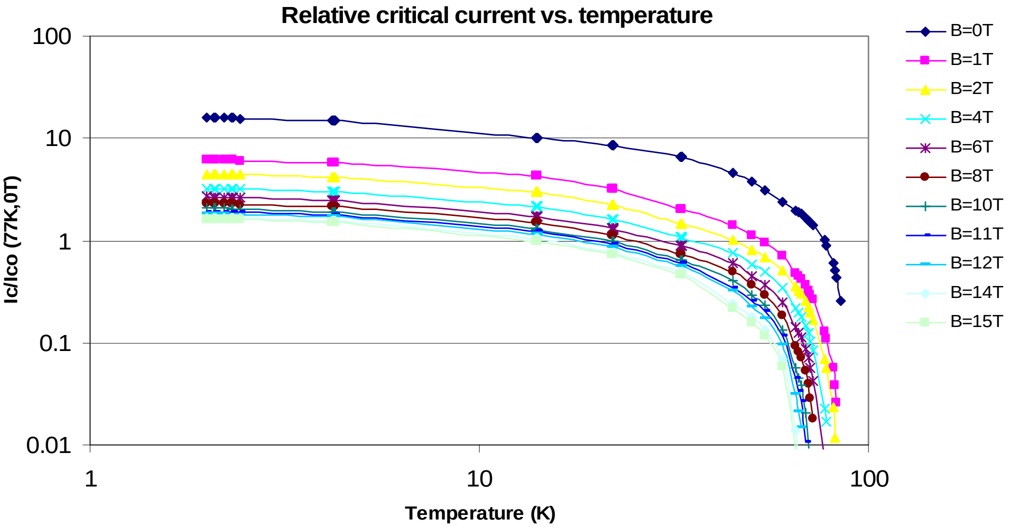


Fig. 4 Relative critical current as a function of temperature at different B field up to 15T.

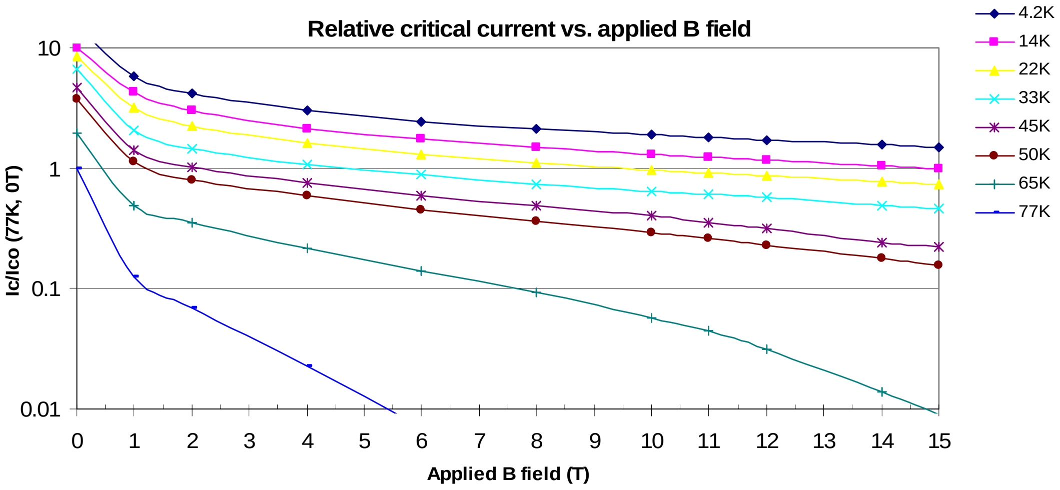


Fig. 5 Relative critical current as a function of applied B field at different temperature.

A grid of network for magnetic field and temperature is constructed based on 1D linear interpolation from the raw data. The critical current density at any point of the 2D B-T grid network is obtained by Lagrange's formula as the followings: [4]

$$\begin{aligned} f(x,y) &= \frac{(x-x_2)(y-y_2)}{(x_1-x_2)(y_1-y_2)} f(x_1,y_1) + \frac{(x-x_2)(y_1-y)}{(x_1-x_2)(y_1-y_2)} f(x_1,y_2) \\ &+ \frac{(x_1-x)(y-y_2)}{(x_1-x_2)(y_1-y_2)} f(x_2,y_1) + \frac{(x_1-x)(y_1-y)}{(x_1-x_2)(y_1-y_2)} f(x_2,y_2) \end{aligned} \tag{1}$$

Sample results are obtained from the subroutine for the critical current density of YBCO vs. temperature at different B field, see Figs. 6 and 7.

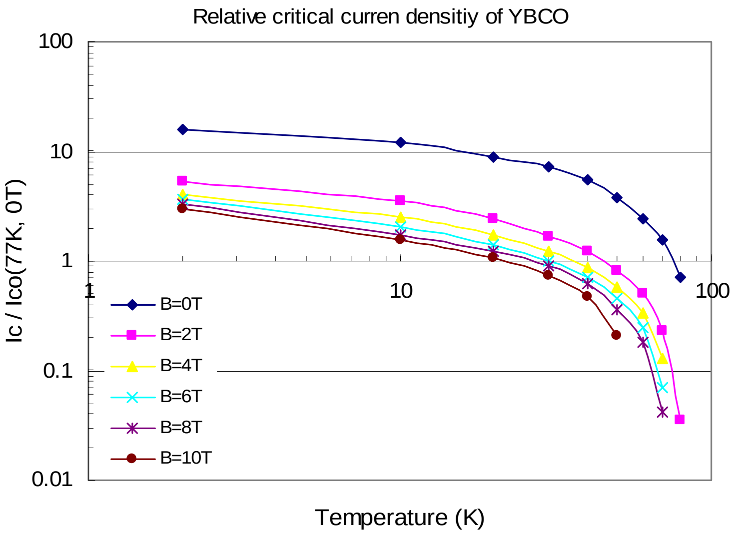


Fig. 6 The relative critical current of YBCO as a function of temperature and B field.

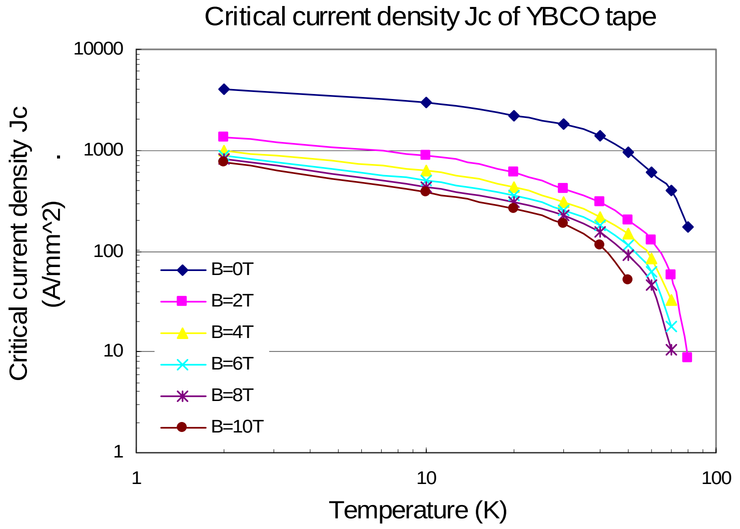


Fig. 7 The critical current density of YBCO as a function of temperature and B field.

3.2 Critical temperature

The data base of YBCO critical temperature covers the applied B field up to 15T. The raw data are listed in Table 4, and shown in Fig. 8.

Table 4 Raw data of critical temperature of YBCO

B (T)	Tc (K)
0	88
1	85
2	83
4	81
6	78
8	75
10	71
11	70
12	68.8
14	67
15	66.2

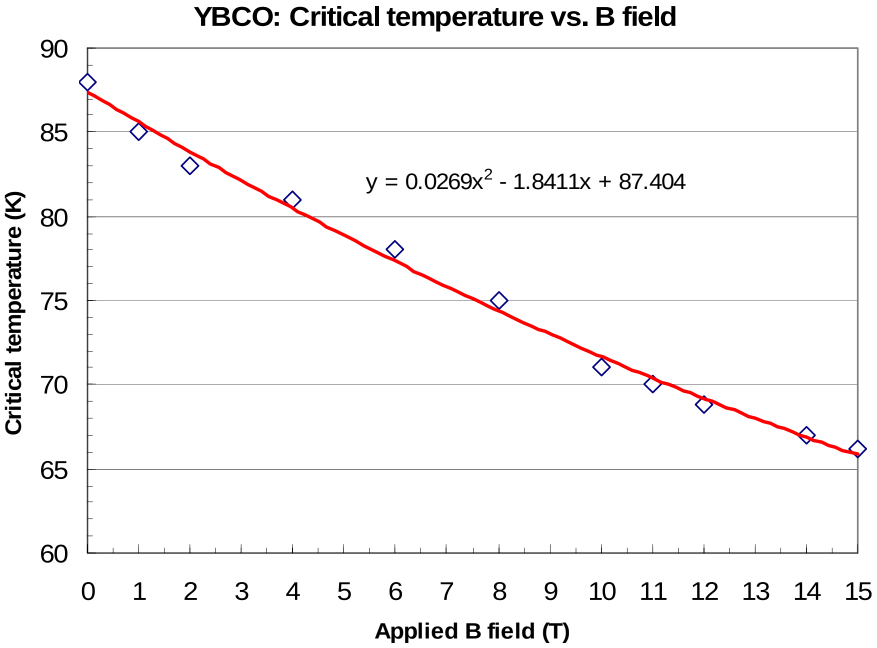


Fig. 8 Graph of the raw data for the critical temperature of YBCO

3.3 Current sharing temperature

The subroutine of YBCO current sharing temperature covers the applied B field up to 15T based on the assumption of B field perpendicular to YBCO tape. The sample results are shown in Fig. 9.

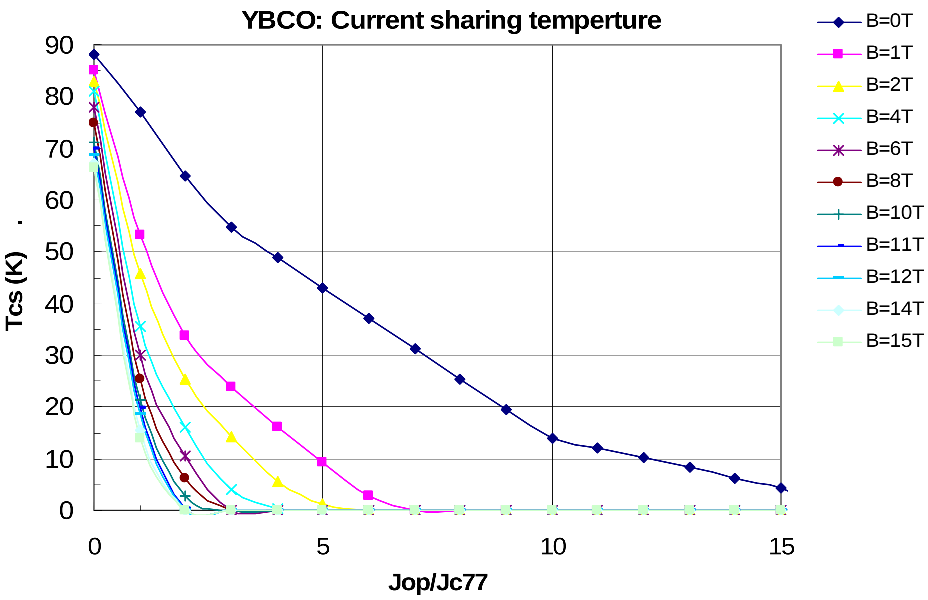


Fig. 9 The current sharing temperature of YBCO vs. relative current density at different B fields.

3.4 *Specific heat*

Assume a segment of YBCO tape is made of several components, e.g., YBCO layer, silver overlayer, copper stabilizer and stainless steel substrate etc.. The total stored energy ΔQ as the temperature increases ΔT is:

$$\Delta Q = Cp * m * \Delta T = Cp\rho V\Delta T \ , \tag{2}$$

where: Cp specific heat, m mass, ρ density, V volume, and T is temperature.

Or it is written as sum of each component:

$$\Delta Q = \left(\sum Cp_i \rho_i V_i\right)\Delta T \ . \tag{3}$$

Therefore, the average specific heat for YBCO tape is:

$$Cp = \sum Cp_i \frac{\rho_i V_i}{\rho V} \ . \tag{4}$$

Define volume fraction for component i as $fi = \frac{V_i}{V}$.

