LBNL Eng. Note: SU-1010-4841

Crosscheck of the ANSYS-COMSOL 2D FEM Implementations for Superconducting Accelerator Magnets

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Within ANSYS there is the capability for users to create their own element type by writing the code which defines the element's properties and the generation of its finite element matrices. After the compilation of a custom ANSYS executable, all other aspects of the software (such as geometry generation, meshing, solving, and post-processing) are compatible with the user element. Control over the generation of the matrices allows for customization of the mathematical formulation, material properties, and many other aspects of the element. This note documents a verification study which was completed to crosscheck results from user defined elements in ANSYS developed at Berkeley [1] with a similar 2D FEM implementation in COMSOL and STEAM developed at CERN [2, 3].

Contents

1 Introduction and General Comments

This note documents a verification study for the 2D ANSYS user elements developed at LBNL. Results are compared between these elements and a similar implementation developed at CERN in COMSOL. Two separate Nb_3Sn dipoles models were used as a basis for the comparison. First a series of tests were performed for a single layer geometry slowly building up checks of inductance, material property fits, IFCC, quench, electromagnetic-thermal coupling, and finally coupling to an external circuit. A second geometry with two layers was then used in a final series of tests which built up the full range of multiphysics effects. For these final tests, both a dump resistor extraction and CLIQ based protection are compared.

More information about the user elements and their use can be found in

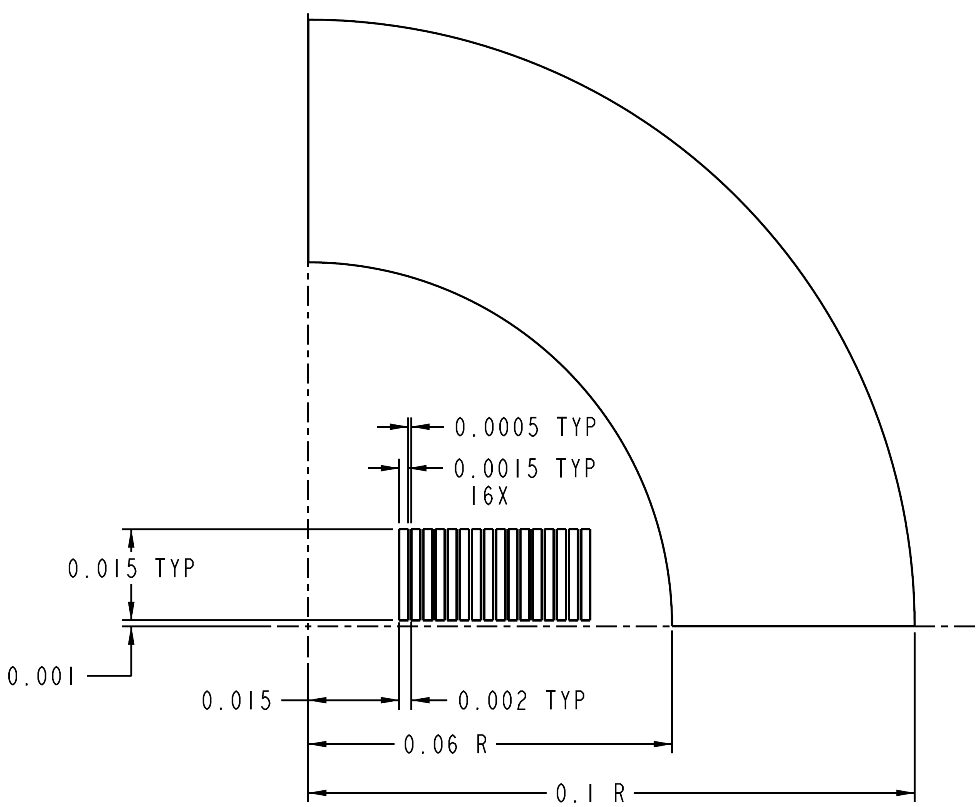
- [4]: general website
- [5]: documentation for USER101
- [6]: documentation for USER102
- [7]: check of equivalent magnetization IFCC in a uniformly changing background field for a single strand (comparison between USER102 results and analytic expectations)

2 A Single Layer Nb_3Sn Dipole Model

2.1 Model and Geometry

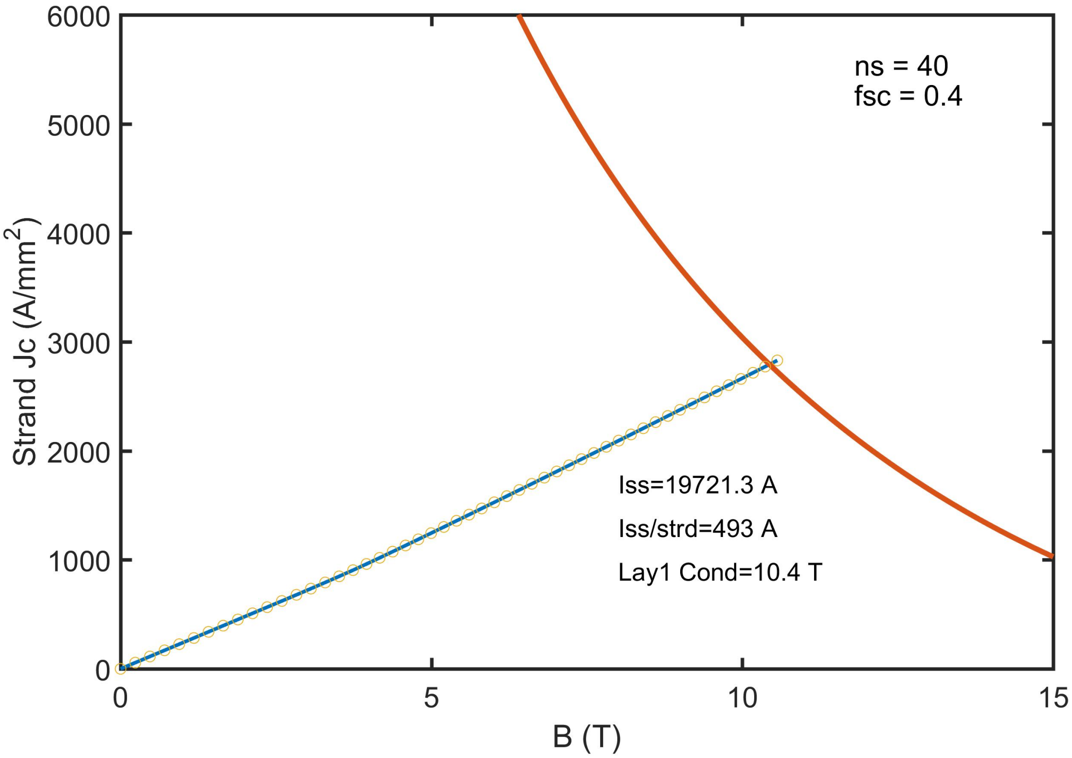
A dipole model was designed to allow for comparison of results in a field and current regime representative of realistic Nb_3Sn accelerator magnets. This model consists of a single, block-like conductor layer surrounded by a cylindrical iron yoke. The figure below details the model dimensions (with units of meters), and a list of high level model parameters are given in the table. The cable and conductor properties are given in Appendices A and B. The non-linear BH curve for the iron yoke can be found in Appendix D. The outer, radial boundary conditions are assumed to be far enough from the coil and yoke to no longer have an impact on the results. There are also .stp and .dxf cad files (named "geo") included. In many cases the compared results are averaged over the first half turn labeled "HT0". This is the cable nearest to the aperture (farthest left of the 16).

Turns (per quadrant)	16	
Nb_3Sn J_c (4.5 K, 12 T)	2040	A/mm^2
Short-sample current (4.5 K)	19.7	kA
Short-sample cond. field (4.5 K)	10.4	T
Lc: effective res. coil length	10.11	m
Li: effective ind. coil length	9.2	m



2.2 Short-Sample

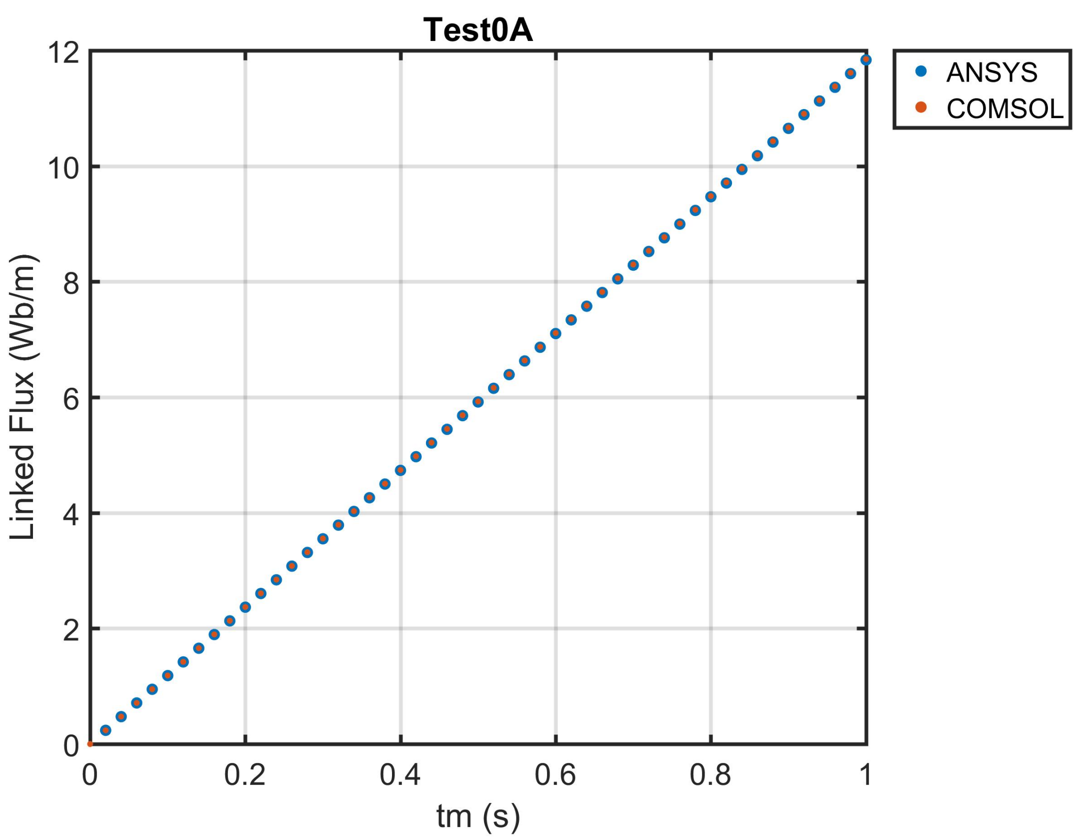
The strand and cable parameters in Appendix A, load line with iron (from Test0B), and J_c fit found in Appendix B were used to calculate the short-sample for the single layer model with iron. As seen in the figure below, the short-sample conductor field is 10.4 T at a current of 19.72 kA when operating at a temperature of 4.5 K.