Since $\rho = \sum \rho_i f_i$, we have average specific heat of YBCO

$$Cp = \sum Cp_i \, f_i \frac{\rho_i}{\sum \rho_i f_i} \; . \qquad (5)$$

Table 5: Parameters for each component (others are neglected)

	Density (kg/m^3)	Volume fraction	Specific heat (J/(kg*K)
YBCO layer	6.3e3	0.01075	Fig. 10 [2]
silver overlayer	10.49e3	0.0215	Fig. 11 [2]
copper stabilizer	8.94e3	0.43	Fig. 12 [2], using subroutine in quench code [1]
stainless steel (Hastelloy)	8.89e3	0.5376	Fig. 13 [2], using subroutine in quench code [1]

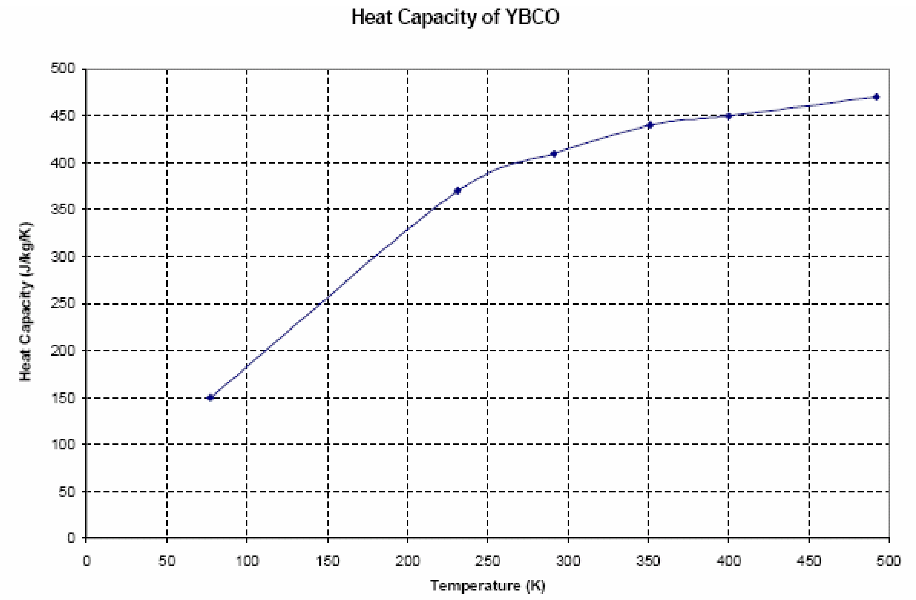


Fig. 10 Specific heat of YBCO as a function of temperature.

$$Cp = \begin{cases} 38.762 + 1.4428T & T \le 230K \\ -23.13 + 2.79T - 0.00563T^2 + 4.0496 \cdot 10^{-6} T^3 & T > 230K \end{cases} \qquad (6)$$

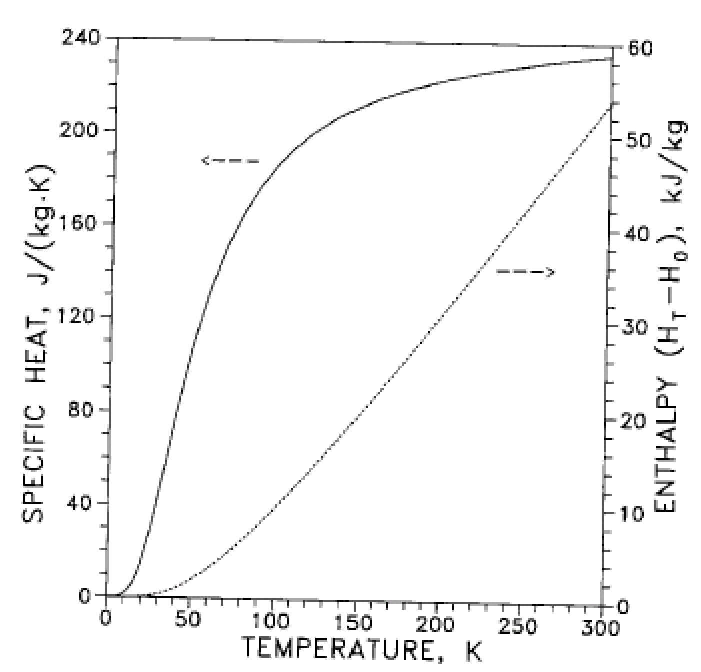


Fig. 11 Specific heat of silver as a function of temperature.

$$Cp = \begin{cases} -2.66454 \cdot 10^{-14} + 0.071T - 0.012T^2 + 0.00201T^3 & 0 - 30K \\ -100.586 + 6.05068T - 0.04289T^2 + 1.11189 \cdot 10^{-4}T^3 & 30 - 125K \\ 116.90736 + 1.0369T - 0.00326T^2 + 3.70101 \cdot 10^{-6}T^3 & 125 - 300K \end{cases} \tag{7}$$

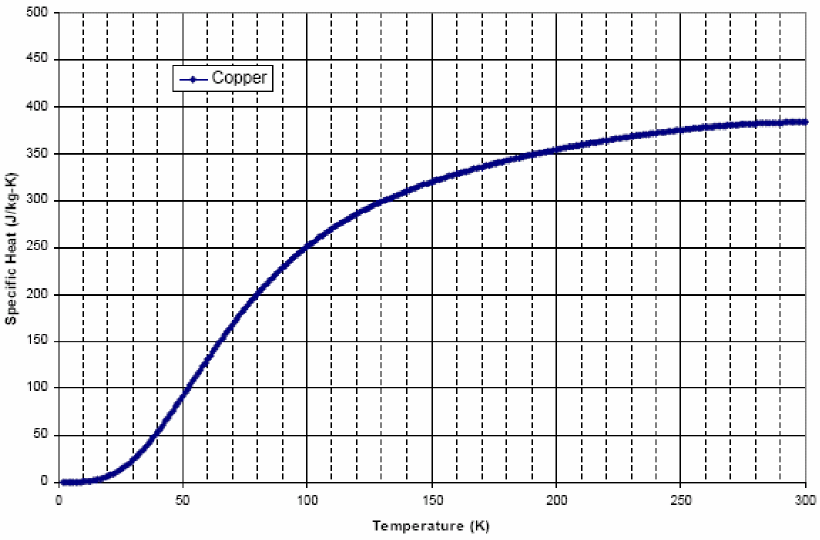
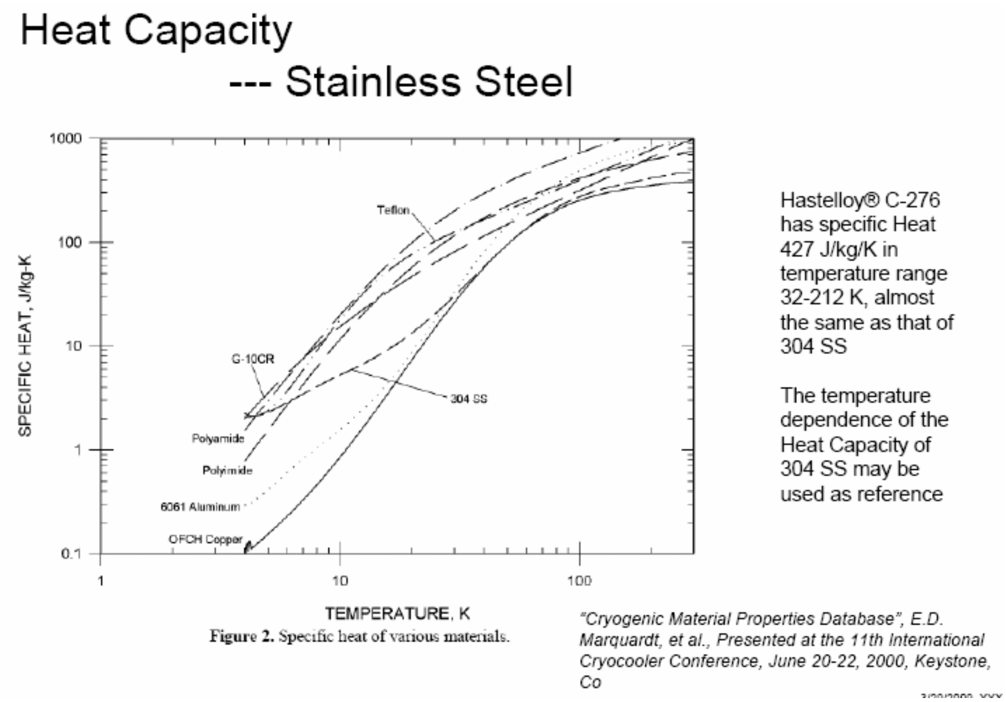


Fig. 12 Specific heat of copper as a function of temperature.



Heat Capacity

--- Stainless Steel

Hastelloy® C-276 has specific Heat 427 J/kg/K in temperature range 32-212 K, almost the same as that of 304 SS

The temperature dependence of the Heat Capacity of 304 SS may be used as reference

Figure 2. Specific heat of various materials.

"Cryogenic Material Properties Database", E.D. Marquardt, et al., Presented at the 11th International Cryocooler Conference, June 20-22, 2000, Keystone, Co

Fig. 13 Specific heat of stainless steel as a function of temperature.

Sample results are shown in Fig. 14

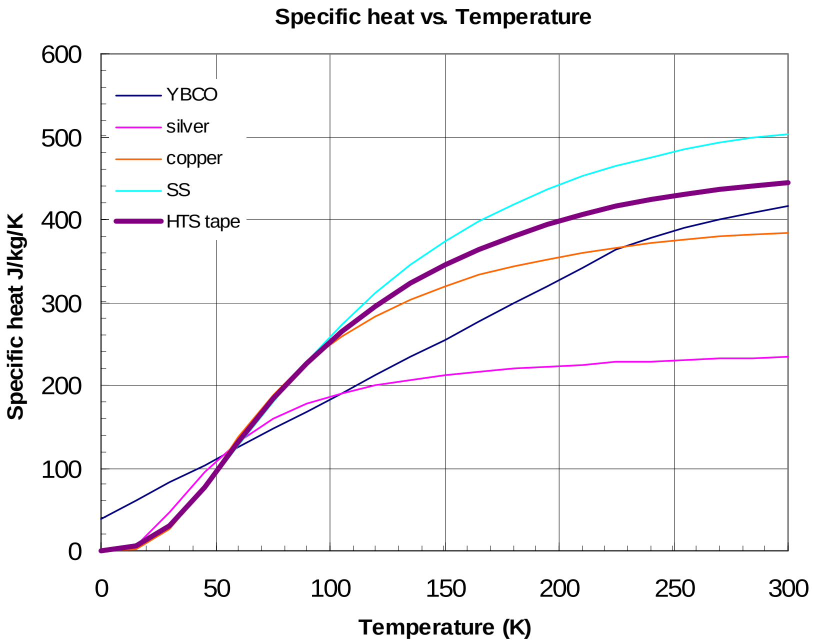


Fig. 14 Specific heat of HTS tape as well as its components as a function of temperature

3.5 Thermal conductivity

Assume a segment of YBCO tape is made of several components, e.g., YBCO layer, silver overlayer, copper stabilizer and stainless steel substrate etc.. The total heat flow at the longitudinal direction is:

$$q = \sum q_i = \sum k_i A_i \frac{\partial T}{\partial x} \quad , \tag{8}$$

where: q is the heat flow, k is conductivity, A is cross section area, and $\frac{\partial T}{\partial x}$ is temperature gradient in the longitudinal direction.

The total heat flow can also be expressed in a general form:

$$q = kA\frac{\partial T}{\partial x} . \tag{9}$$

Therefore, the heat conductivity of the YBCO tape is

$$k = \sum f_i k_i \ , \tag{10}$$

where: area fraction for *ith* component is

$$f_i = \frac{A_i}{A} \quad .$$

Table 6: Heat conductivity for each component

	Volume fraction	Heat conductivity (W/m/K)
YBCO layer	0.01075	Fig. 15 [2]
silver overlayer	0.0215	Fig. 16 [2]
copper stabilizer	0.43	Fig. 17 [2], using subroutine in quench code [1]
Hastelloy	0.5376	Fig. 18 [2],

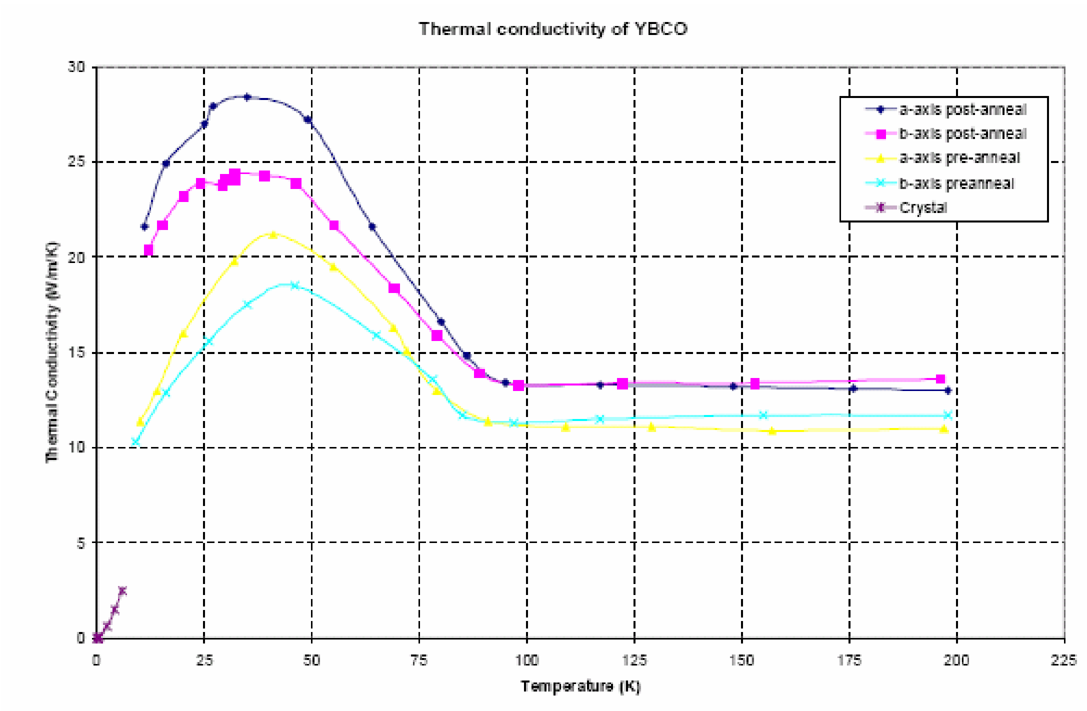


Fig. 15 Thermal conductivity of YBCO as a function of temperature.

Table 7: Thermal conductivity of YBCO as a function of temperature.

process	First stage	Second stage
a axis post-annealing	Y =13.33702+0.92649 X-0.01521 X2+1.85828E-5 X3+4.0925E-7 X4 (=<100K)	Y =13.2+0.003 X-2E-5 X2 (>100K)
b axis post-annealing	Y =11.72295+0.89017 X-0.01836 X2+1.04224E-4 X3-8.05345E-8 X4 (=<100K)	Y =13.1+0.002 X (>100K)
a axis pre-annealing	Y =6.43182+0.34362 X+0.01552 X2-5.68373E-4 X3+5.49419E-6 X4-1.65864E-8 X5 (=<100K)	Y =11.6-0.004 X (100-150K)
		11 (>150K)
b axis pre-annealing	Y =6.91846+0.35147 X+0.00331 X2-1.67834E-4 X3+1.04056E-6 X4 (=<100K)	Y =10.5+0.008 X (100-150K)
		11.7 (>150K)

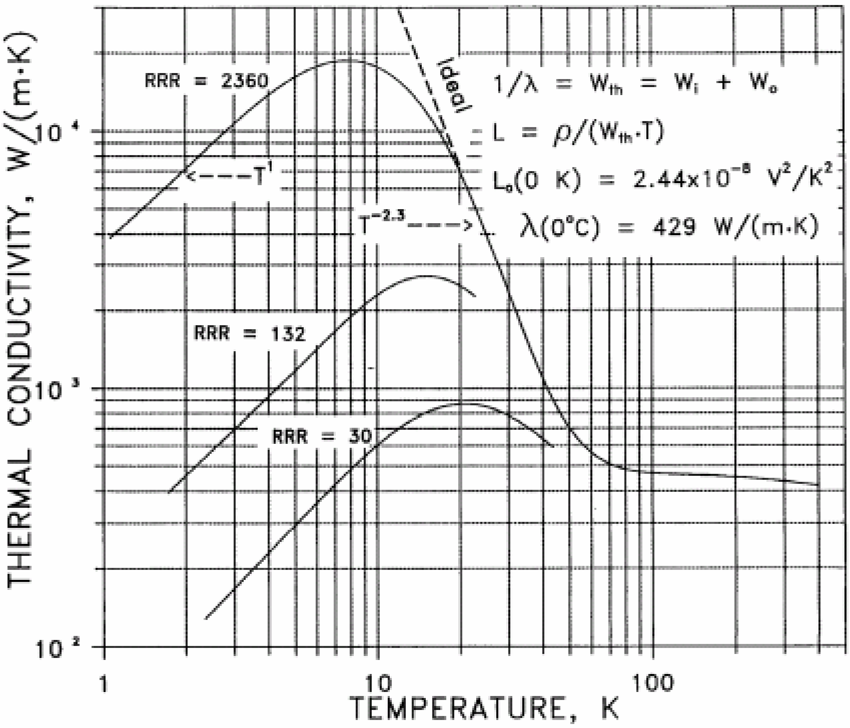


Fig. 8. Thermal conductivity λ as a function of temperature for residual resistance ratios (*RRR*) of 30, 132, and 2360. [161]

[J. Res. Natl. Inst. Stand. Technol. 100, 119 (1995)]

Low-Temperature Properties of Silver

Fig. 16 Thermal conductivity of silver as a function of temperature.

Table 8: Thermal conductivity of silver as a function of temperature.

RRR	First stage (T=<30K)	Second stage (30<T<100K)	Third stage (T>100K)
2360	Y=3.5658-0.1332x+4.429x^2 -4.9781x^3+1.3427x^4	Y=30.295-39.687x+18.99x^2 -3.0252x^3	Y=4.9392-3.0532x +1.3874x^2-0.2131x^3
132	Y=2.3825-0.1305x+3.643x^2 -3.2826x^3+0.7624x^4	Y=21.281-25.943x +12.052x^2-1.8659x^3	Y=4.9392-3.0532x +1.3874x^2-0.2131x^3
30	Y=1.7147+0.4971x+1.9519x^2 -1.775x^3+0.3959x^4	Y=11.153-12.087x +5.7511x^2-0.9134x^3	Y=4.9392-3.0532x +1.3874x^2-0.2131x^3

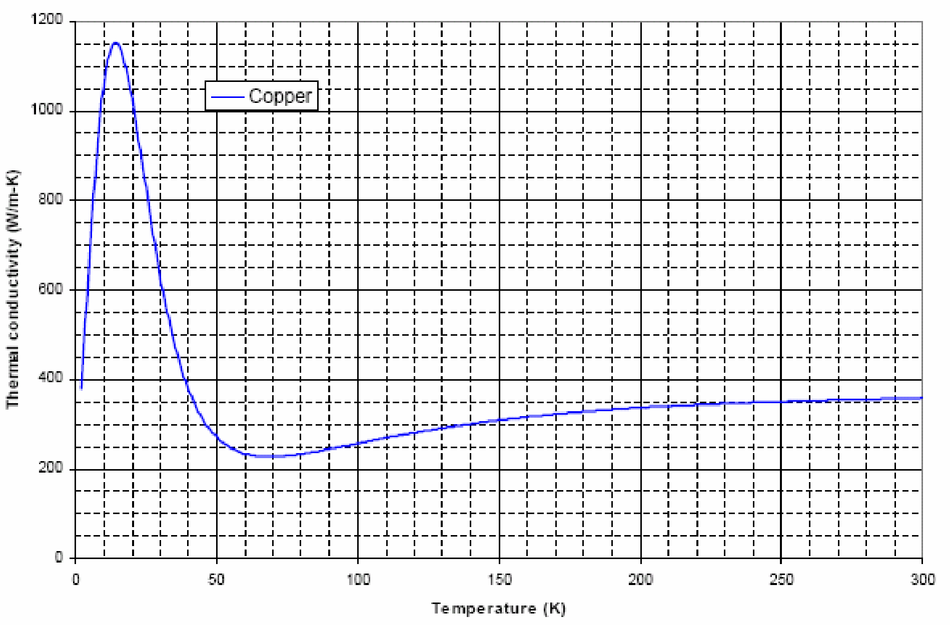


Fig. 17 Thermal conductivity of copper as a function of temperature.

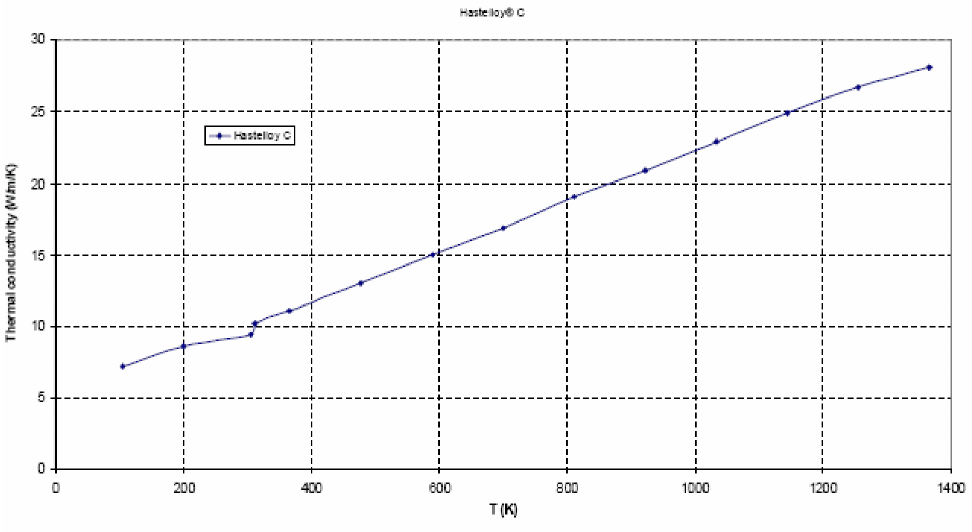


Fig. 18 Thermal conductivity of Hastelloy as a function of temperature.

The thermal conductivity of a 2G YBCO tape is plotted along with those of each component as a function of time in Figs. 19 and 20 in linear and log format respectively. Apparently, the thermal conductivity of a 2G YBCO tape is determined by mainly that of copper and Hastelloy.

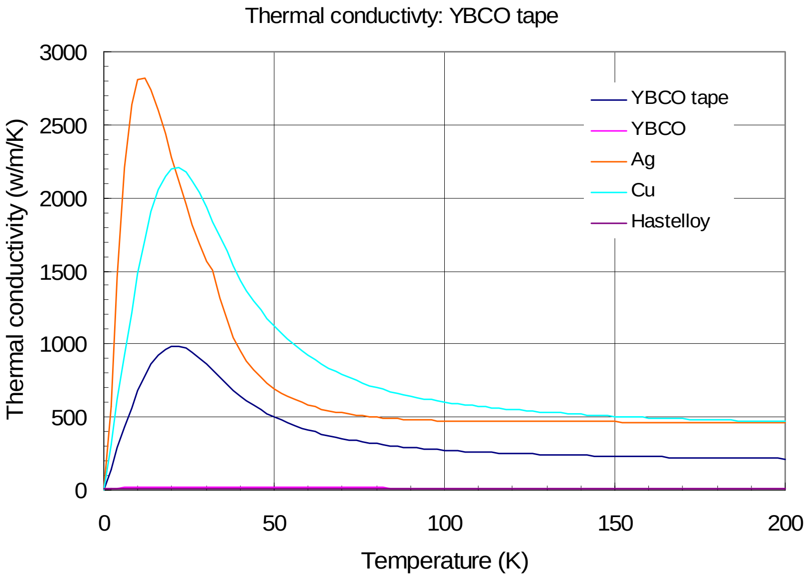


Fig. 19 Thermal conductivity of a 2G YBCO tape and its components as a function of temperature in linear format.