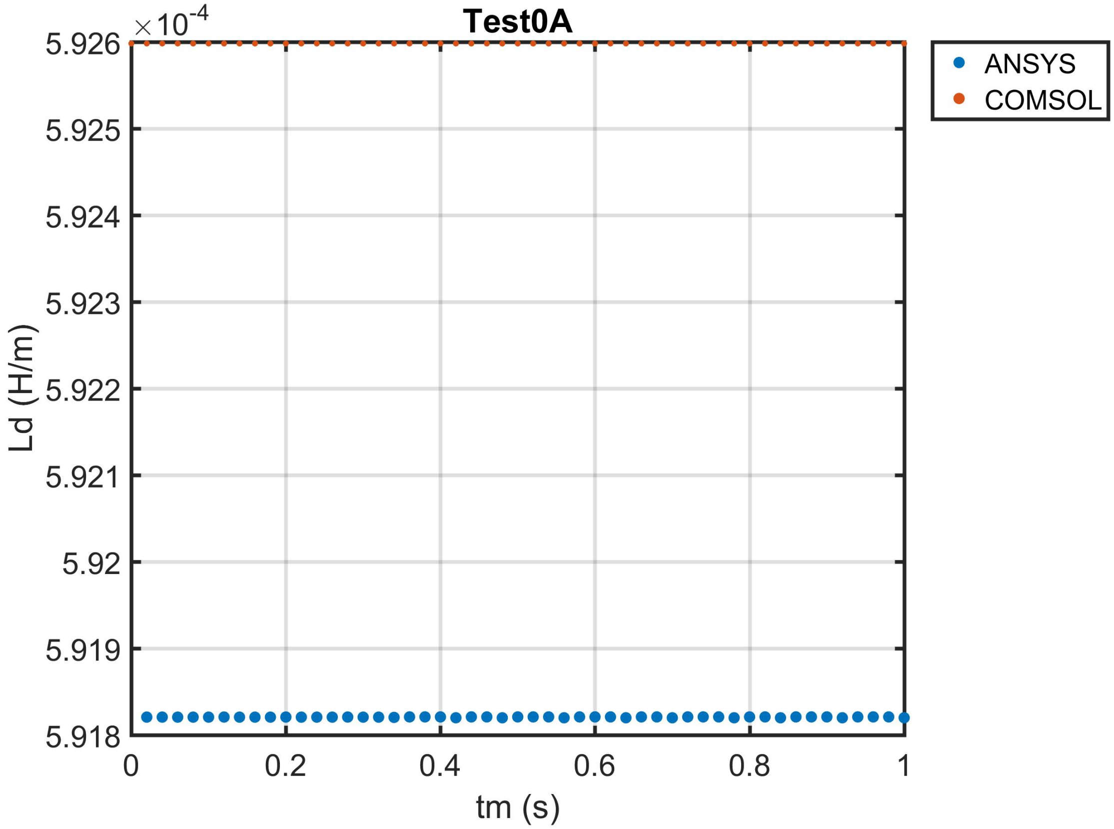


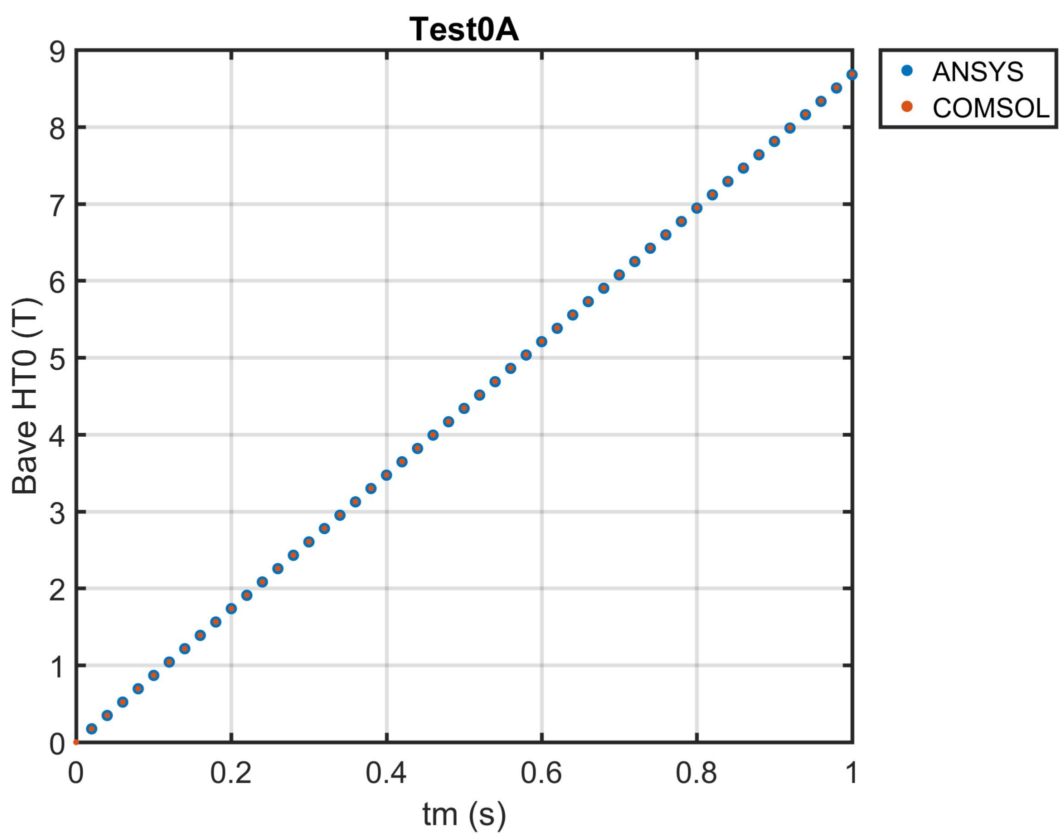
3 Single Layer Tests

3.1 Test 0.A Differential Inductance (no iron yoke)

Active physics	EM
Iron yoke	NO
IFCC	NO
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	None
External loads	Linear ramp-up, t=(0,1) [s], Δt=20e-3 [s], i=(0,20e3) [A]
Output	Coil magnetic flux ϕ [Wb/m]
	Differential inductance as $L_d = \Delta\phi/\Delta i$ [H/m] (finite difference)
	B_{aveHT0} [T]

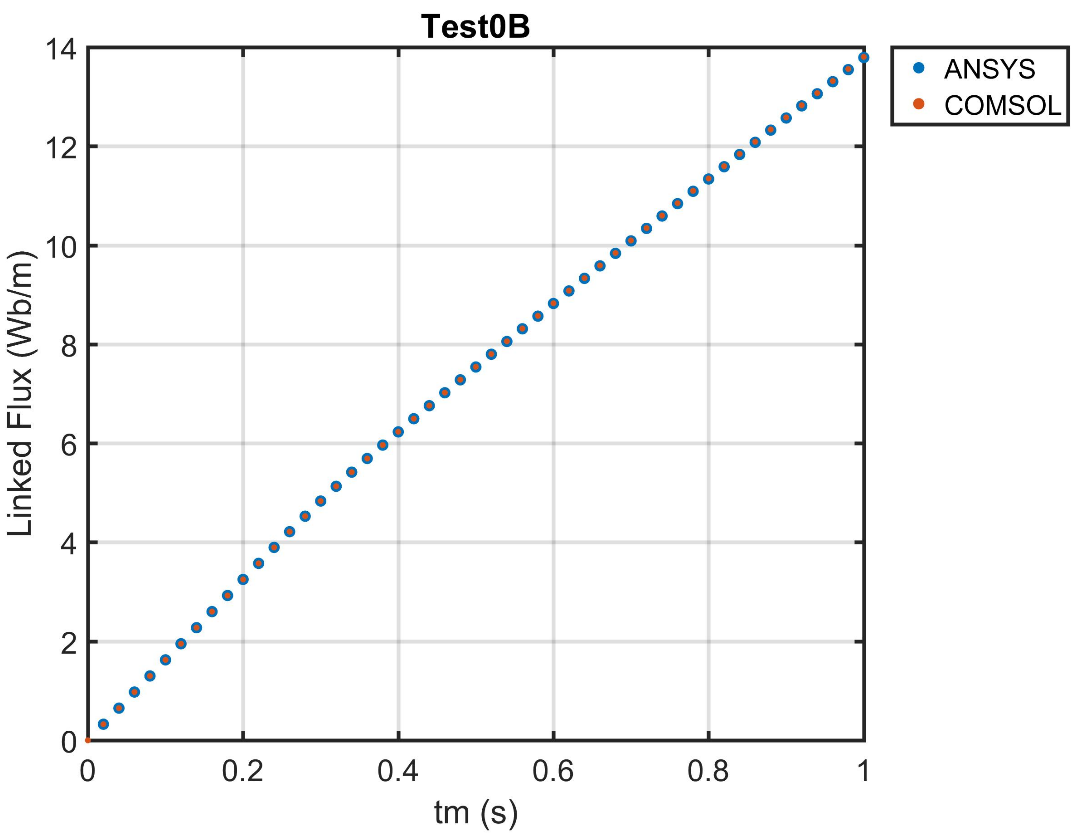


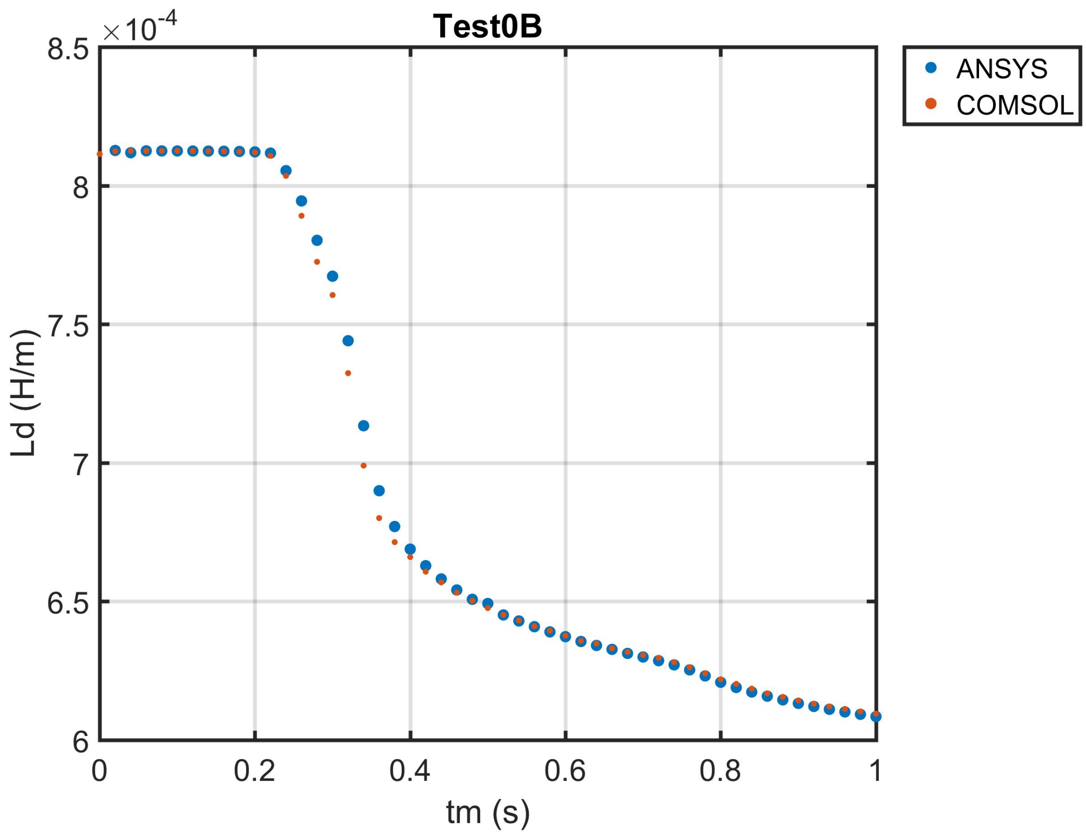

Test0A
×10^-4
5.926
5.925
5.924
5.923
5.922
5.921
5.92
5.919
5.918
Ld (H/m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

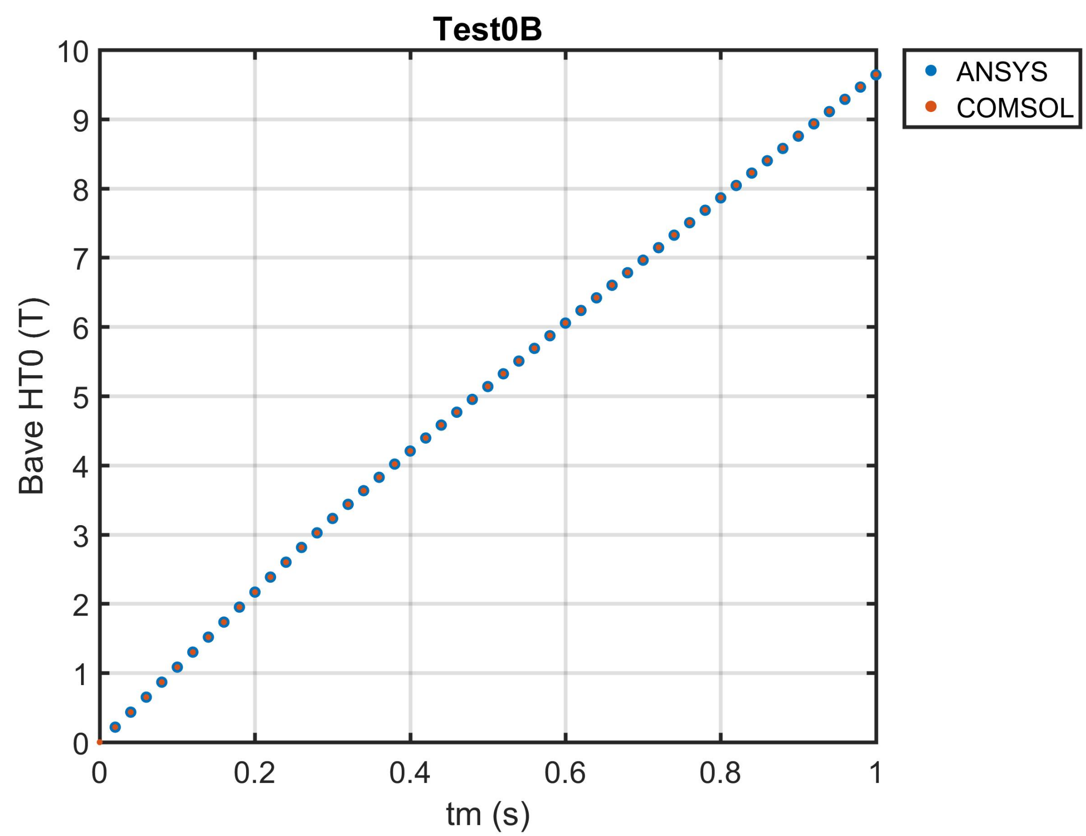

Test0A
9
8
7
6
5
4
3
2
1
0
Bave HT0 (T)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

3.2 Test 0.B Differential Inductance (with iron yoke)

Active physics	EM
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	None
External loads	Linear ramp-up, t=(0,1) [s], Δt=20e-3 [s], i=(0,20) [kA]
Output	Coil magnetic flux ϕ [Wb/m]
	Differential inductance as $L_d = \Delta\phi/\Delta i$ [H/m] (finite difference)
	B_{aveHT0} [T]