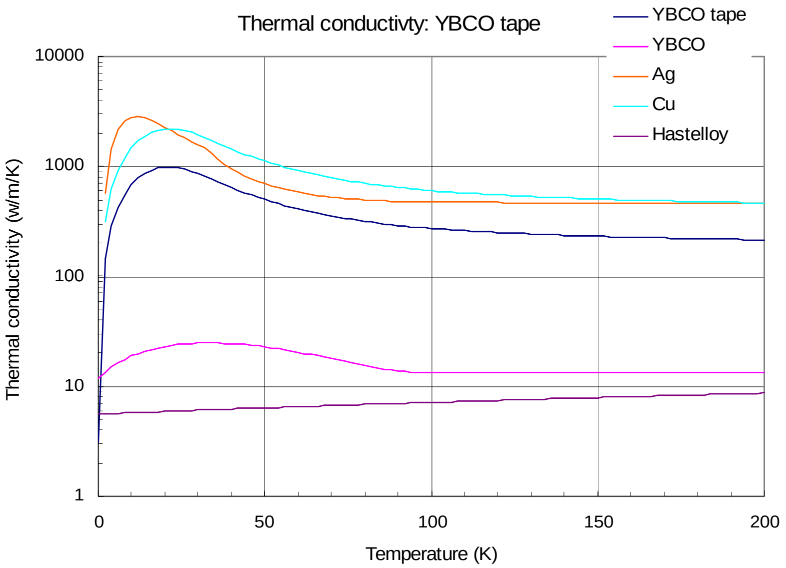


Fig. 20 Thermal conductivity of a 2G YBCO tape and its components as a function of temperature in log format.

4. Sample simulation

4.1 Superconductor mode

A simulation for sample central solenoids is summarized. The sample solenoids are equivalent to ITER Central Solenoid (CS1 to CS3), and Poloidal Field (PF1-PF6) except that the superconductors are made of HTS YBCO tapes.

The simulation has been performed by a modified thermohydraulic-quench code “Solxport3D-Quench”. The applied property subroutines of YBCO tape are listed in Table 9. The reference current scenarios of this simulation are shown in Fig. 21 for CS and PF magnets. The sample results of this simulation are shown in Figs. 22a to 22d.

Table 9: Property subroutines of YBCO tape

Property	Subroutine
Critical current dencity	JcYBCO(B,T,Jc)
Critical temperature	TcYBCO(B)
Current sharing temperature	TcsYBCO(B,J,Tcs)
Density	DENYBTAPE(T)
Thermal conductivity	CONDYBTAPE(T)
Specific heat	CPYBTAPE(T)

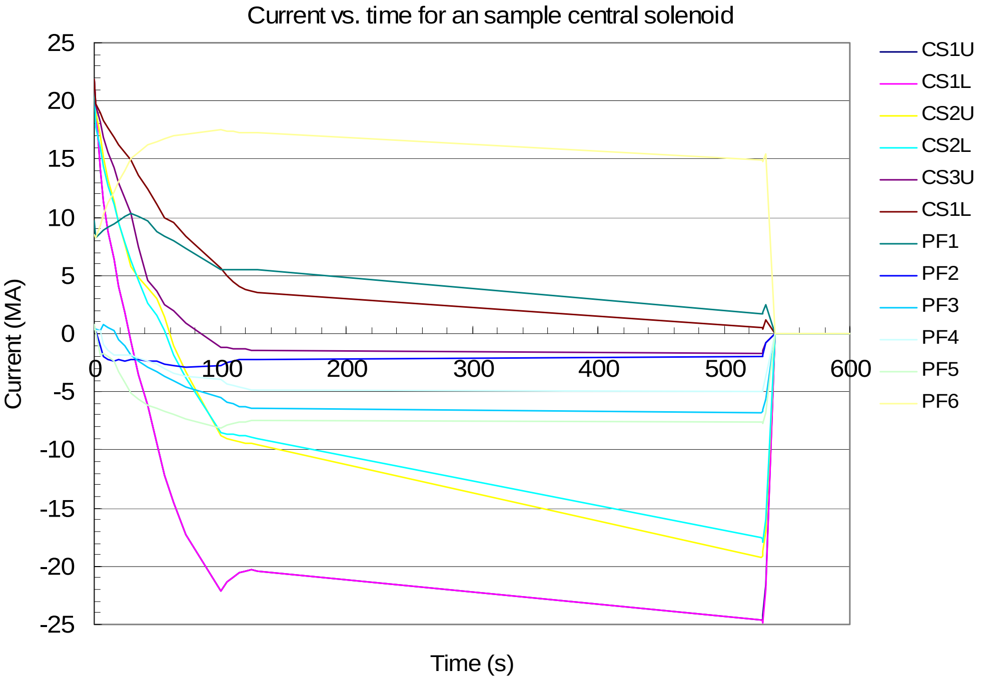


Fig. 21 Reference current scenarios of CS and PF magnets

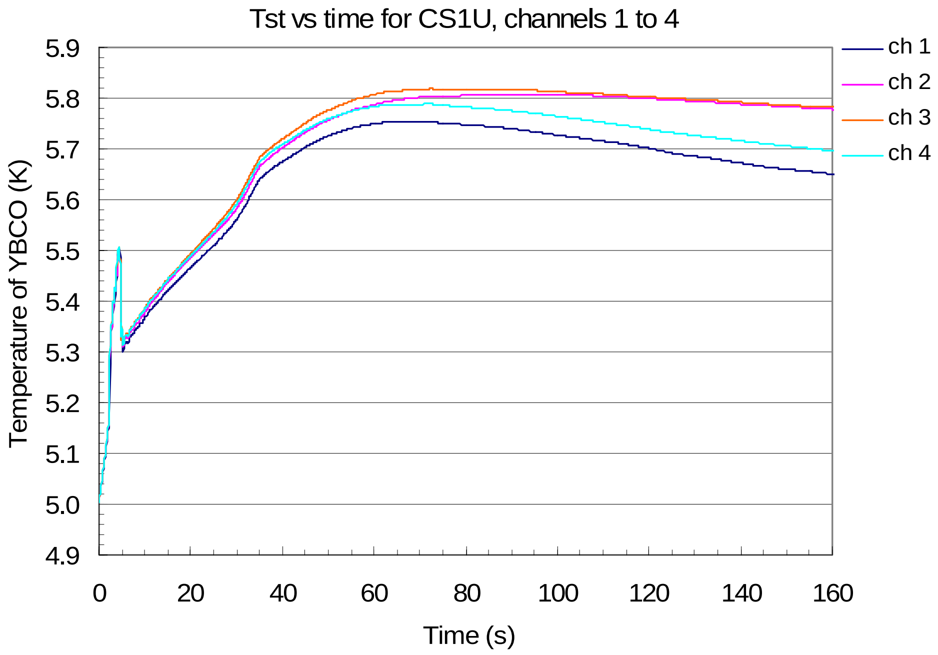


Fig. 22a Maximum temperature of YBCO tape as a function of time for CS1U, channels 1 to 4

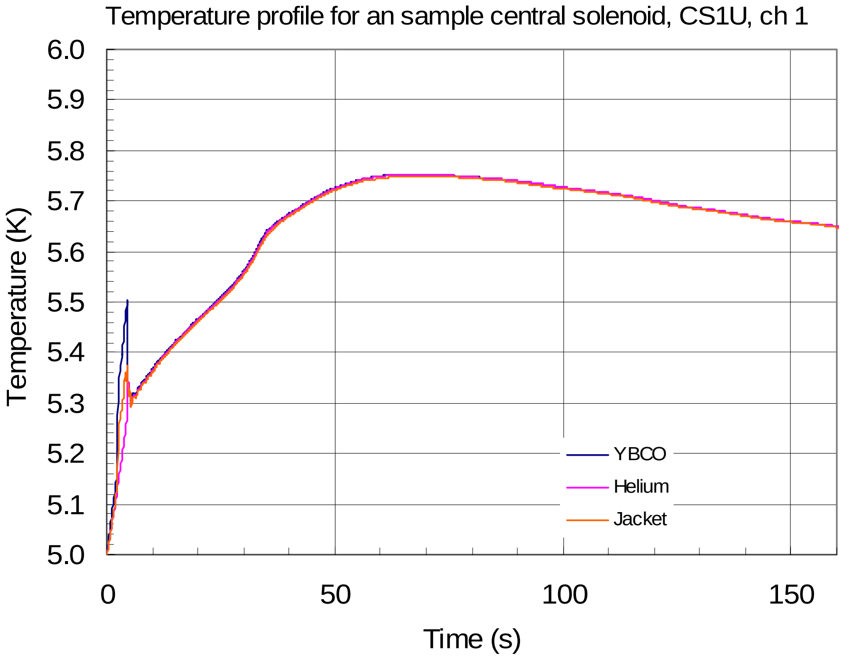


Fig. 22b Max temperature as a function of time for YBCO, helium and jacket

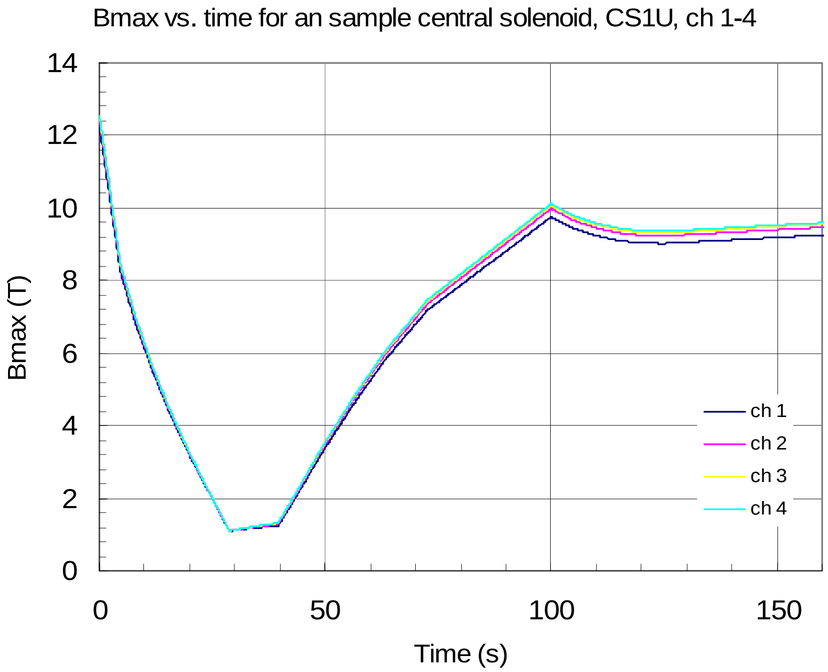


Fig. 22c Max B field as a function of time for CS1U, channels 1 to 4

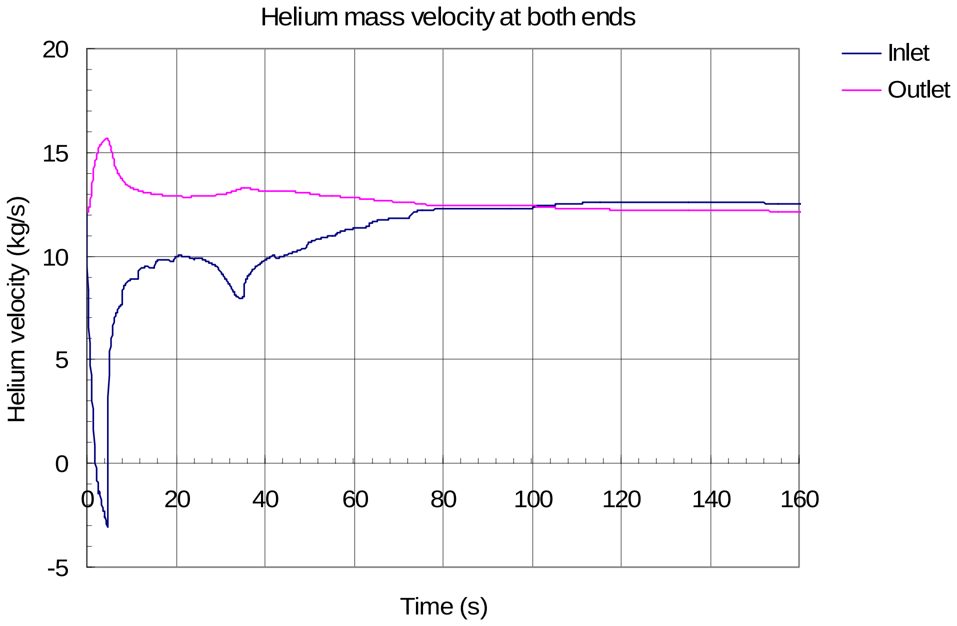


Fig. 22d Helium mass flow rate at both inlet and outlet as a function of time for CS1U

4.2 Quench simulation for a sample central solenoid made of YBCO superconductors, quench starts at t=1 second

The simulation of a sampling quench process has been performed by Solxport3D-Quench code for equivalent ITER CS1U, channels 1 to 3. It starts from superconducting mode at t=0s, and then switches to quenching at t=1s by raising temperature from 5K to 20K while both inlet and outlet keep 5K.

The quenching process recovers back to superconducting mode after ~0.5 second. It is due to high critical current density at higher temperature for HTS YBCO conductors. The sample results are shown in Figs. 23a to 23f.

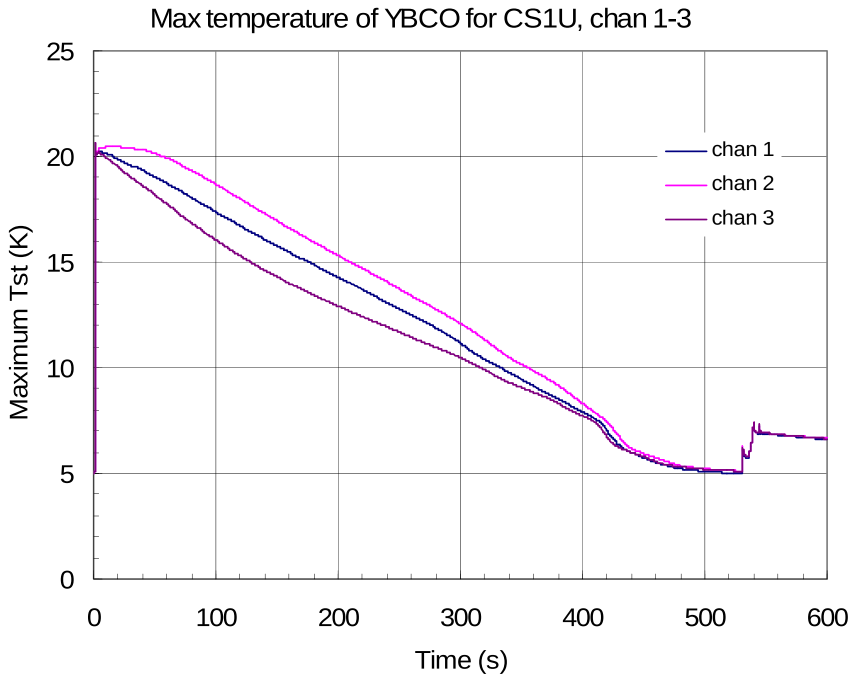


Fig. 23a Maximum YBCO temperature as a function of time for CS1U channels 1 to 3.

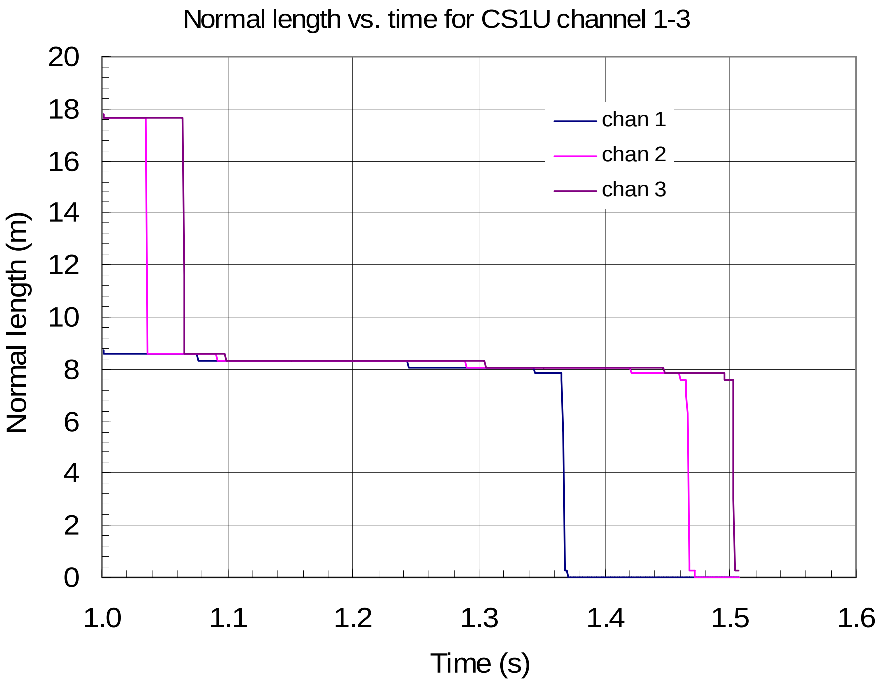


Fig. 23b Normal length as a function of time for CS1U, channels 1 to 3.

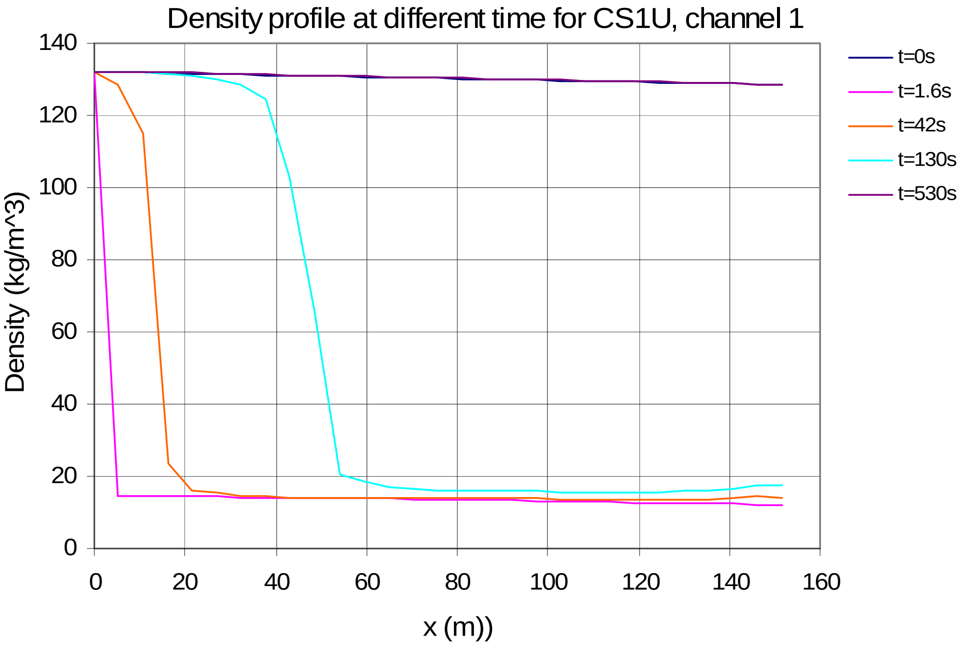


Fig. 23c Helium density profile along channel length at different time moments for CS1U chan 1.

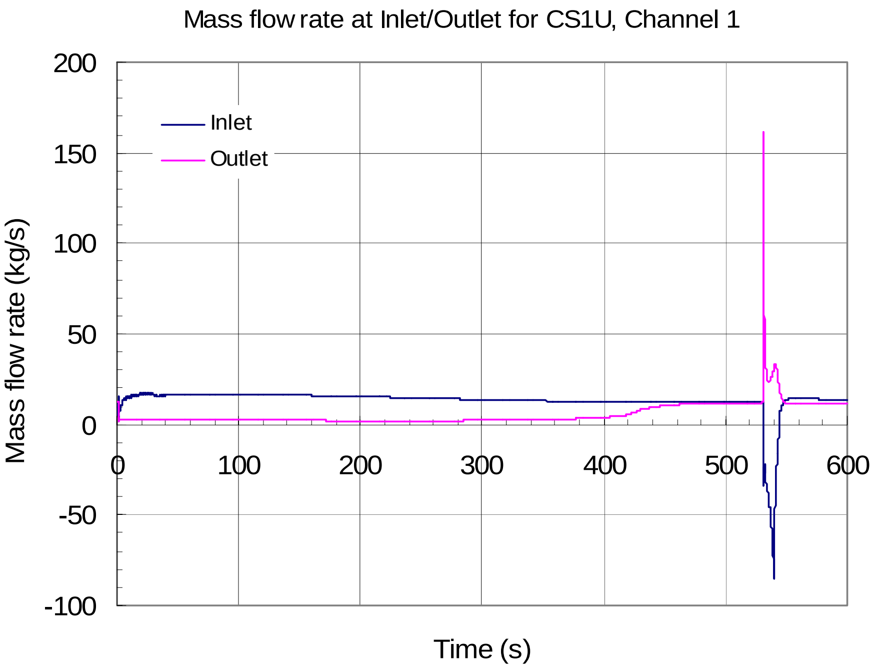


Fig. 23d Mass flow rate at outlet/inlet as a function of time for CS1U, channel 1.

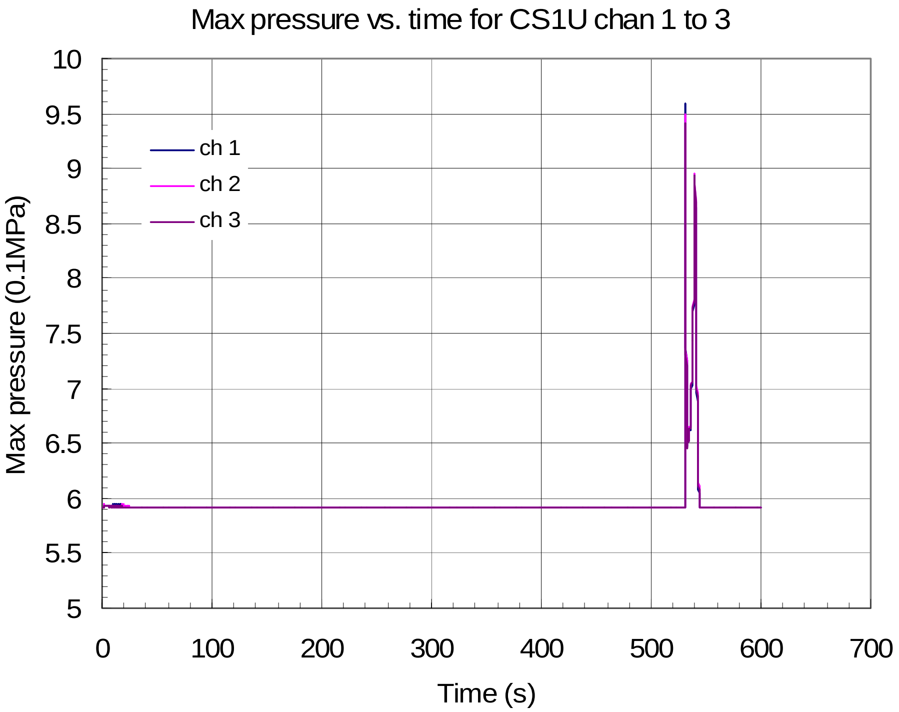


Fig. 23e Maximum pressure as a function of time for CS1U, channels 1 to 3.

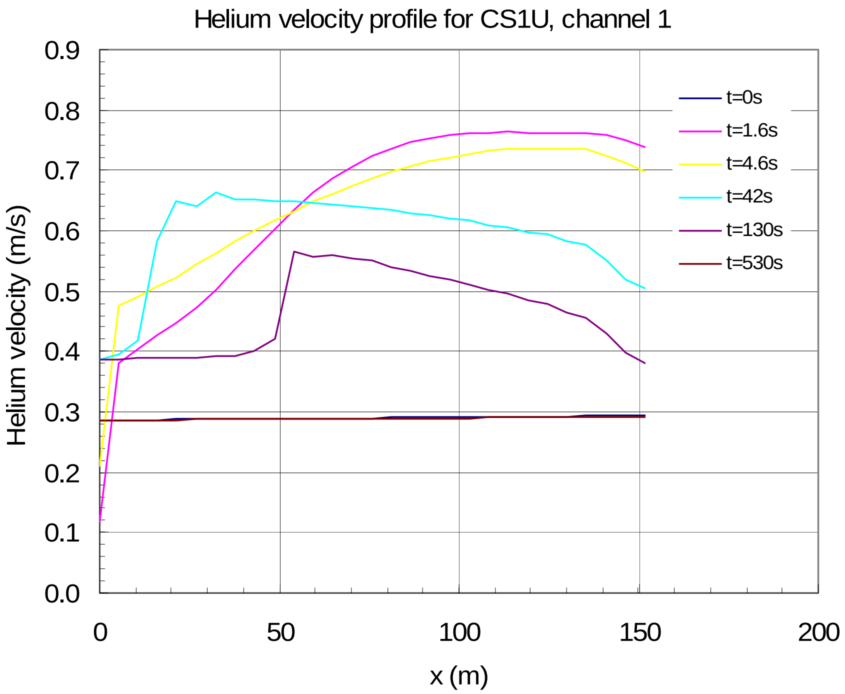


Fig. 23f Helium velocity profile at different time moments for CS1U channel 1.