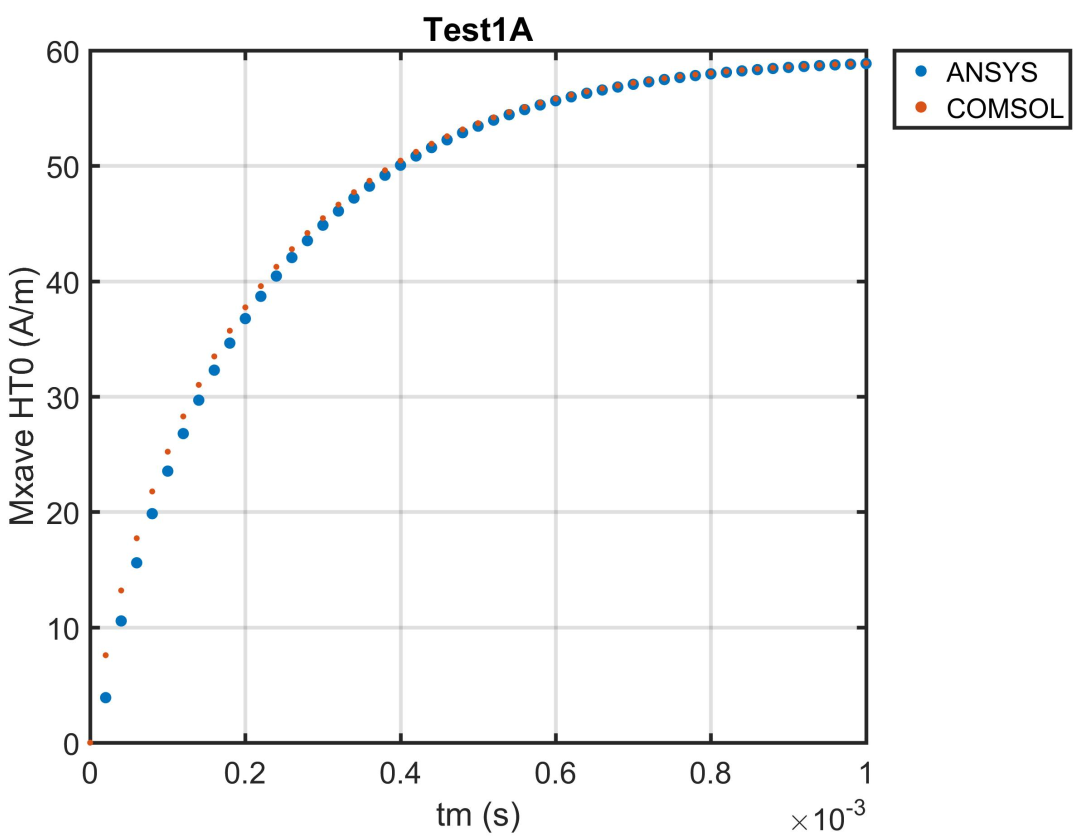


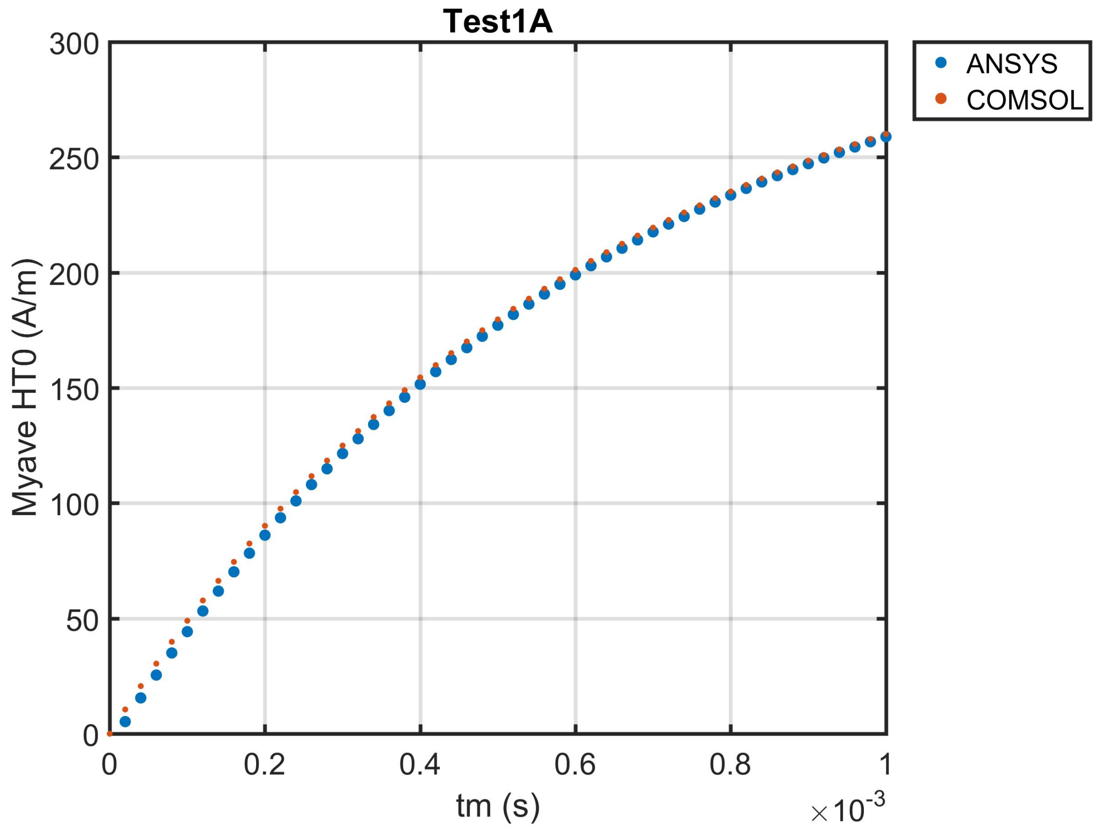

Test0B
×10^-4
8.5
8
7.5
7
6.5
6
Ld (H/m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

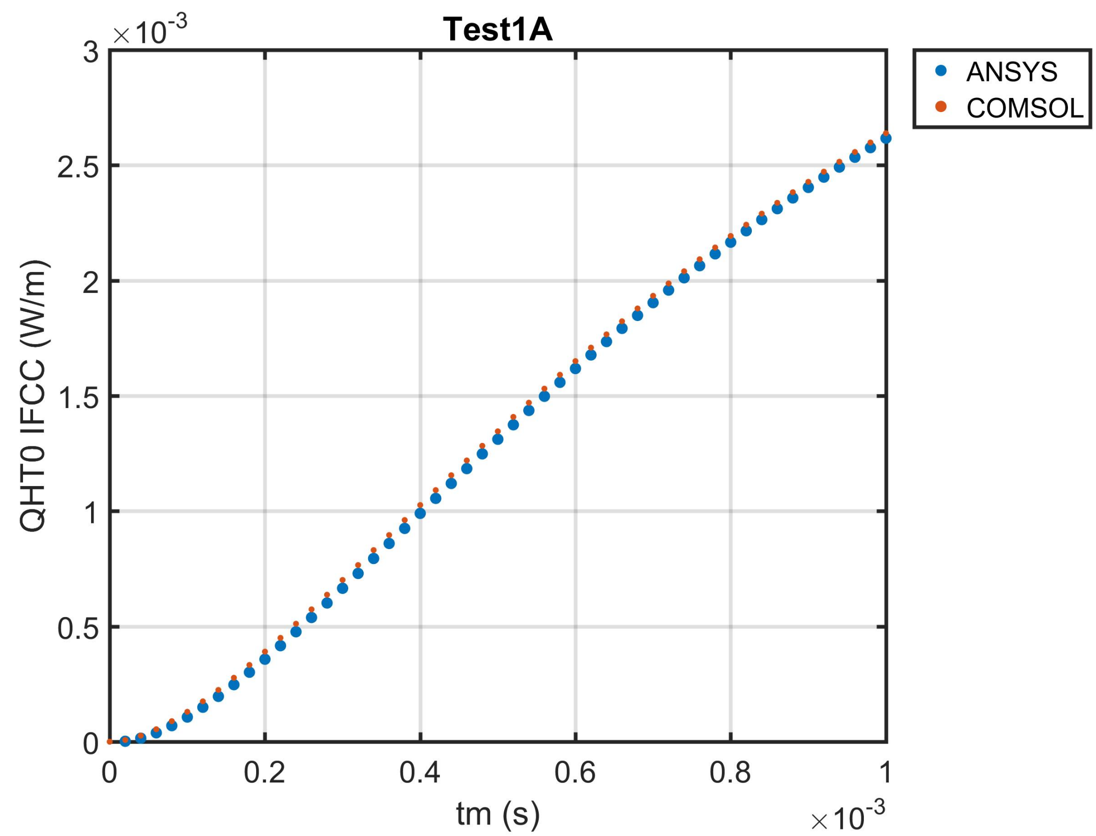

Test0B
10
9
8
7
6
5
4
3
2
1
0
Bave HT0 (T)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

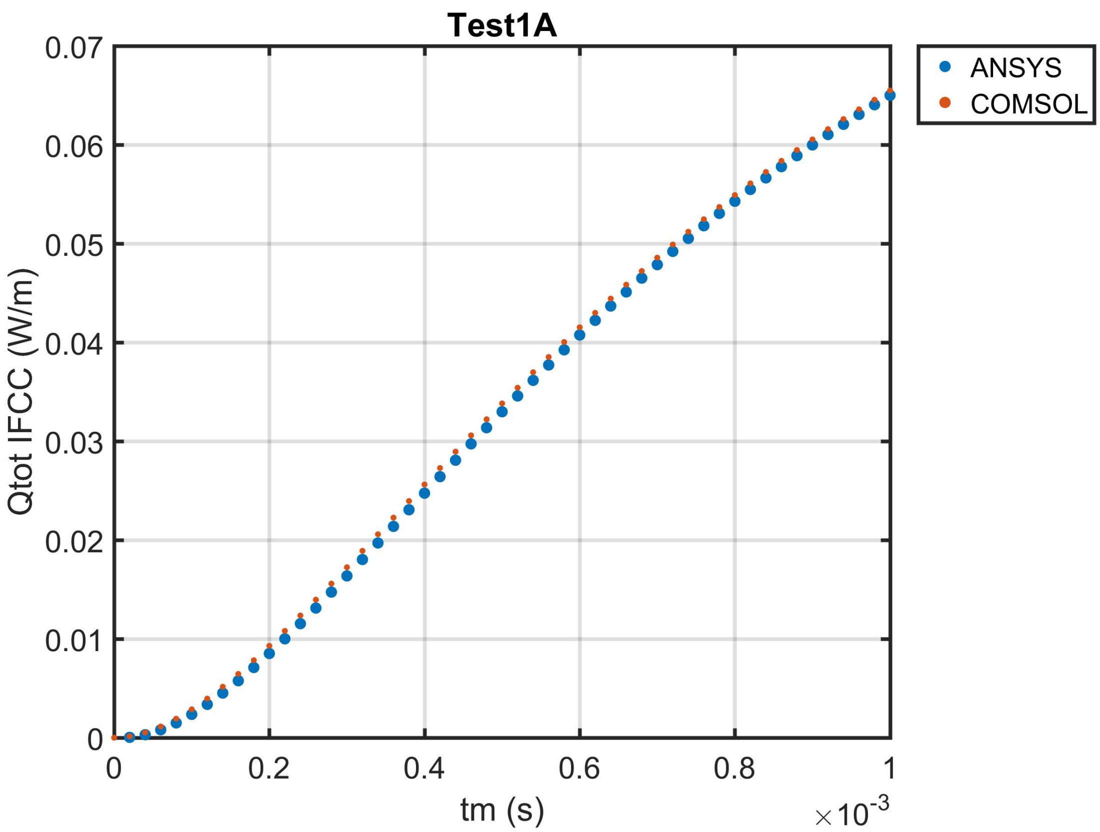
3.3 Test 1.A Interfilament Coupling Currents

Active physics	EM
Iron yoke	YES
IFCC	YES
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	None
External loads	Linear ramp-up, t=(0,1e-3) [s], Δt=20e-6 [s], i=(0,1) [A]
Fixed τ-IFCC	1e-3 [s]
Output	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W]
	Q-IFCC$_{totcoil}$ [W]



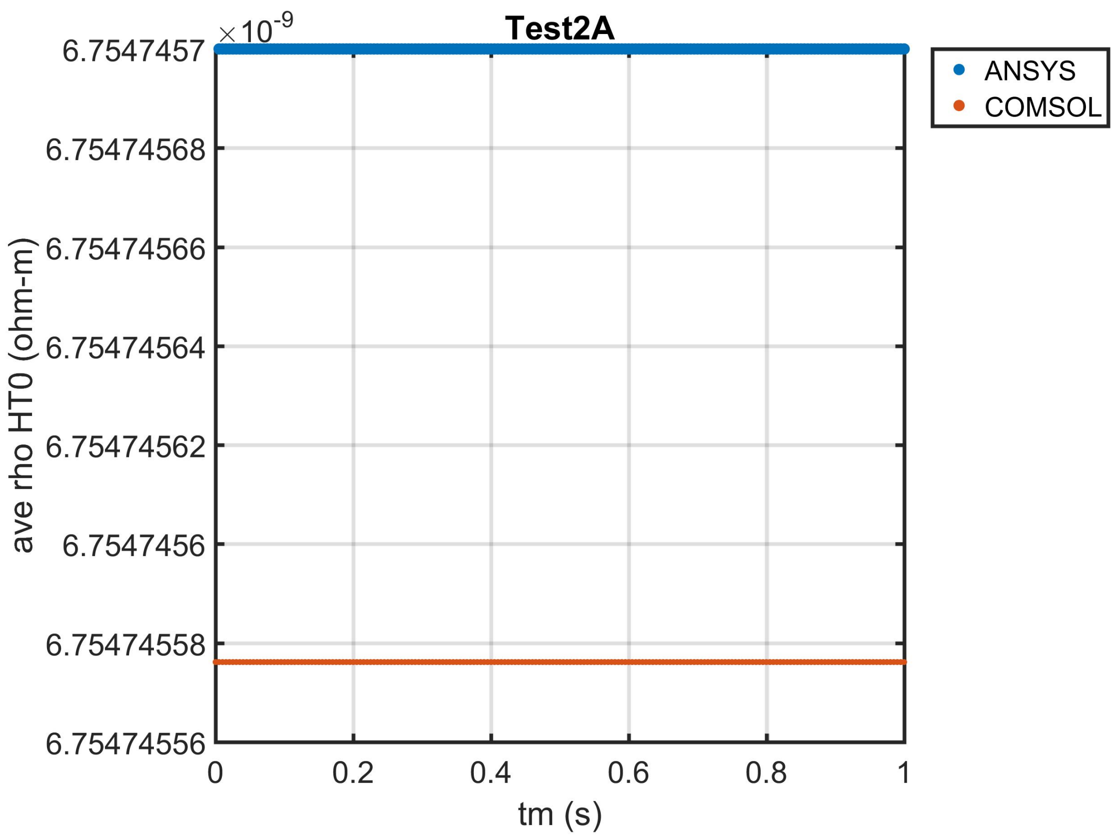

Test1A
ANSYS
COMSOL
Myave HT0 (A/m)
tm (s)
×10^-3
0
50
100
150
200
250
300
0
0.2
0.4
0.6
0.8
1