4.3 Quench simulation for a sample central solenoid made of YBCO superconductors, quench starts at t=0 second within 12 meter

The simulation of a sampling quench process has been performed by Solxport3D-Quench code for equivalent ITER CS1U, channels 1 to 3. Quench starts at t=0s by applying high temperature of 100K at the first 12 meter cable of each channel while both inlet and outlet keep 5K. The sample results are shown in Fig. 24a to 24f.

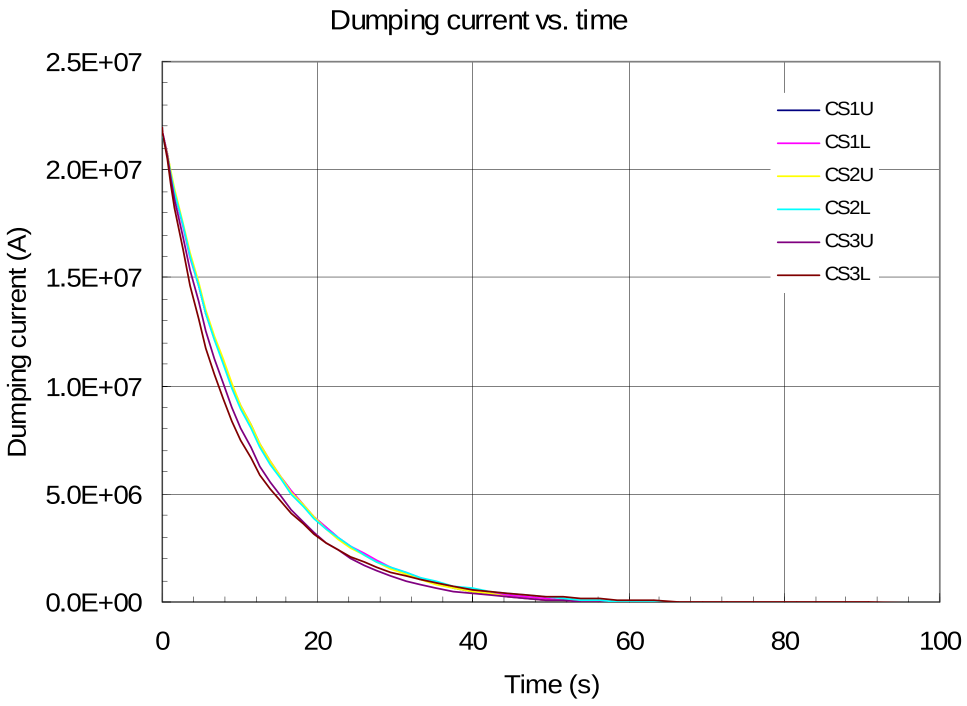


Fig. 24a Quench and dumping current vs time

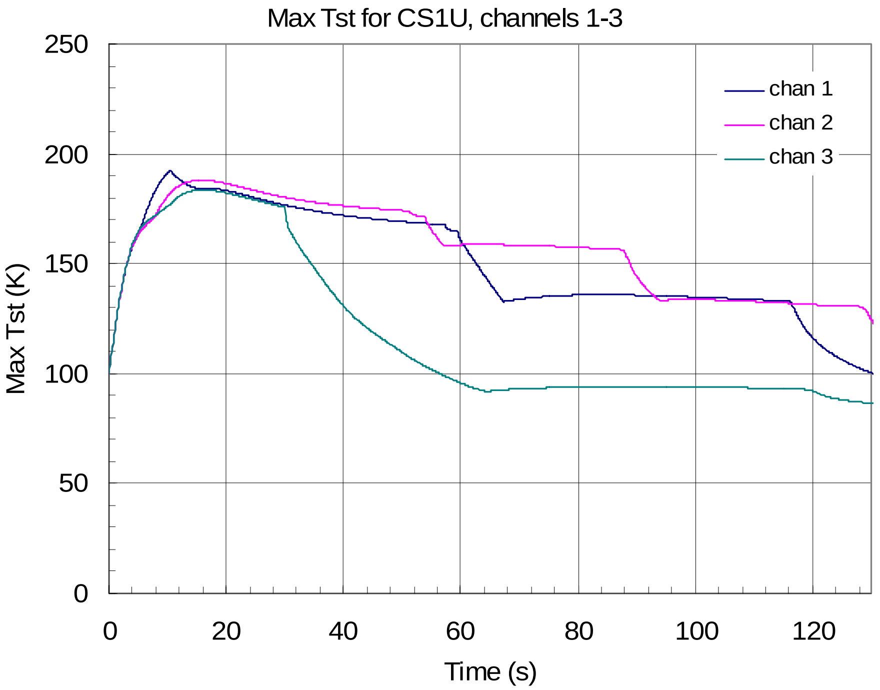


Fig. 24b Maximum YBCO temperature as a function of time for CS1U channels 1 to 3.