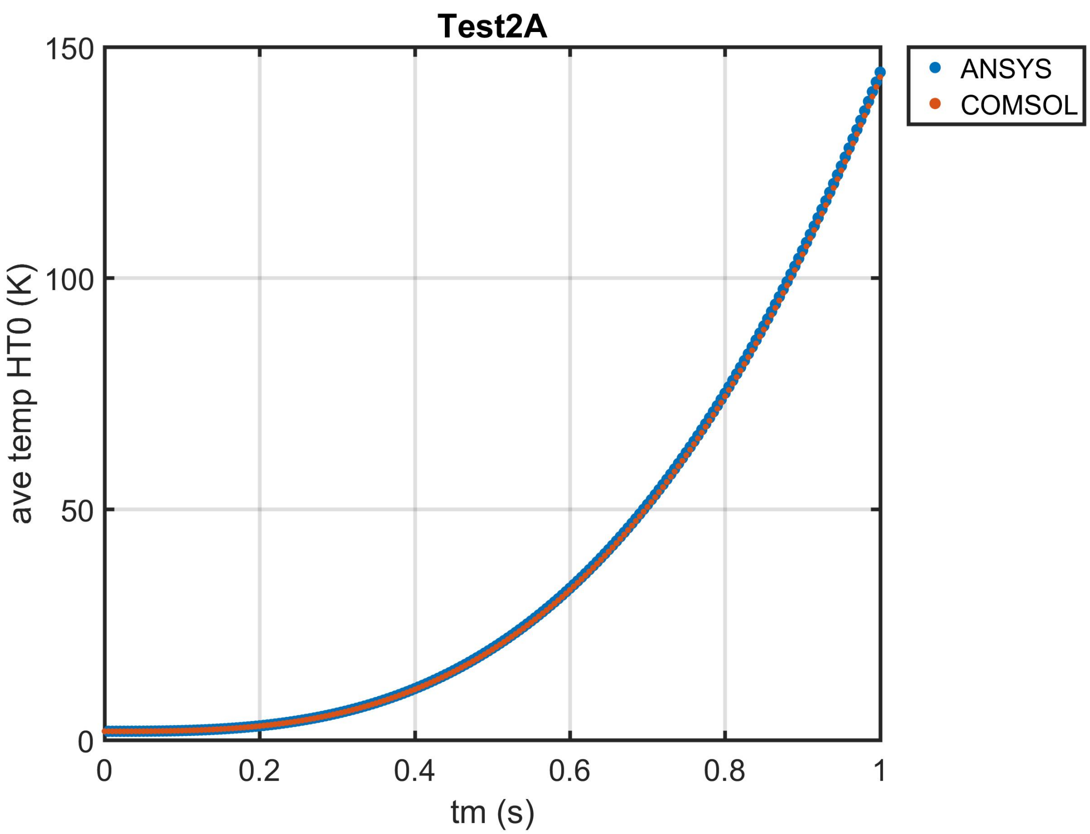

Test1A
ANSYS
COMSOL
×10^-3
QHT0 IFCC (W/m)
tm (s)
×10^-3
0
0.5
1
1.5
2
2.5
3
0
0.2
0.4
0.6
0.8
1

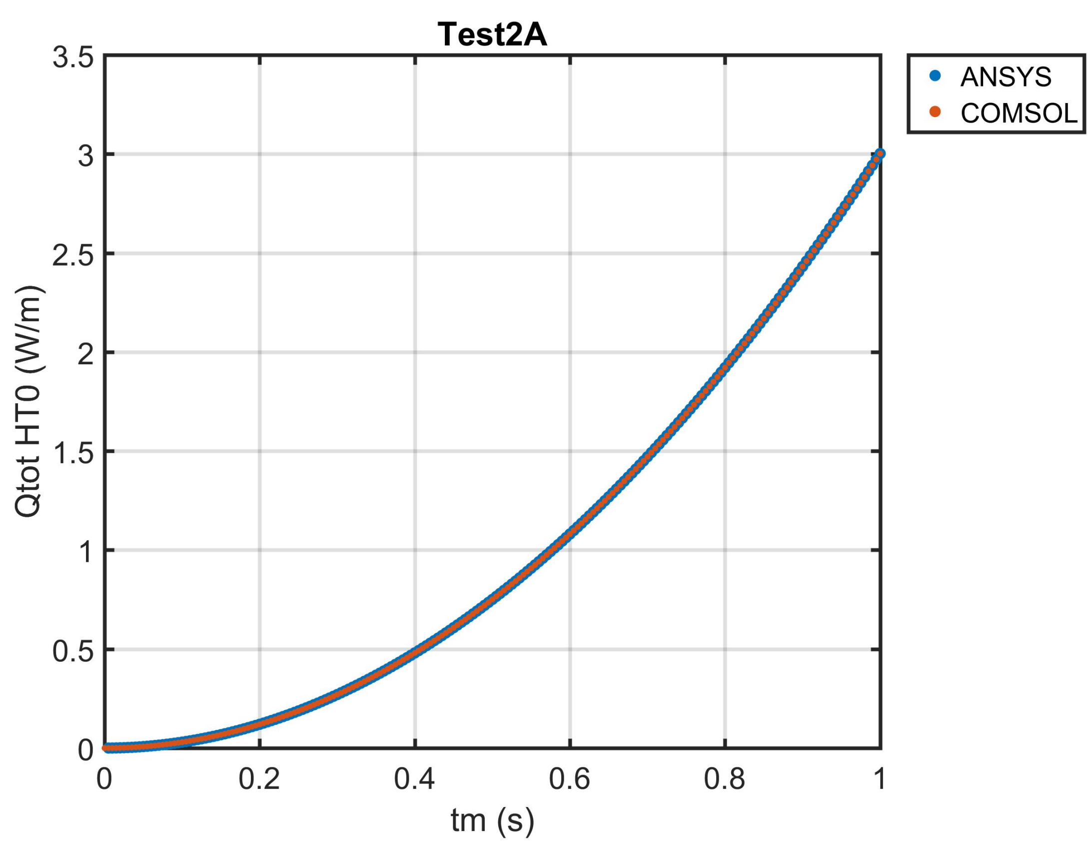

Test1A
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
Qtot IFCC (W/m)
0
0.2
0.4
0.6
0.8
1
tm (s)
×10-3
ANSYS
COMSOL

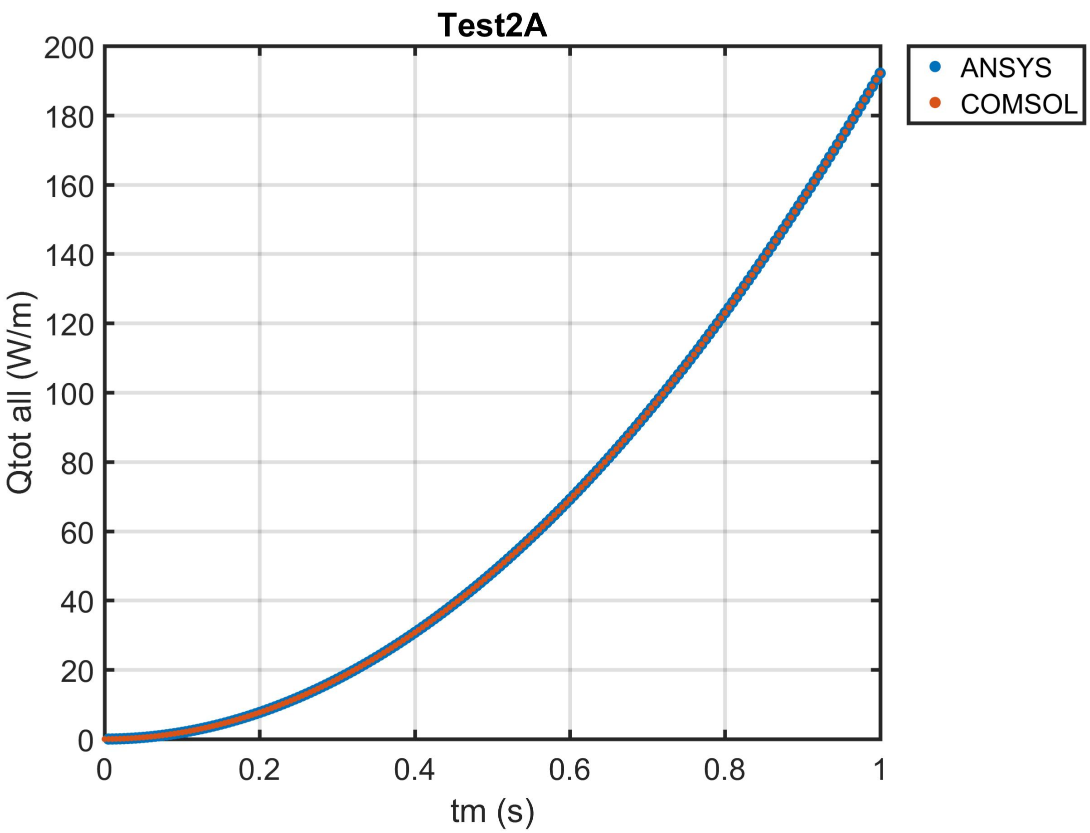
3.4 Test 2.A Ohmic Losses - Bare Cable

Active physics	EM, TH
Coil initial temp	1.9 [K]
Iron yoke	YES
IFCC	NO
Quench state	Force Quenched
Cable insulation material	None
Cable voids filling material	None
External loads	Constant, t=(0,1) [s], Δt=0.02 [s], i=(0,100) [A]
Material prop.	Fixed, see Appendix F
Output	ρ_{aveHT0} [Ωm]
	T_{aveHT0} [K]
	Q_{totHT0} [W]
	$Q_{totcoil}$ [W]



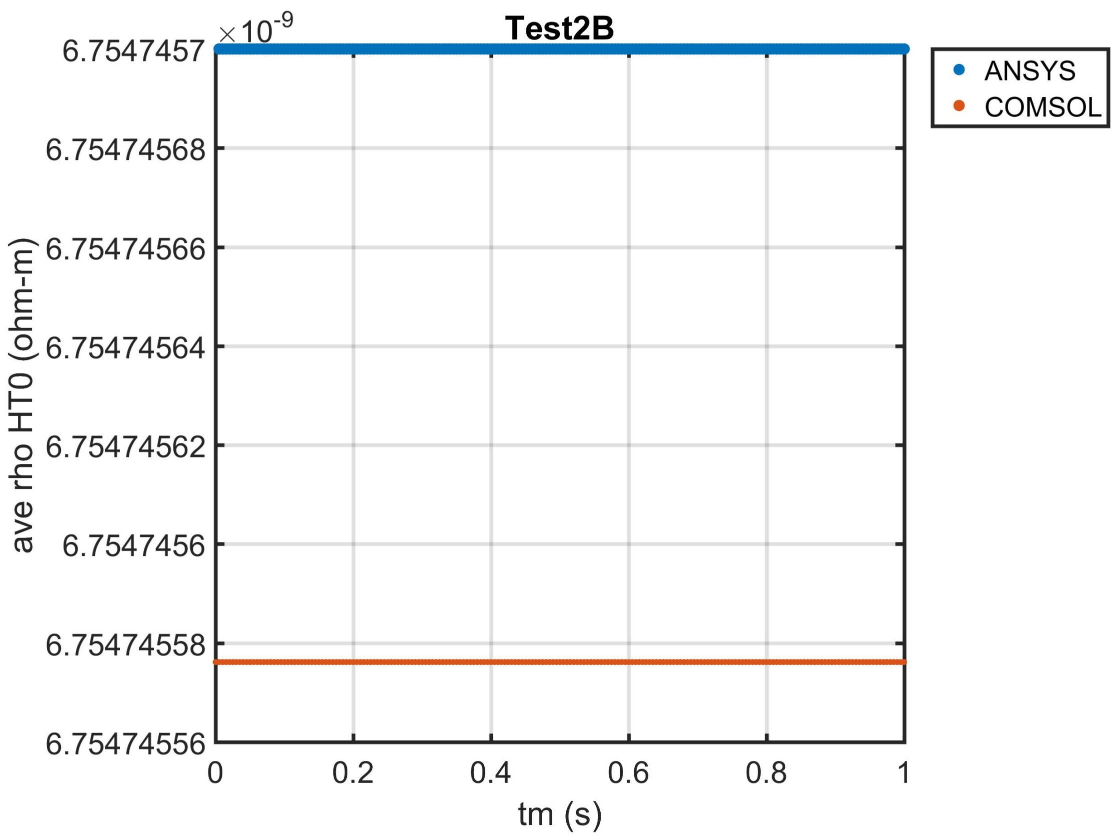

Test2A
ANSYS
COMSOL
ave temp HT0 (K)
tm (s)
150
100
50
0
0
0.2
0.4
0.6
0.8
1

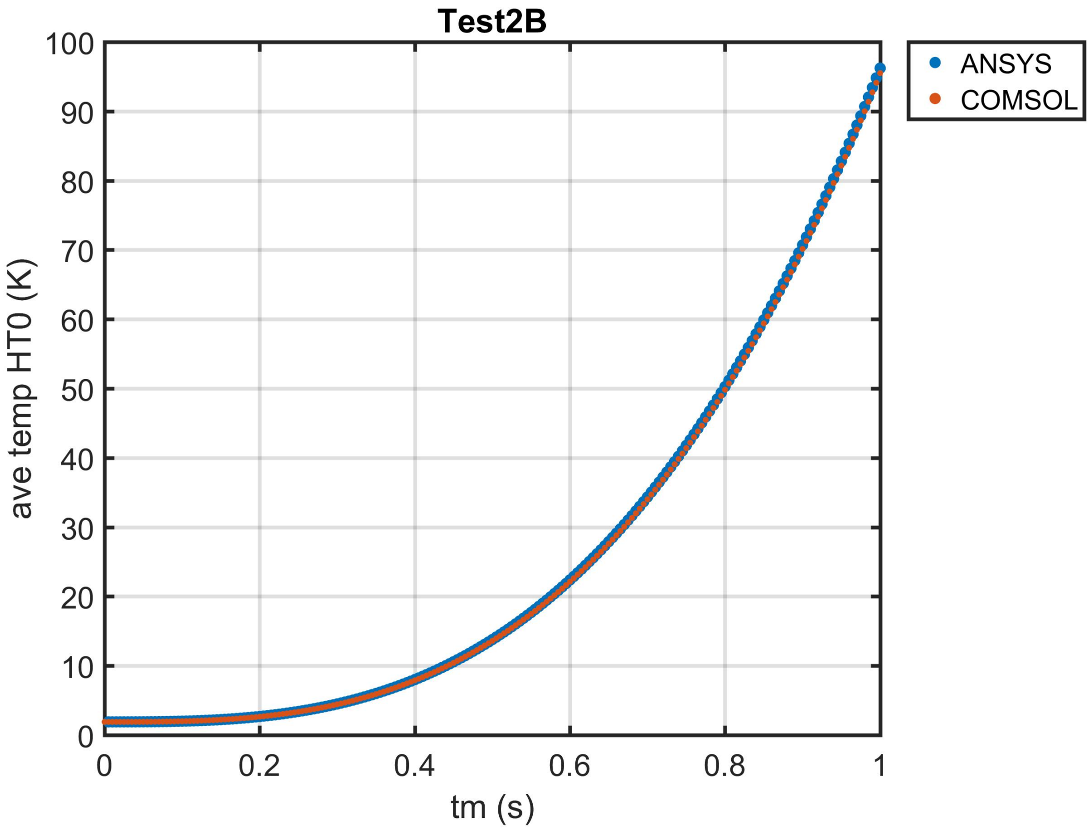

Test2A
ANSYS
COMSOL
Qtot HT0 (W/m)
tm (s)
3.5
3
2.5
2
1.5
1
0.5
0
0
0.2
0.4
0.6
0.8
1