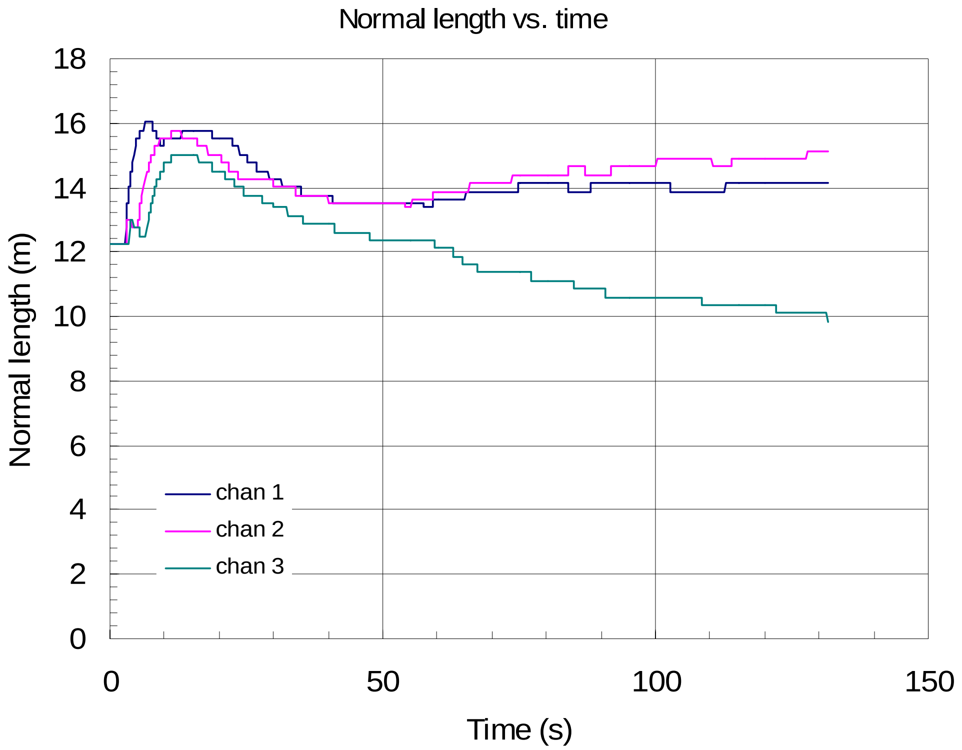


Fig. 24c Normal length vs. time

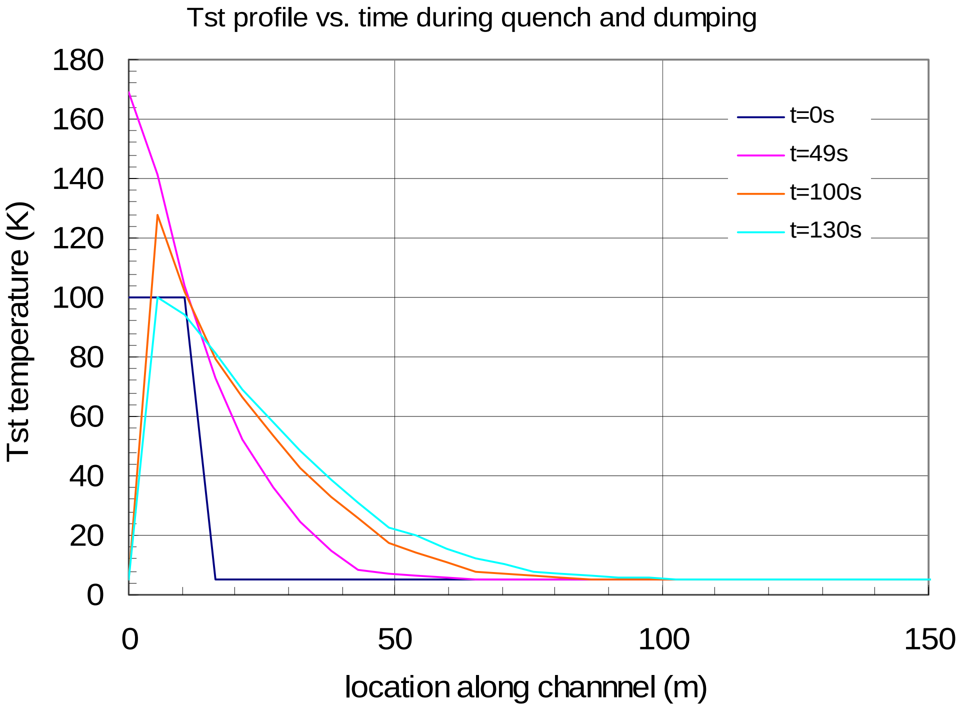


Fig. 24d YBCO temperature profile at different time moments

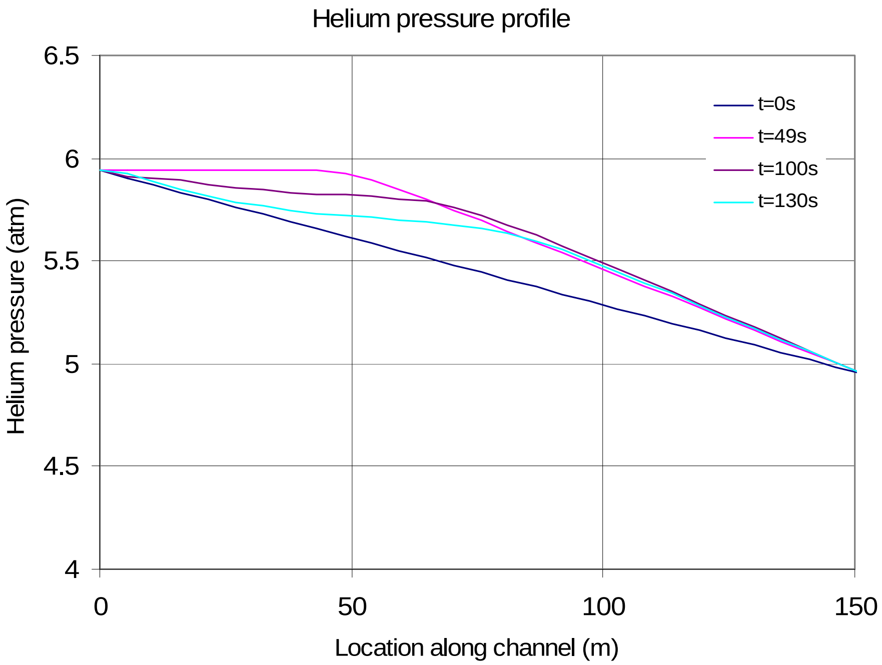


Fig. 24e Helium pressure profile at different time moments

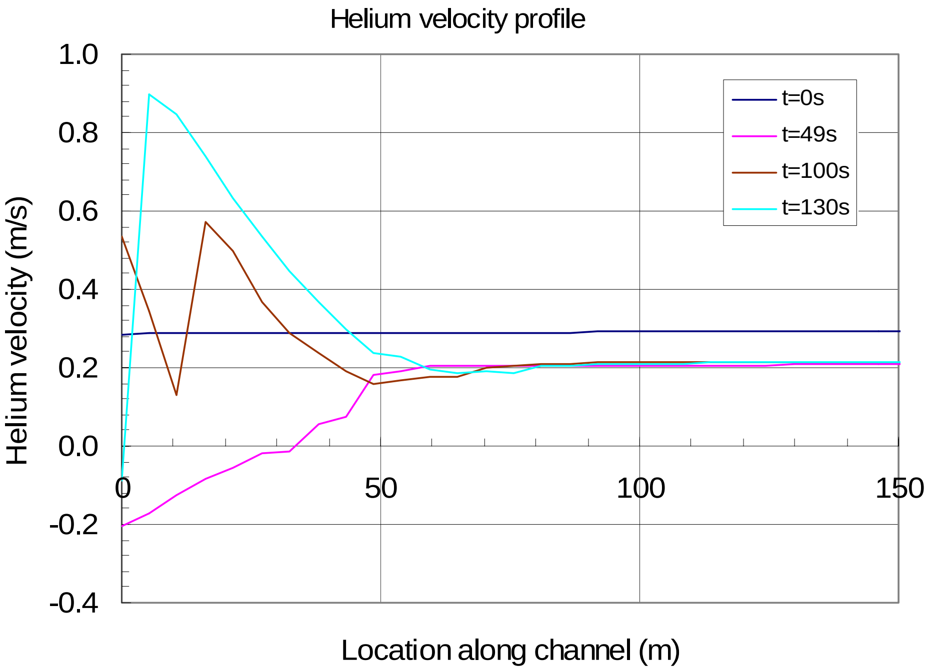


Fig. 24f Helium velocity profile at different time moment

5. Discussion

There are big differences in modeling between the LTS and HTS YBCO tape. First, the critical current density of YBCO tape is a function of applied field direction, Jc is maximum as B field is parallel to the tape plane, and Jc is minimum as B field is perpendicular to the tape plane. Since the YBCO tape is twisted inside a cable, the tape angle varies from point to point along current direction as well as in the same cross section, as the results, the Jc varies as well. For simplicity, the Jc value in the perpendicular direction is used in the simulation; Secondly, the current does not share with any neighboring YBCO tape or copper component during quench since the tape to tape is electrically insulated although thermal conduction is still ok in all directions; Third, the applied simulation model assumes one dimension, i.e., the thermal-hydraulic parameters (T, P, v) is the same in one cross section, as we know from the first point, it is not true in a SC cable made of YBCO tapes.

6. Conclusion

A thermohydraulic-quench code “Solxport3D-Quench” developed in MIT has been modified to simulate the thermohydraulic-quench behavior of a YBCO-made superconducting cable. The YBCO tape property subroutines are summarized based on SuperPower database, they include subroutines for critical current density, critical temperature, current sharing temperature, specific heat and thermal conductivity. Several sample simulations including superconducting and quench mode are performed for demonstration. Further improvement is needed for consideration of tape orientation and tape twist pattern etc..

References

[1] Jun Feng, Joel Schultz, and Joe Minervini, “A thermohydraulic-quenching code for superconducting magnets in network circuits,” presented in CEC/ICMC 2009.
[2] SuperPower Inc., 2009.
[3] Private communication, Joe Minervini, Jan. 2010
[4] William H. Press et. al., Numerical Recipes in Fortran, 2nd Ed., Pub. by Cambridge University Press, 1992.

Acknowledgement

Thanks for Dr. Joe Minervini and Dr. Makoto Takayasu for valuable discussion. Thanks are also due to SuperPower Inc. for providing the raw property data of YBCO tape.

Appendix : Subroutines of YBCO tape property

A1 : Critical current density subroutine

```
      subroutine JcYBCO(B,T,Jc)
c Critical current density of 2G YBCO tape,  6/8/2010 by Jun Feng
c B: mag field (T)  <15T
c T: temperature (K)  (2K,88K)
c Jc: critical current density (A/m^2)
c Jc77=250A/mm^2 :  Jc @B=0 and T=77K

c       include 'defpara.cmn'
c       implicit double precision (a-h, o-z)
        parameter (nb=11, nt=52)
        real Jc, Jc77
        real bfield(nb),temp(nt),curden(nb,nt)

   data Jc77 /250./  !A/mm^2

        data bfield/  0.0, 1.0,2.0,4.0,6.0,8.0,10.0,11.0,
     &          12.0,14.0,15.0/

   data temp/2.0,2.089,2.107,2.212,
     &  2.303,   2.325,   2.431,   4.20,
     &  4.214,   4.222,   4.238,   4.256,
     &  4.264,   4.269,   14.00,   14.05,
     &  14.051,   14.056,   14.060,   14.074,
     &  14.090,   22.000,   22.050,   22.070,
     &  22.086,   22.090,   22.093,   22.097,
     &  33.000,   33.029,   33.094,   33.116,
     &  33.120,   45.000,   50.000,   54.000,
     &  60.000,   65.000,   66.200,   67.000,
     &  68.800,   70.000,   71.000,   72.000,
     &  75.000,   77.000,   78.000,   81.000,
     &  82.000,   83.000,   85.000,   88.000/

        data curden/15.80000     ,   6.200000     ,   4.500000     ,
     &   3.200000     ,   2.700000     ,   2.300000     ,   2.100000,
     &   1.920000     ,   1.820000     ,   1.670000     ,   1.620000,
     &   15.77261     ,   6.126804     ,   4.429900     ,
     &   3.190601     ,   2.668934     ,   2.292058     ,   2.083212,
     &   1.914903     ,   1.815182     ,   1.665578     ,   1.615336,
     &   15.76707     ,   6.112000     ,   4.427658     ,
     &   3.188700     ,   2.662651     ,   2.290452     ,   2.079816,
     &   1.913872     ,   1.814207     ,   1.664684     ,   1.614392,
     &   15.73476     ,   6.095196     ,   4.414575     ,
     &   3.177611     ,   2.626000     ,   2.281083     ,   2.060010,
     &   1.907858     ,   1.808523     ,   1.659467     ,   1.608889,
     &   15.70676     ,   6.080633     ,   4.403236     ,
     &   3.168000     ,   2.618449     ,   2.272963     ,   2.042845,
     &   1.902646     ,   1.803597     ,   1.654946     ,   1.604120,
     &   15.69999     ,   6.077112     ,   4.400495     ,
     &   3.166002     ,   2.616624     ,   2.271000     ,   2.038695,
     &   1.901386     ,   1.802406     ,   1.653853     ,   1.602967,
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&  1.895315    ,  1.796667    ,  1.648587    ,  1.597412,
&  15.12300    ,  5.777042    ,  4.166874    ,
&  2.995735    ,  2.461053    ,  2.132426    ,  1.889026,
&  1.794000    ,  1.700900    ,  1.560700    ,  1.504700,
&  15.11559    ,  5.774802    ,  4.165130    ,
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&  1.791844    ,  1.698871    ,  1.558743    ,  1.502743,
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&  15.08911    ,  5.766800    ,  4.158900    ,
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&  2.135753    ,  1.742398    ,  1.489280    ,  1.302054,
&  1.238000    ,  1.177600    ,  1.056100    ,  1.000000,
&  9.925461    ,  4.267827    ,  3.002835    ,
&  2.131366    ,  1.738733    ,  1.486000    ,  1.299060,
&  1.235994    ,  1.175614    ,  1.054289    , 0.9983062,
&  9.925290    ,  4.267674    ,  3.002717    ,
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&  1.599525    ,  1.299875    ,  1.112000    , 0.9713625,
&  0.9150336    , 0.8579558    , 0.7646729    , 0.7272748,
&  8.552997    ,  3.196533    ,  2.225064    ,
&  1.598464    ,  1.299000    ,  1.111441    , 0.9708846,
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     & 0.9145842     , 0.8575343     , 0.7642781     , 0.7268804,
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     & 0.9144718     , 0.8574289     , 0.7641794     , 0.7267819,
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     &  6.689000     ,  2.040072     ,  1.465965     ,
     &  1.071196     , 0.8820908     , 0.7300000     , 0.6448600,
     & 0.6080000     , 0.5700000     , 0.4950000     , 0.4579000,
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     &  1.069795     , 0.8809831     , 0.7294195     , 0.6442683,
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     &  4.7728002E-02 ,  2.1170000E-02 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
     &   1.000500     ,  0.1269000     ,  6.9190003E-02 ,
     &  2.2800000E-02 ,  7.0566665E-03 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.9016800     ,  0.1092060     ,  5.7732001E-02 ,
     &  1.7100001E-02 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
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     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
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     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.4286000     ,  2.5620000E-02 ,  0.0000000E+00 ,
     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 ,
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     &  0.0000000E+00 ,  0.0000000E+00 ,  0.0000000E+00 ,0.0000000E+00 /


C Use Lagrange linear formula
      if (B.gt.15..or.T.gt.88.) then
              q=0.
      else
        call qlinear(B,T,nb,nt,bfield,temp,curden,q)
           endif
           Jc=q*Jc77  *1.e6   !A/m^2

          return
          end
```

A2: Critical temperature subroutine

```
          function TcYBCO(B)
c Critical temperature of 2G YBCO,  6/9/2010 by Jun Feng
c B: mag field (T)  <15T
c T: temperature (K)

c         implicit double precision (a-h, o-z)

    TcYBCO = 0.0269*b**2 - 1.8411*b + 87.404

          return
          end
```

A3: Current sharing temperature subroutine

```
      subroutine TcsYBCO(B,cur,t)
c Current sharing temperature of 2G YBCO,  2/26/2010 by Jun Feng
c B: mag field (T) <15T
c T: temperature (K)
c Jc: critical current density (A/mm^2)
c Jc77:  Jc @B=0 and T=77K
c cur: Jop (A/m^2)

c     include 'defpara.cmn'
c     implicit double precision (a-h, o-z)
      parameter (nb=11, nc=106)
      real Jc77
      real bfield(nb),curden(nc),temp(nb,nc)

   data Jc77 /250./  !A/mm^2

   data bfield/0.000,1.000,2.000,4.000000,
  &      6.000,8.000,10.00,11.00000,
  &      12.00,14.00,15.000/
      data curden/0.000,8.9999996E-03,1.1900000E-02,1.4000000E-02,
  &1.8110000E-02 ,  2.2800000E-02 ,  3.0999999E-02 ,  3.8430002E-02 ,
  &4.2339999E-02 ,  4.4799998E-02 ,  5.6699999E-02 ,  6.9190003E-02 ,
  &8.5120000E-02 ,  9.3110003E-02 ,  0.1269000     ,  0.1416000     ,
  &0.1570000     ,  0.1689000     ,  0.1769000     ,  0.2182200     ,
  &0.2200000     ,  0.2276000     ,  0.2400000     ,  0.2582000     ,
  &0.2619500     ,  0.2920000     ,  0.3200000     ,  0.3500000     ,
  &0.3568000     ,  0.3646900     ,  0.4000000     ,  0.4286000     ,
  &0.4546200     ,  0.4579000     ,  0.4855000     ,  0.4898000     ,
  &0.4950000     ,  0.5064000     ,  0.5700000     ,  0.5873600     ,
  &0.5989700     ,  0.6080000     ,  0.6448600     ,  0.7290000     ,
  &0.7300000     ,  0.7509500     ,  0.7664000     ,  0.8030000     ,
  &0.8598000     ,  0.8785000     ,  0.9170000     ,  0.9719600     ,
  &1.000000     ,  1.000500     ,  1.031000     ,  1.056100     ,
  &1.065400     ,  1.112000     ,  1.131570     ,  1.177600     ,
  &1.238000     ,  1.299000     ,  1.394000     ,  1.411000     ,
  &1.457900     ,  1.486000     ,  1.504700     ,  1.560700     ,
  &1.598000     ,  1.620000     ,  1.670000     ,  1.700900     ,
  &1.738000     ,  1.794000     ,  1.820000     ,  1.888000     ,
  &1.920000     ,  2.018700     ,  2.037000     ,  2.100000     ,
  &2.130800     ,  2.130840     ,  2.224000     ,  2.271000     ,
  &2.300000     ,  2.381000     ,  2.457900     ,  2.626000     ,
  &2.700000     ,  2.990650     ,  3.000000     ,  3.095000     ,
  &3.168000     ,  3.196000     ,  3.200000     ,  4.158900     ,
  &4.261700     ,  4.429900     ,  4.500000     ,  5.766000     ,
  &6.112000     ,  6.200000     ,  6.689000     ,  9.934000     ,
  &15.12300     ,  15.80000 /
   data temp/88.00000,   85.00000,   83.00000,
  &  81.00000,   78.00000,   75.00000,   71.00000,
  &  70.00000,   68.80000,   67.00000,   66.20000,
  &  87.89500,   84.29742,   82.24370,
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&   0.00000,   0.00000,   0.00000,   0.00000,
&  63.47629,  32.43439,  23.88052,
&  14.52117,   9.12103,   4.69145,   2.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  63.09526,  32.14368,  23.43752,
&  14.05660,   8.70081,   4.22200,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  63.09476,  32.14331,  23.43694,
&  14.05600,   8.70026,   4.22146,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  61.94227,  31.26404,  22.09700,
&  12.99417,   7.42923,   2.96094,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  61.36082,  30.82044,  21.61107,
&  12.45848,   6.78798,   2.32500,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  61.00206,  30.54672,  21.31124,
&  12.12794,   6.39232,   2.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  60.00000,  29.78222,  20.47379,
&  11.20471,   5.28719,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  59.35378,  29.05642,  19.67873,
&  10.32821,   4.23800,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  57.94118,  27.46984,  17.94076,
&   8.41223,   2.21200,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  57.31933,  26.77140,  17.17567,
&   7.56879,   2.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  54.87689,  24.02816,  14.17067,
&   4.25600,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  54.79832,  23.93991,  14.07400,
&   4.15304,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  54.00000,  23.04327,  13.26983,
&   3.10688,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  53.57346,  22.35427,  12.65189,
&   2.30300,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  53.40985,  22.09000,  12.41487,
&   2.03787,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  53.38648,  22.05997,  12.38101,
&   2.00000,   0.00000,   0.00000,   0.00000,
&   0.00000,   0.00000,   0.00000,   0.00000,
&  47.78356,  14.86170,   4.26400,
&   0.00000,   0.00000,   0.00000,   0.00000,
```

```
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   47.18289,   14.09000,    3.43894,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   46.20008,   12.99189,    2.08900,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   45.79049,   12.53423,    2.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   38.39316,    4.26900,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   36.37145,    2.10700,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   35.85727,    2.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   33.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &   14.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    4.20000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    2.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000,
     &    0.00000,    0.00000,    0.00000,    0.00000/

C Use Lagrange linear formula
      rj=cur*1.e-6/Jc77
      if (B.gt.15..or.rj.gt.15.8) then
          t=0.
         else
       call qlinear(B,rj,nb,nc,bfield,curden,temp,q)
          t=q
         endif

         return
         end
```