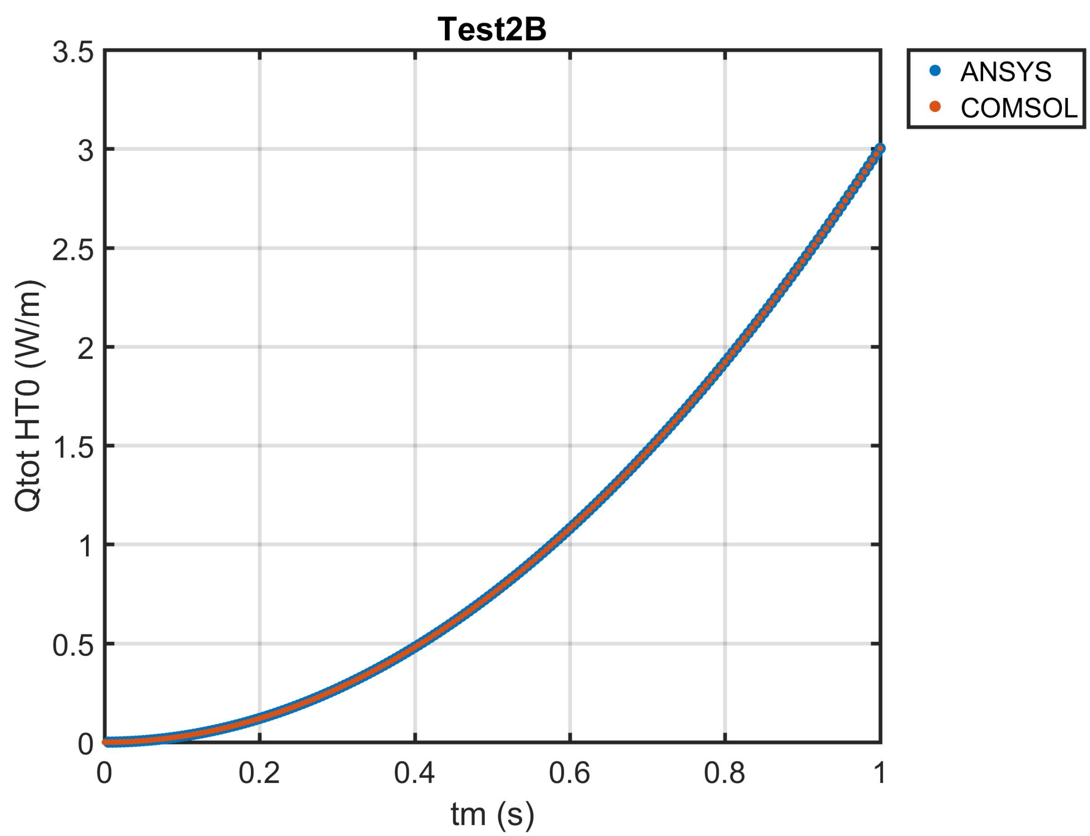

Test2A
ANSYS
COMSOL
Qtot all (W/m)
tm (s)
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1

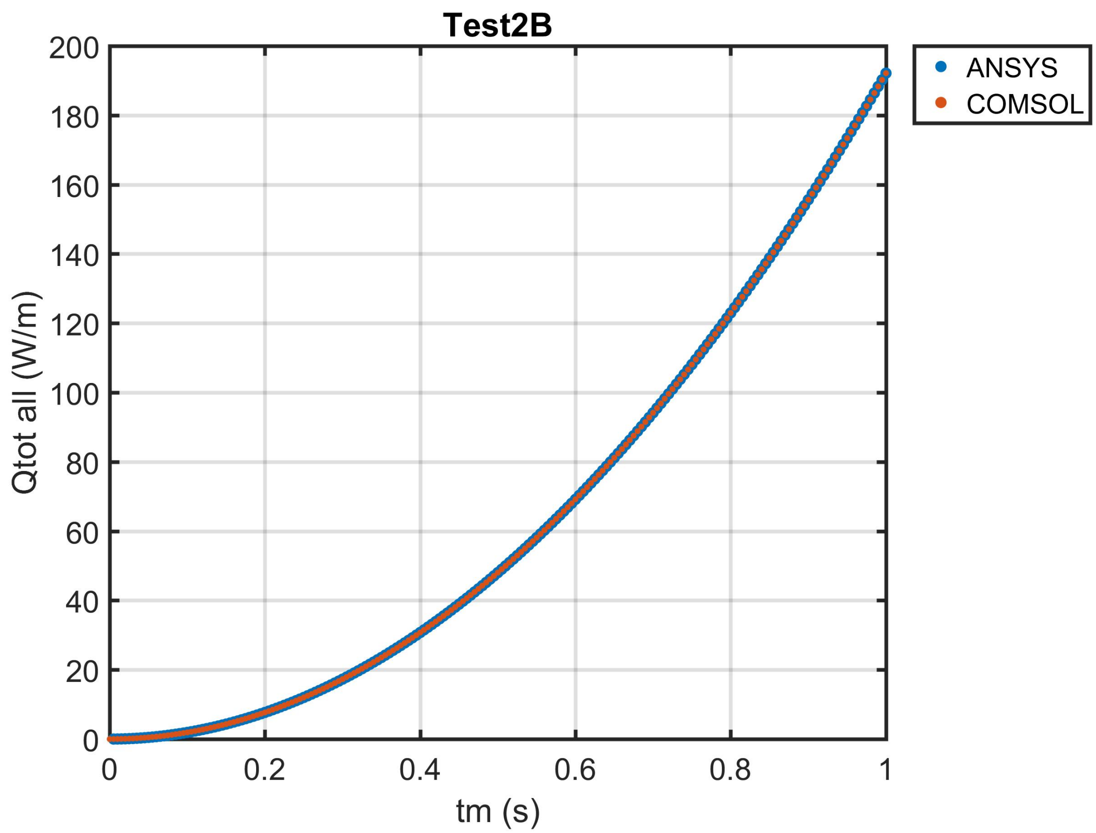
3.5 Test 2.B Ohmic Losses - Bare Cable with Filler

Active physics	EM, TH
Coil initial temp	1.9 [K]
Iron yoke	YES
IFCC	NO
Quench state	Force Quenched
Cable insulation material	None
Cable voids filling material	Glass Fiber
External loads	Constant, t=(0,1) [s], Δt=0.02 [s], i=(0,100) [A]
Material prop.	Fixed, see Appendix F
Output	ρ_{aveHT0} [Ωm]
	T_{aveHT0} [K]
	Q_{totHT0} [W]
	$Q_{totcoil}$ [W]



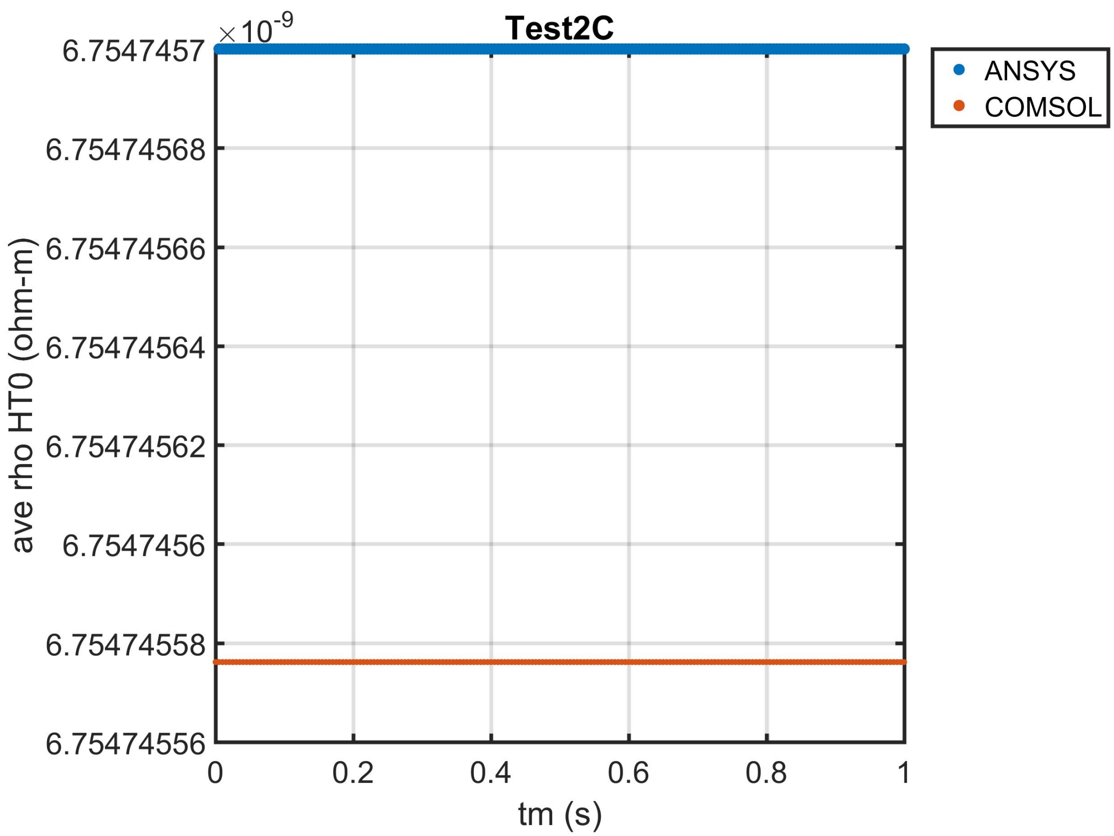

Test2B
ANSYS
COMSOL
ave temp HT0 (K)
tm (s)
0
10
20
30
40
50
60
70
80
90
100
0
0.2
0.4
0.6
0.8
1

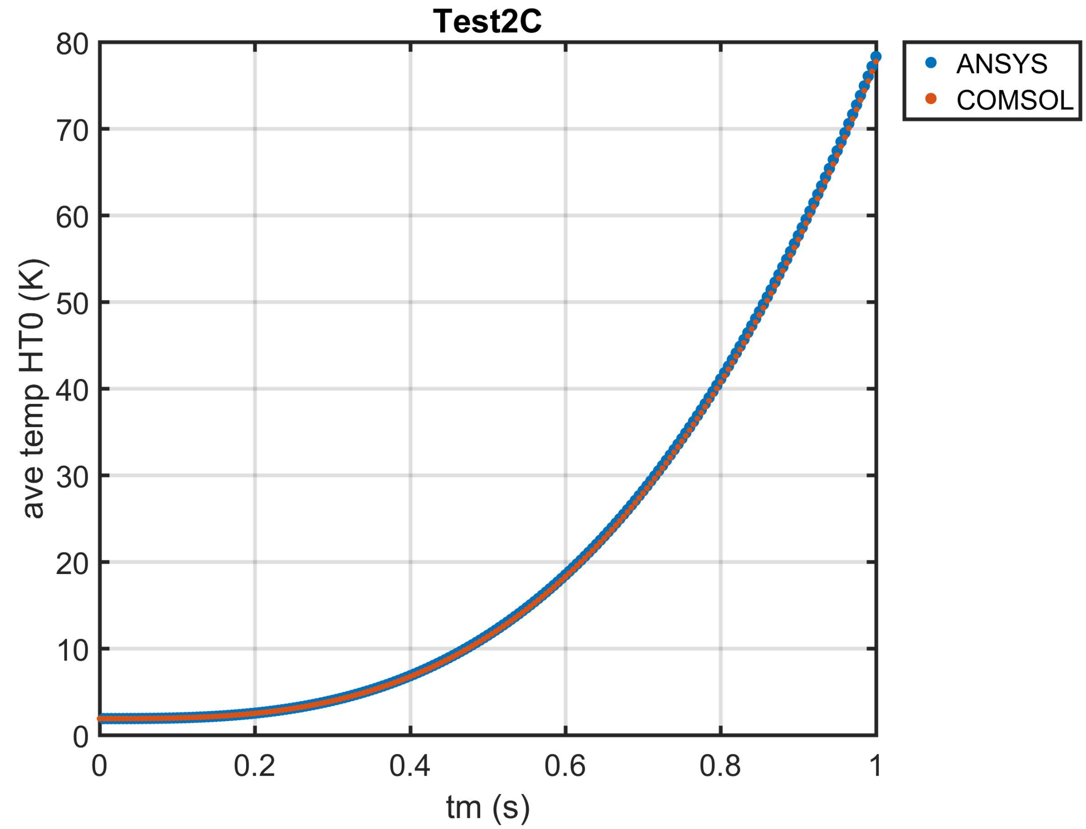

Test2B
ANSYS
COMSOL
Qtot HT0 (W/m)
tm (s)
0
0.5
1
1.5
2
2.5
3
3.5
0
0.2
0.4
0.6
0.8
1