A4: Density subroutine

```
C ######################################################################
      REAL FUNCTION DENYBTAPE(T)
C ######################################################################
C #
C # Density of YBCO tape in Kg/m^3
C #  0<T<300, based on Superpower 2G-YBCO tape data
```

```
C #
C # variable    I/O              meaning                      units
C # -------------------------------------------------------------------
C #   T         x           absolute temperature                 K
C #   DENYBTAPE      x           density                      Kg/m^3
C #
C # Author : Jun Feng
C # Version: 1.0  4/8/2010
C #
C ######################################################################
      data den_YB/6.3e3/,den_ag/10.49e3/,den_cu/8.9e3/,den_ss/8.89e3/
              data fr_YB/0.01075/,fr_AG/0.0215/,fr_CU/0.43/,fr_SS/0.5376/

              denybtape=den_YB*fr_YB+den_ag*fr_ag+den_cu*fr_cu+den_ss*fr_ss

C *
      RETURN
      END
```

A5: Thermal conductivity subroutine

```
C ######################################################################
      REAL FUNCTION CONDYBCO(mode,T)
C ######################################################################
C #
C # Thermal conductivity of YBCO in W/m K as a function of temperature
C # based on Superpower 2G-YBCO tape
C #
C # variable    I/O              meaning                      units
C # -------------------------------------------------------------------
C #   T           x           absolute temperature                 K
C #   CONDYBCO    x           thermal conductivity                 W/m K
C #
C # Author : Jun Feng
C # Version: 1.0  4/27/2010
C #
C ######################################################################
      real a(5),b(3),c(5),d(2),f(6),g(2),h(5),p(2)

              data T1/100./,T2/150./
      data a/13.33702,0.92649,-0.01521,1.85828E-5,4.0925E-7/
              data b/13.2,0.003,-2E-5/
              data c/11.72295,0.89017,-0.01836,1.04224E-4,-8.05345E-8/
              data d/13.1,0.002/
              data f/6.43182,0.34362,0.01552,-5.68373E-4,5.49419E-6,
     &               -1.65864E-8/
              data g/11.6,-0.004/
              data h/6.91846,0.35147,0.00331,-1.67834E-4,1.04056E-6/
              data p/10.5,0.008/

C *
```

```
c      mode=1     !default input
c mode 1: a axis post-annealing
      if (mode.eq.1) then
                  if (T.le.T1) then
                        CONDYBCO=a(1)+a(2)*T+a(3)*T**2+a(4)*T**3+a(5)*T**4
                  else
                        CONDYBCO=b(1)+b(2)*T+b(3)*T**2
                  endif
            endif

c mode 2: b axis post-annealing
      if (mode.eq.2) then
                  if (T.le.T1) then
                        CONDYBCO=c(1)+c(2)*T+c(3)*T**2+c(4)*T**3+c(5)*T**4
                  else
                        CONDYBCO=d(1)+d(2)*T
                  endif
            endif

c mode 3: a axis pre-annealing
            if (mode.eq.3) then
                  if (T.le.T1) then
                        CONDYBCO=f(1)+f(2)*T+f(3)*T**2+f(4)*T**3
     &            +f(5)*T**4+f(6)*T**5
                  else
                        CONDYBCO=g(1)+g(2)*T
                  endif
              if (T.gt.T2) CONDYBCO=11.
            endif

c mode 4: b axis pre-annealing
      if (mode.eq.4) then
                  if (T.le.T1) then
                        CONDYBCO=h(1)+h(2)*T+h(3)*T**2+h(4)*T**3+h(5)*T**4
                  else
                        CONDYBCO=p(1)+p(2)*T
                  endif
              if (T.gt.T2) CONDYBCO=11.7
            endif

C *
      RETURN
      END


C ##########################################################################
      REAL FUNCTION CONDAG(RRR,T)
C ##########################################################################
C #
C # Thermal conductivity of Ag in W/m K as a function of temperature
C # based on Superpower 2G-YBCO tape
C #
C # variable    I/O              meaning                        units
C # --------------------------------------------------------------------
C #   T           x           absolute temperature                  K
C #   CONDAG    x             thermal conductivity                  W/m K
```

```
C #
C # Author : Jun Feng
C # Version: 1.0  5/3/2010
C #
C ######################################################################
      parameter (n=3)
        real xa(n),ya(n)
      data rrr1/30./,rrr2/132./,rrr3/2360./

        if (abs(T).gt.1.) then
                xa(1)=rrr1
                xa(2)=rrr2
                xa(3)=rrr3
                ya(1)=condagrr1(T)
                ya(2)=condagrr2(T)
                ya(3)=condagrr3(T)
                call NBISECX(rrr,Xa,YVAL,Ya,IX,N)
                CONDAG=yval
        else
           CONDAG=0.
        endif

        return
        end


        REAL FUNCTION CONDAGRR1(T)
c Conductivity of Ag at RRR=30.

      real a(5),b(4),c(4)

        data T1/100./, T2/30./
      data a/1.7147,0.4971,1.9519,-1.775,0.3959/
        data b/11.153,-12.087,5.7511,-0.9134/
        data c/4.9392,-3.0532,1.3874,-0.2131/

        T0=log10(T)
        if (T.le.T2) then
         y=a(1)+a(2)*T0+a(3)*T0**2+a(4)*T0**3+a(5)*T0**4
         elseif (T.le.T1) then
         y=b(1)+b(2)*T0+b(3)*T0**2+b(4)*T0**3
         else
         y=c(1)+c(2)*T0+c(3)*T0**2+c(4)*T0**3
        endif

        CONDAGRR1=10**Y

      RETURN
      END

        REAL FUNCTION CONDAGRR2(T)
c Conductivity of Ag at RRR=132.

      real a(5),b(4),c(4)

        data T1/100./, T2/30./
```

```
      data a/2.3825,-0.1305,3.643,-3.2826,0.7624/
        data b/21.281,-25.943,12.052,-1.8659/
        data c/4.9392,-3.0532,1.3874,-0.2131/

        T0=log10(T)
        if (T.le.T2) then
         y=a(1)+a(2)*T0+a(3)*T0**2+a(4)*T0**3+a(5)*T0**4
         elseif (T.le.T1) then
         y=b(1)+b(2)*T0+b(3)*T0**2+b(4)*T0**3
         else
         y=c(1)+c(2)*T0+c(3)*T0**2+c(4)*T0**3
        endif

        CONDAGRR2=10**Y

      RETURN
      END

        REAL FUNCTION CONDAGRR3(T)
c Conductivity of Ag at RRR=2360.

      real a(5),b(4),c(4)

        data T1/100./, T2/30./
      data a/3.5658,-0.1332,4.429,-4.9781,1.3427/
        data b/30.295,-39.687,18.99,-3.0252/
        data c/4.9392,-3.0532,1.3874,-0.2131/

        T0=log10(T)
        if (T.le.T2) then
         y=a(1)+a(2)*T0+a(3)*T0**2+a(4)*T0**3+a(5)*T0**4
         elseif (T.le.T1) then
         y=b(1)+b(2)*T0+b(3)*T0**2+b(4)*T0**3
         else
         y=c(1)+c(2)*T0+c(3)*T0**2+c(4)*T0**3
        endif

        CONDAGRR3=10**Y

      RETURN
      END

C ####################################################################
      REAL FUNCTION CONDHASTELLOY(T)
C ####################################################################
C #
C # Thermal conductivity of HASTELLOY C in W/m K as a function of temperature
C # based on Superpower 2G-YBCO tape
C #
C # variable    I/O          meaning                units
C # ------------------------------------------------------------------
C #   T          x        absolute temperature           K
C #   CONDAG    x          thermal conductivity          W/m K
C #
C # Author : Jun Feng
C # Version: 1.0  5/6/2010
```

```
C #
C ########################################################################
      parameter (n=14)
           real xa(n),ya(n)

           data xa/103.,200.,304.5,310.1,364.,476.,588.,700.,809.,920.5,
     &     1032.5,1143.1,1254.4,1365./
           data ya/7.2,8.7,9.4,10.2,11.1,13.,15.,16.9,19.,20.9,22.9,24.9,
     &     26.8,28.2/

           call NBISECX(T,Xa,YVAL,Ya,IX,N)

           CONDHASTELLOY=yval

           return
           end


C ########################################################################
      REAL FUNCTION CONDYBTAPE(T)
C ########################################################################
C #
C # Thermal conductivity of YBCO tape in W/m/K as a function of temperature
C # based on Superpower 2G-YBCO tape data
C #
C # variable    I/O              meaning                      units
C # ------------------------------------------------------------------
C #   T         x           absolute temperature                 K
C #   CONDYBTAPE      x       thermal conductivity              W/m/K
C #
C # Author : Jun Feng
C # Version: 1.0  5/7/2010
C #
C ########################################################################

           data fr_YB/0.01075/,fr_AG/0.0215/,fr_CU/0.43/,fr_SS/0.5376/

           condybtape=fr_YB*condybco(2,T)+fr_AG*condag(100.,T)
     &     +fr_CU*condcu(T,0.,100.)+fr_ss*condhastelloy(T)

C *
      RETURN
      END
```

A6: Specific heat subroutine

```
C ##########################################################################
      REAL FUNCTION CPYBTAPE(T)
C ##########################################################################
C #
C # Specific Heat of YBCO tape in J/Kg K as a function of temperature
C #  0<T<300, based on Superpower 2G-YBCO tape data
C #
C # variable    I/O             meaning                      units
C # ------------------------------------------------------------------------
C #   T         x           absolute temperature                  K
C #   CPYBCOTAPE      x           specific heat                       J/Kg K
C #
C # Author : Jun Feng
C # Version: 1.0  4/8/2010
C #
C ##########################################################################
      data den_YB/6.3e3/,den_ag/10.49e3/,den_cu/8.9e3/,den_ss/8.89e3/
          data fr_YB/0.01075/,fr_AG/0.0215/,fr_CU/0.43/,fr_SS/0.5376/

          ave_den=den_YB*fr_YB + den_ag*fr_ag + den_cu*fr_cu + den_ss*fr_ss
          CPYBTAPE=(CPYBCO(T)*fr_YB*den_YB + CPAG(T)*fr_AG*den_AG
     &       + CPCU(T)*fr_CU*den_CU + CPSS(T)*fr_SS*den_SS)/ave_den
C *
      RETURN
      END
```