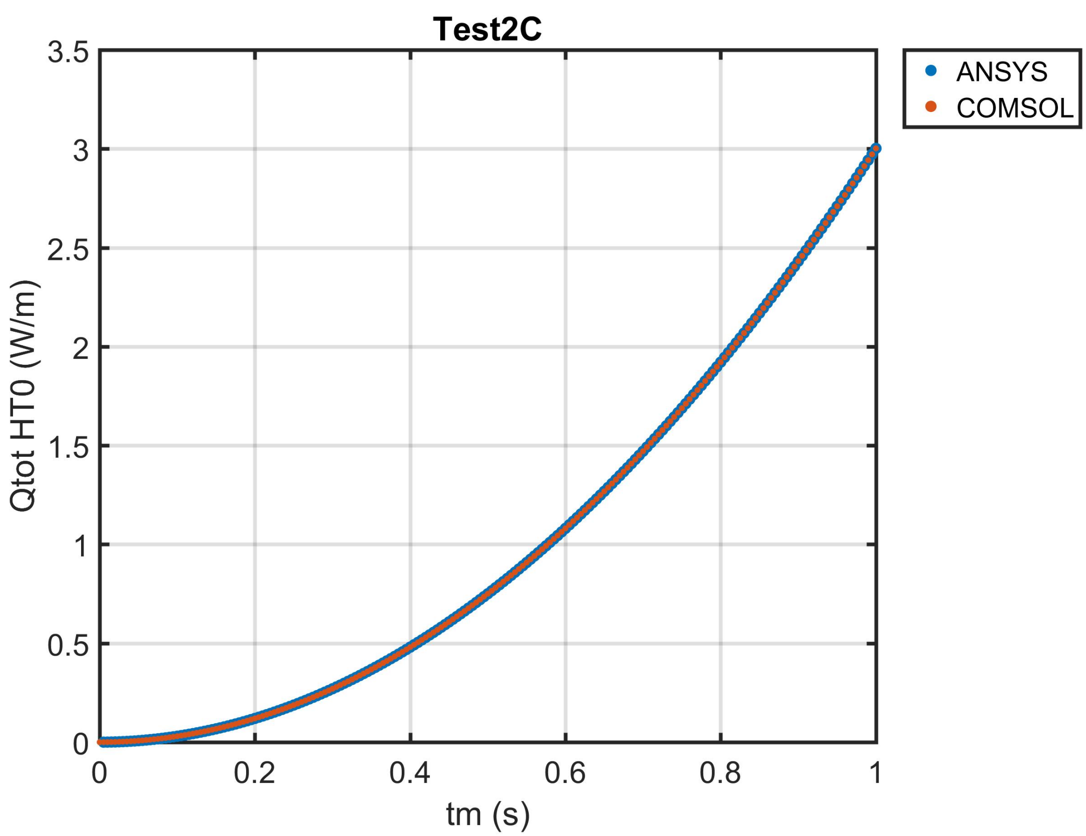

Test2B
Qtot all (W/m)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1

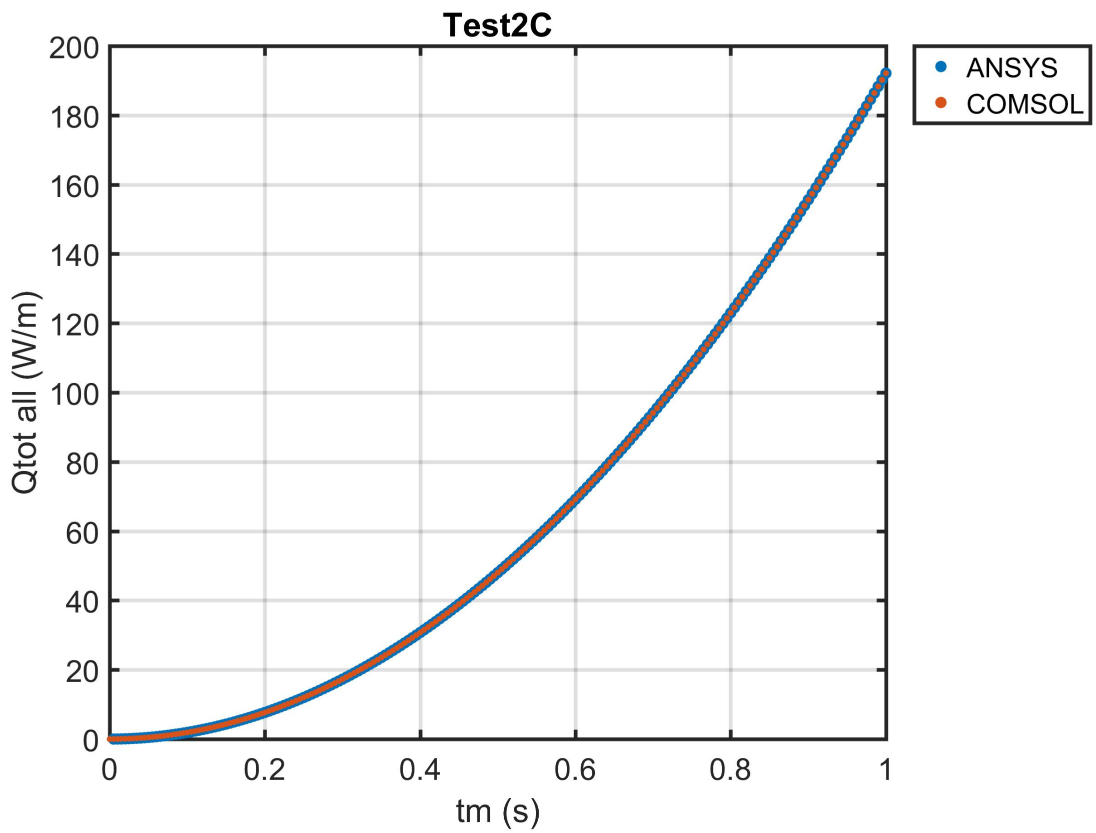
3.6 Test 2.C Ohmic Losses - Ins. Cable with Filler

Active physics	EM, TH
Coil initial temp	1.9 [K]
Iron yoke	YES
IFCC	NO
Quench state	Force Quenched
Cable insulation material	Glass Fiber
Cable voids filling material	Glass Fiber
External loads	Constant, t=(0,1) [s], Δt=0.02 [s], i=(0,100) [A]
Material prop.	Fixed, see Appendix F
Output	ρ_{aveHT0} [Ωm]
	T_{aveHT0} [K]
	Q_{totHT0} [W]
	$Q_{totcoil}$ [W]




Test2C
ANSYS
COMSOL
ave temp HT0 (K)
tm (s)
0
10
20
30
40
50
60
70
80
0
0.2
0.4
0.6
0.8
1

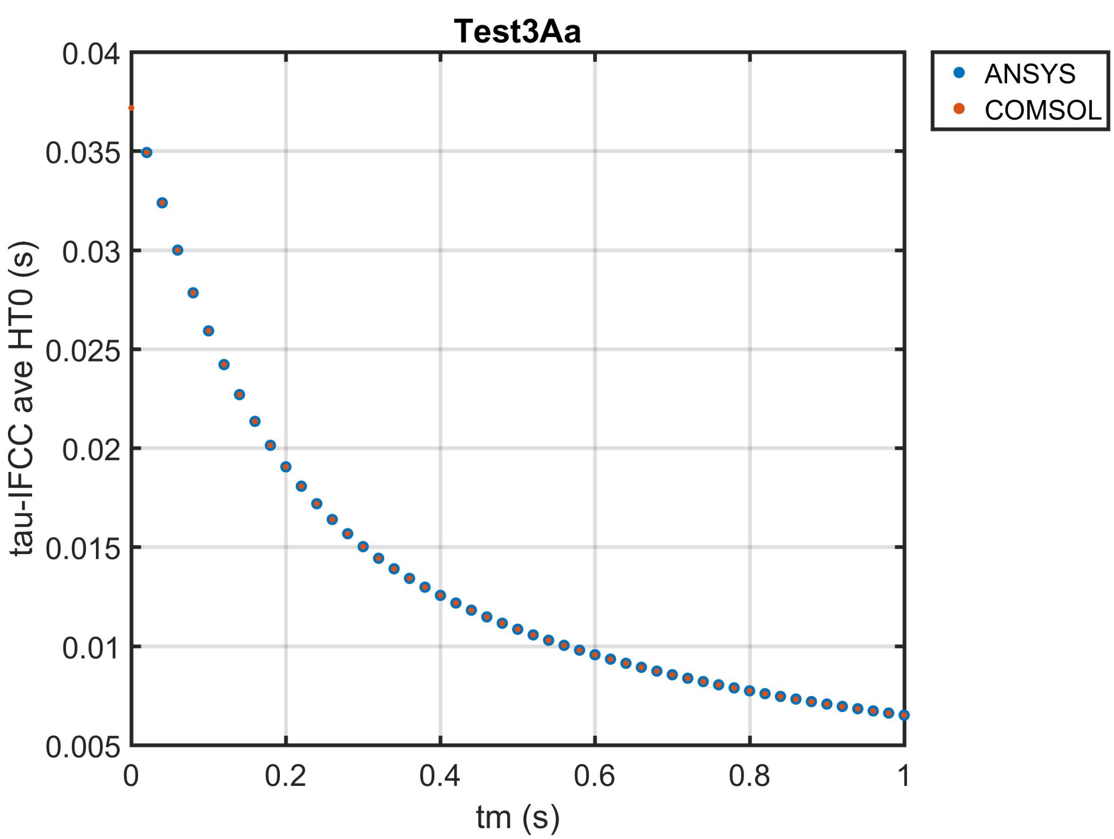

Test2C
ANSYS
COMSOL
Qtot HT0 (W/m)
tm (s)
0
0.5
1
1.5
2
2.5
3
3.5
0
0.2
0.4
0.6
0.8
1

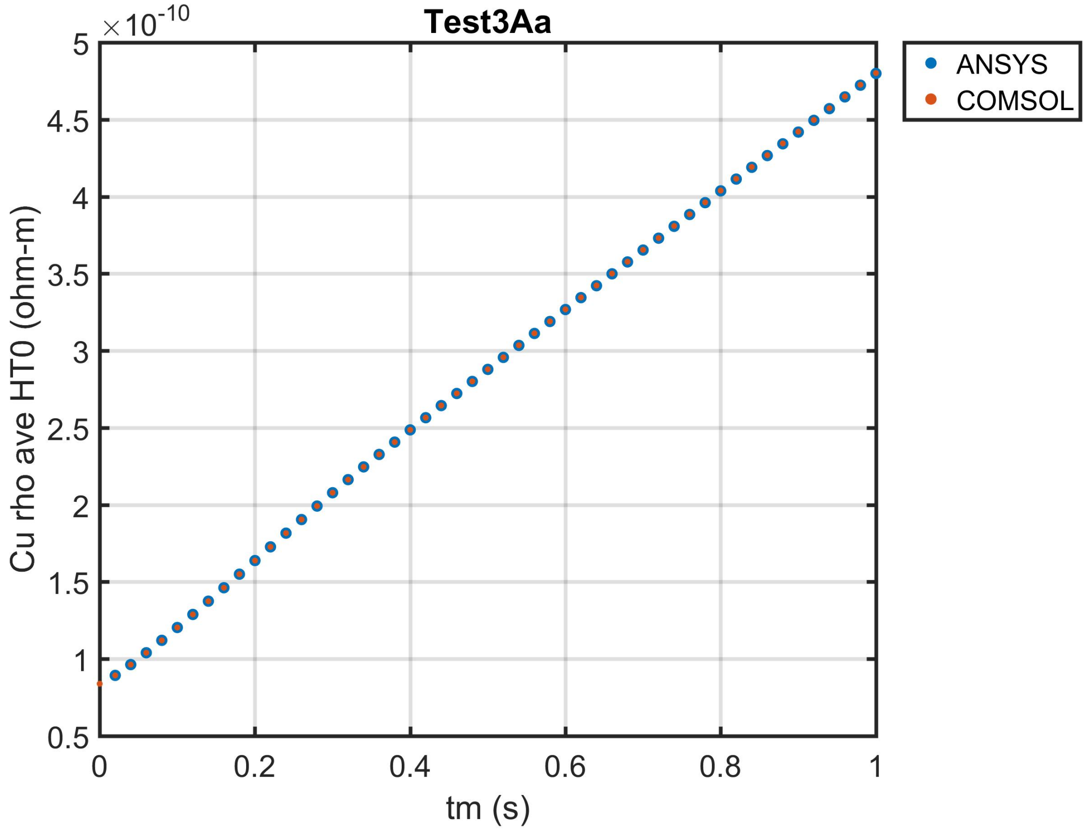

Test2C
Qtot all (W/m)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
140
160
180
200
0
0.2
0.4
0.6
0.8
1

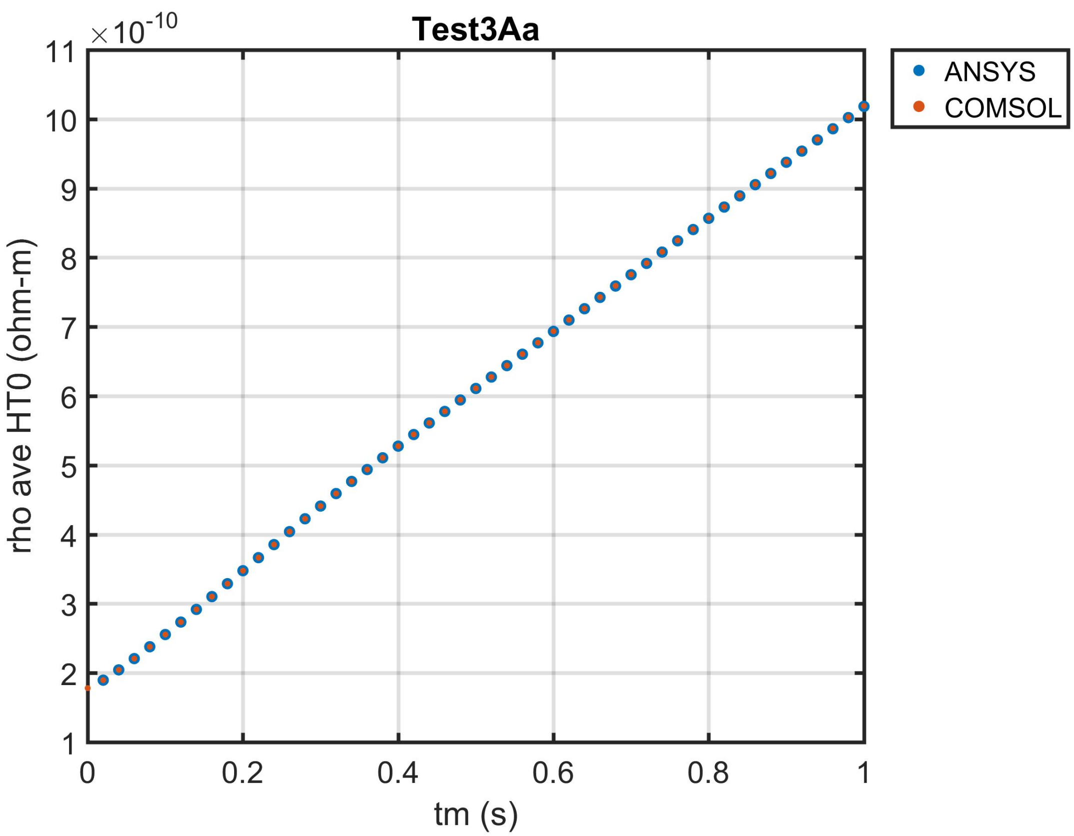
3.7 Test 3.A Resistivity and Tau IFCC (B and T dependence)

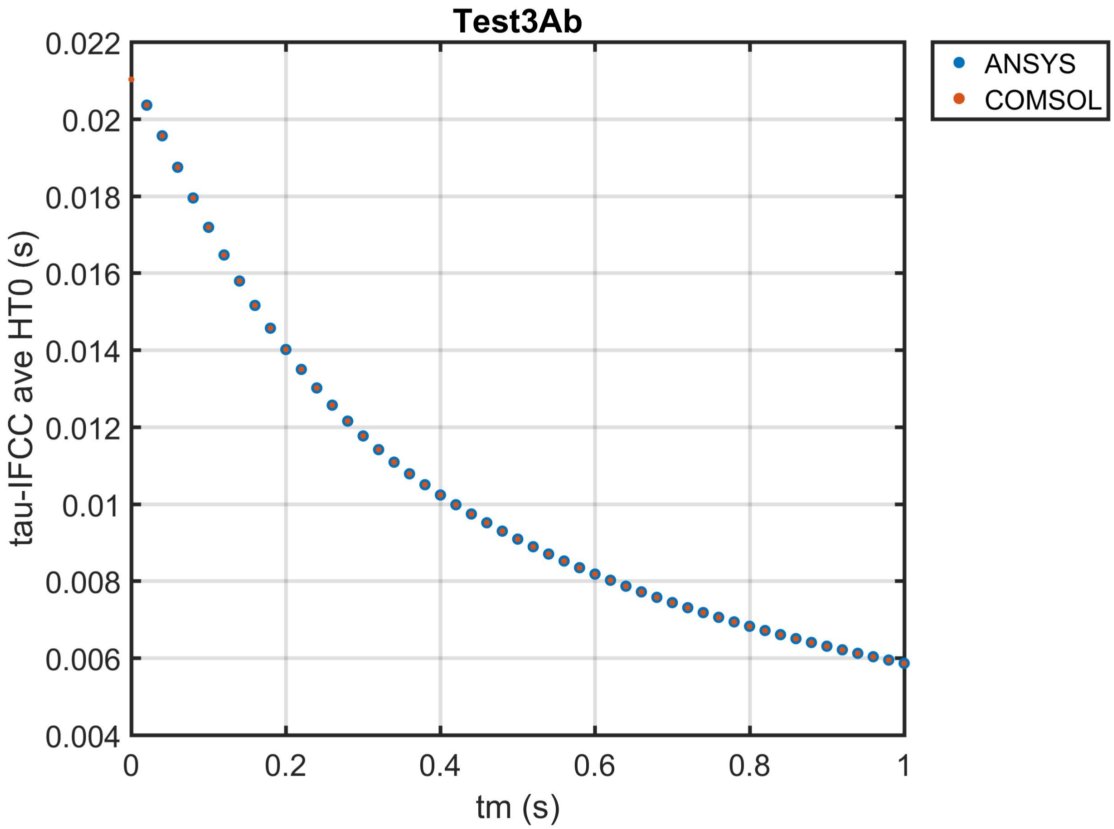
This test is added to check the temperature and field dependence of the resistivity of the copper using the NIST fit, as well as the calculation method for tau. The temperature is keep fixed for three different cases "a", "b", and "c" as shown in the table. In this case the effect of the IFCC currents (magnetization) is not included, only the material properties and tau are output.

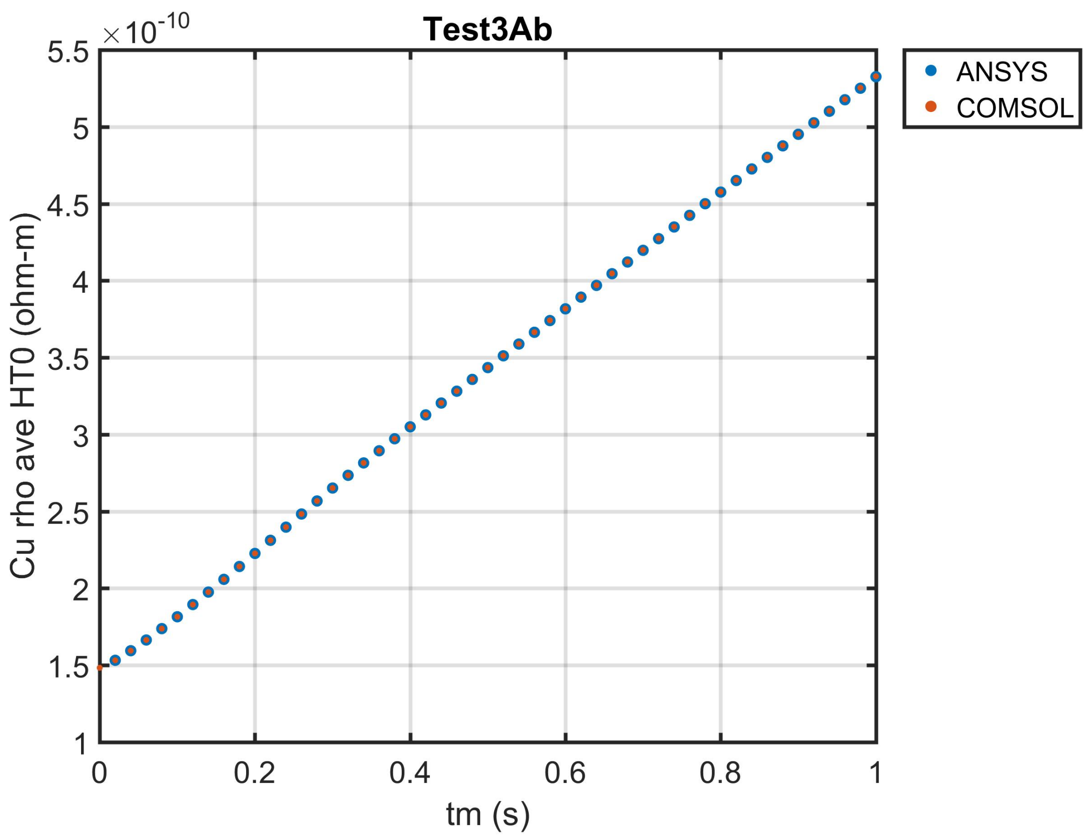
Active physics	EM
Coil initial temp	a=1.9 [K], b=30 [K], c=100 [K]
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	None
External loads	Linear ramp-up, t=(0,1) [s], Δt=20e-3 [s], i=(0,20) [kA]
ρ_{cu} fit	NIST, see Appendix E
Output	Tau-IFCC$_{aveHT0}$ [s]
	ρ_{cuHT0} [Ωm]
	ρ_{aveHT0} [Ωm]

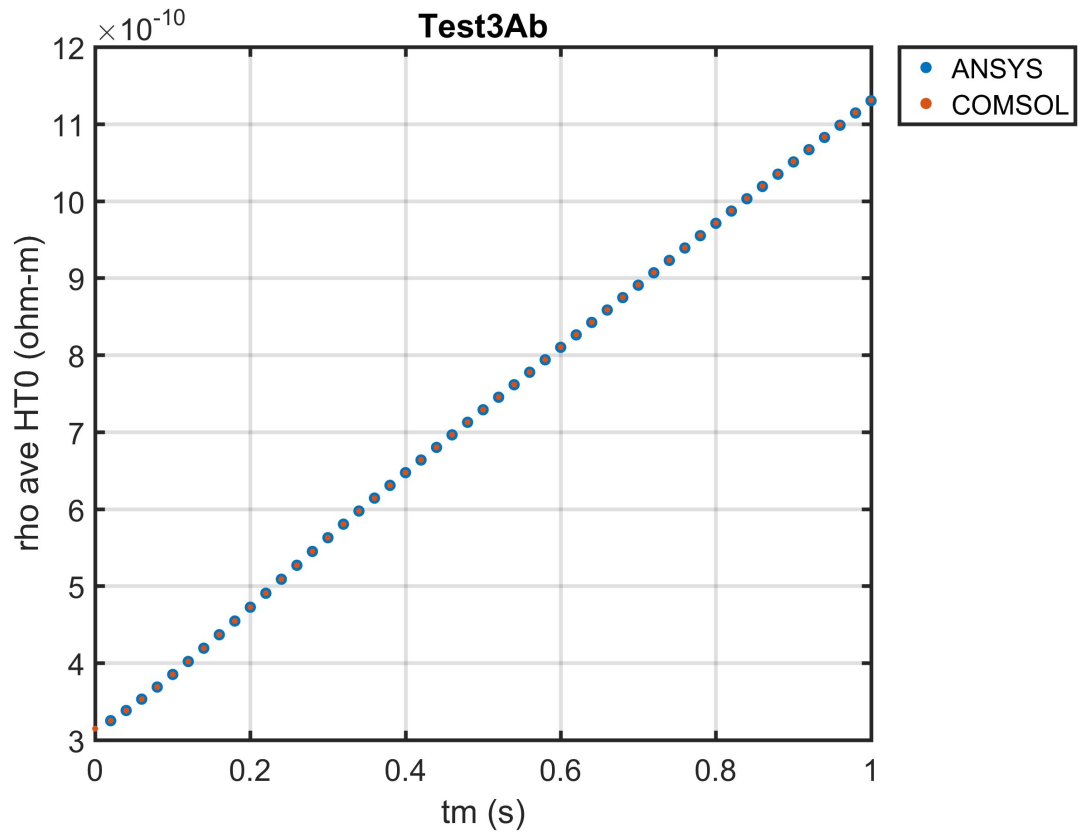


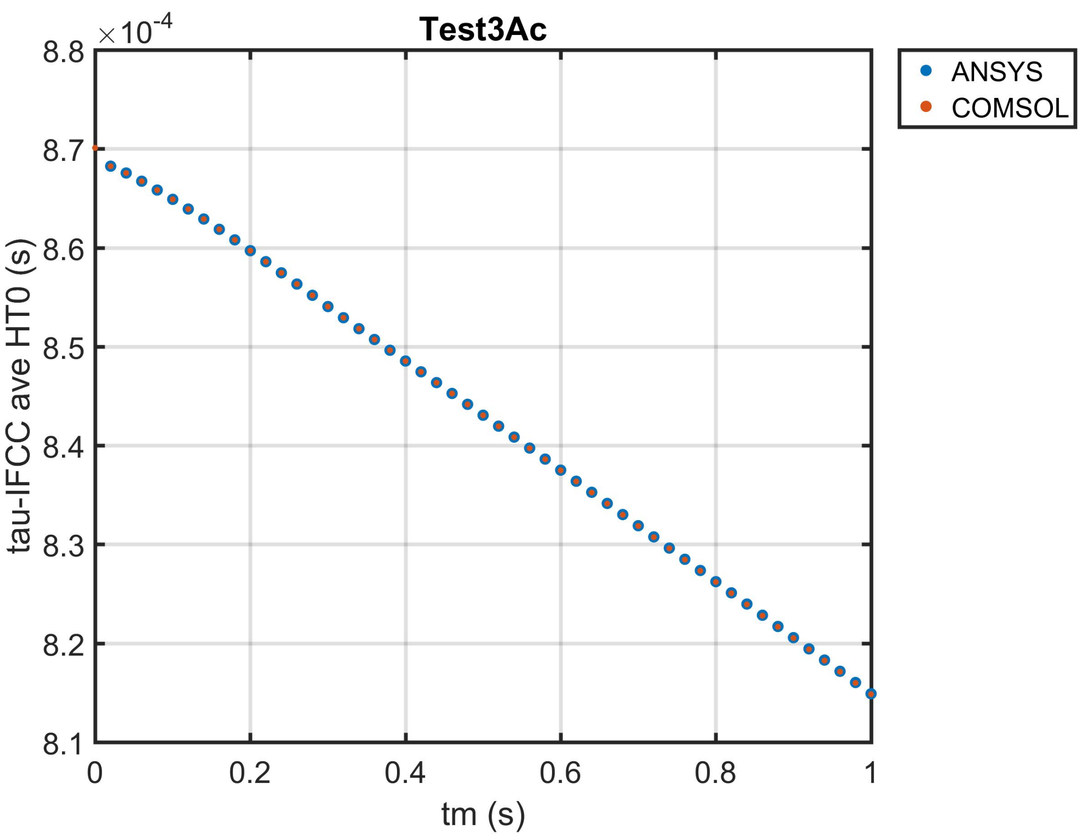

Test3Aa
×10^-10
Cu rho ave HT0 (ohm-m)
tm (s)
ANSYS
COMSOL
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.2
0.4
0.6
0.8
1

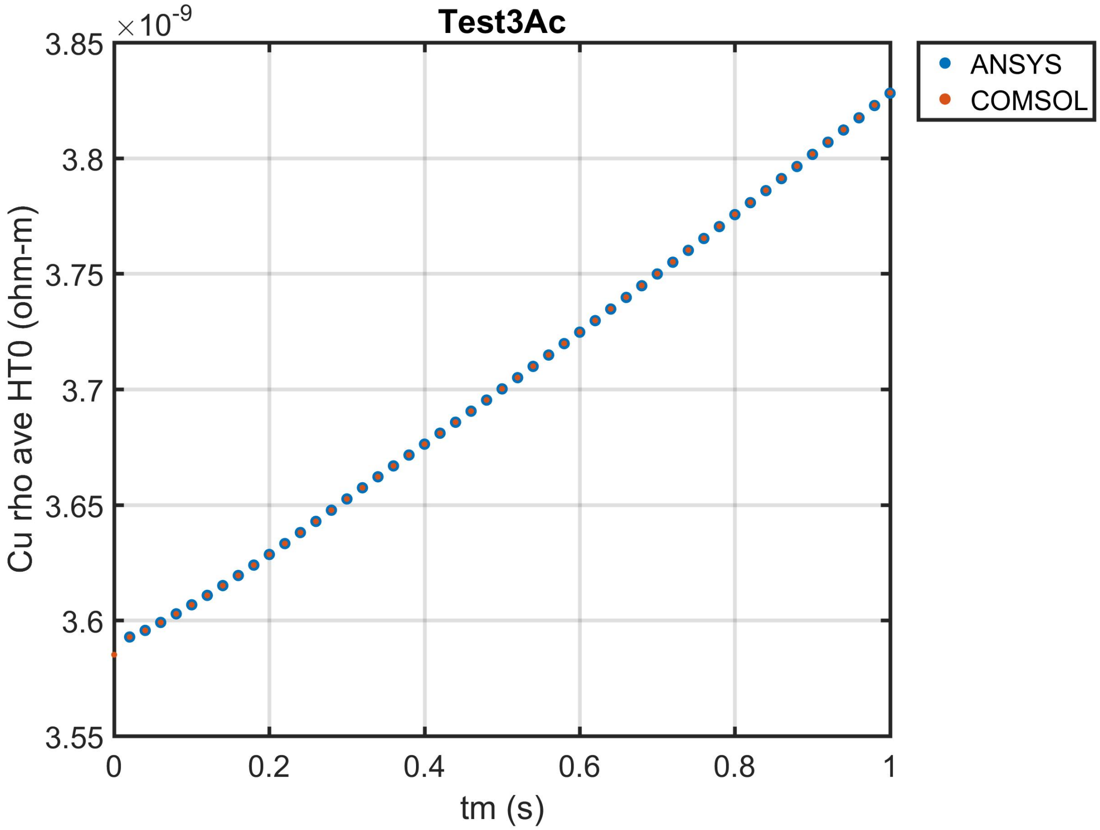

Test3Aa
×10^-10
rho ave HT0 (ohm-m)
tm (s)
ANSYS
COMSOL
11
10
9
8
7
6
5
4
3
2
1
0
0.2
0.4
0.6
0.8
1

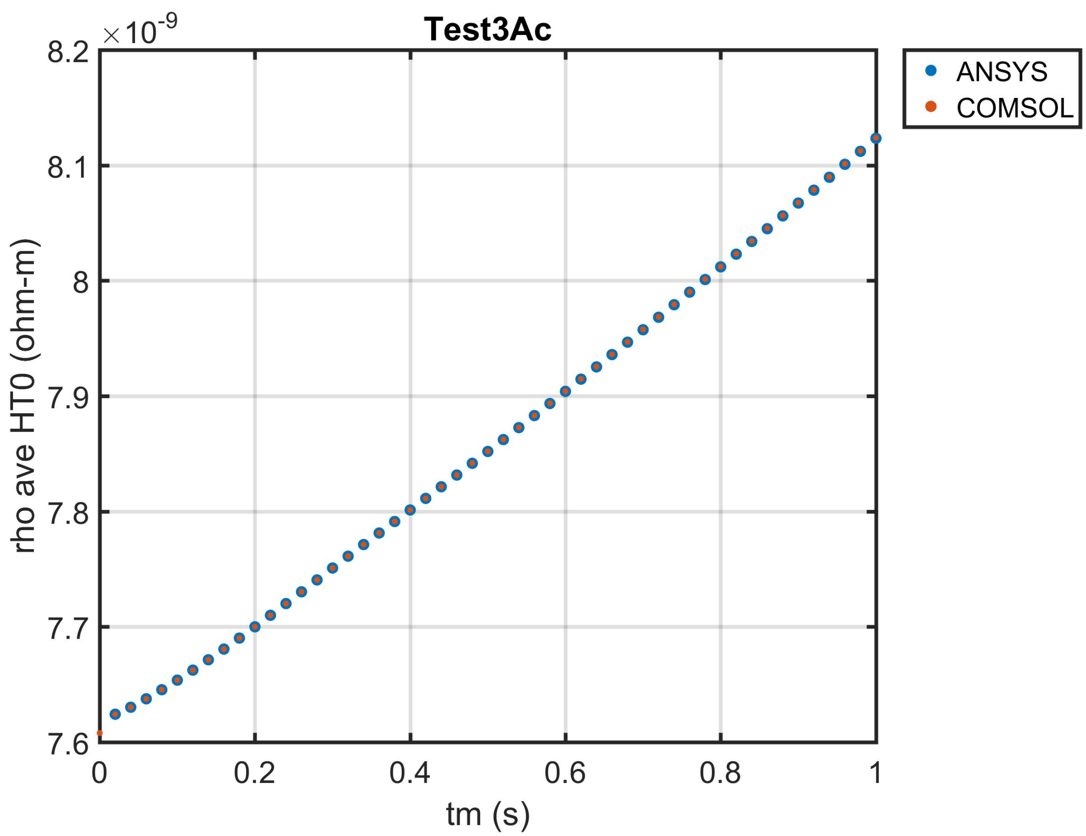

Test3Ab
tau-IFCC ave HT0 (s)
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL


Test3Ab
×10^-10
Cu rho ave HT0 (ohm-m)
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL


Test3Ab
×10^-10
12
11
10
9
8
7
6
5
4
3
rho ave HT0 (ohm-m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL


Test3Ac
×10^-4
8.8
8.7
8.6
8.5
8.4
8.3
8.2
8.1
tau-IFCC ave HT0 (s)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL


Test3Ac
×10^-9
3.85
3.8
3.75
3.7
3.65
3.6
3.55
Cu rho ave HT0 (ohm-m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

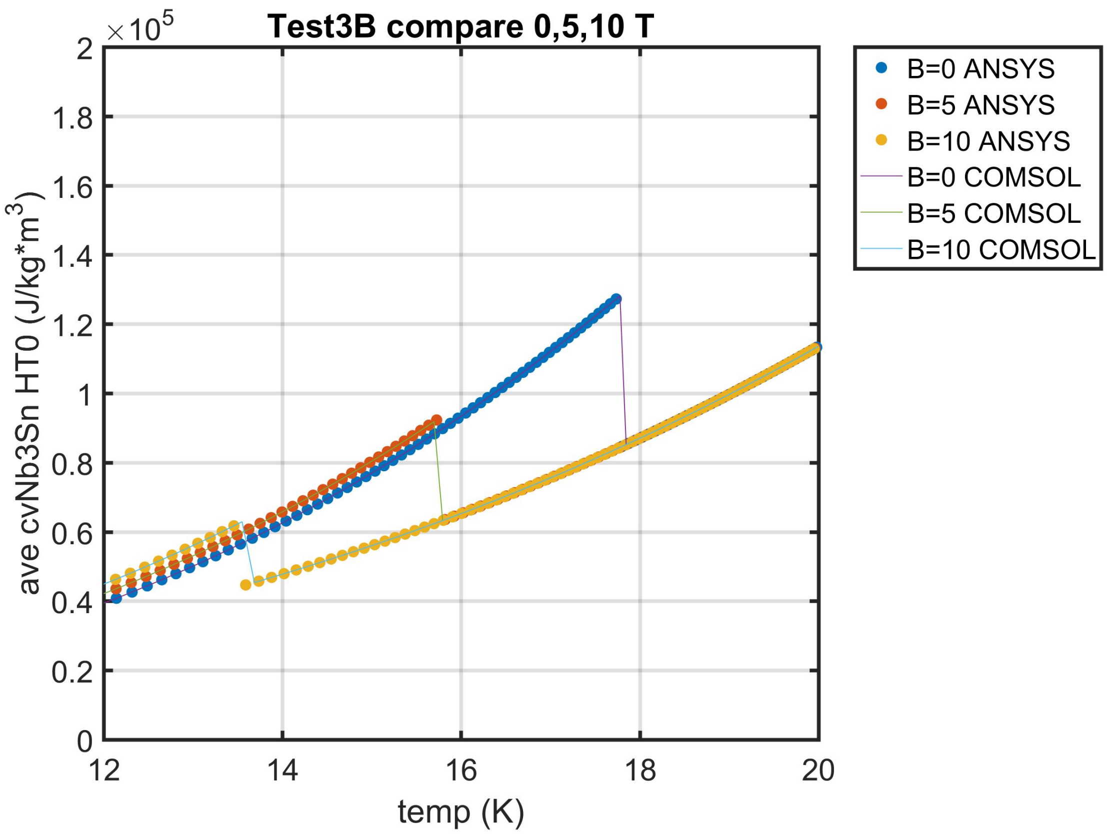

Test3Ac
×10^-9
8.2
8.1
8
7.9
7.8
7.7
7.6
rho ave HT0 (ohm-m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

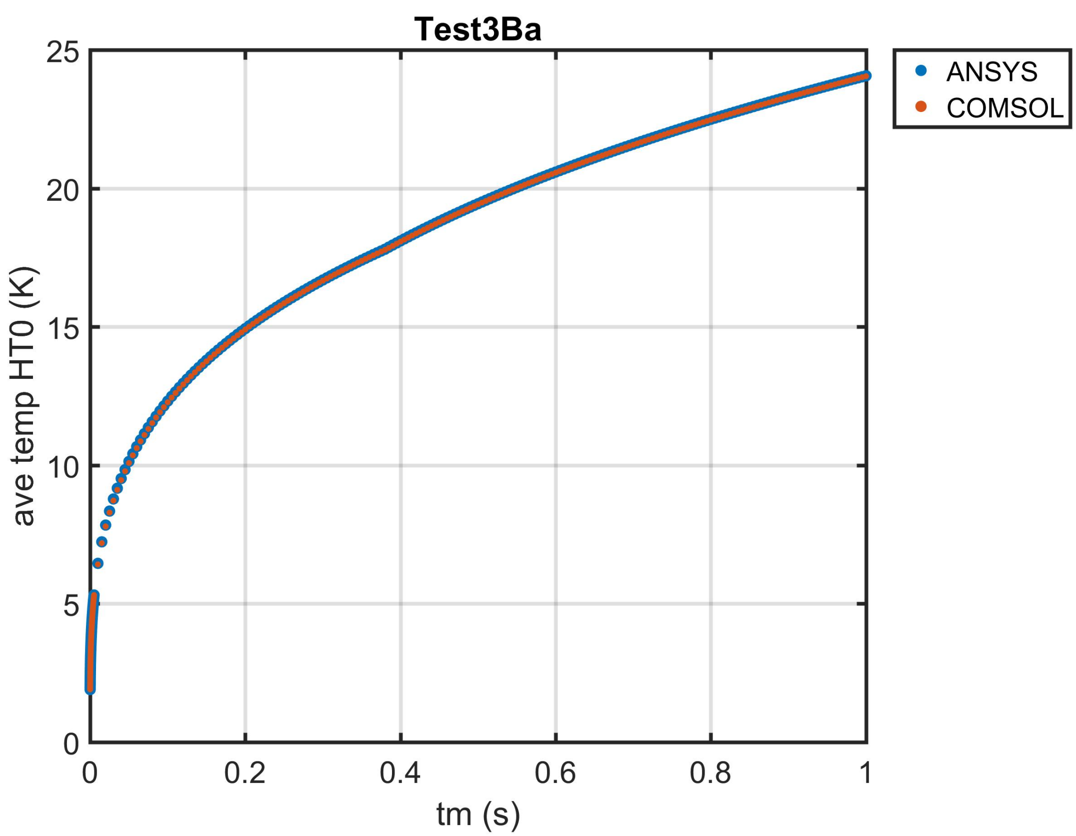
3.8 Test 3.B Heat Capacity (B and T dependence)

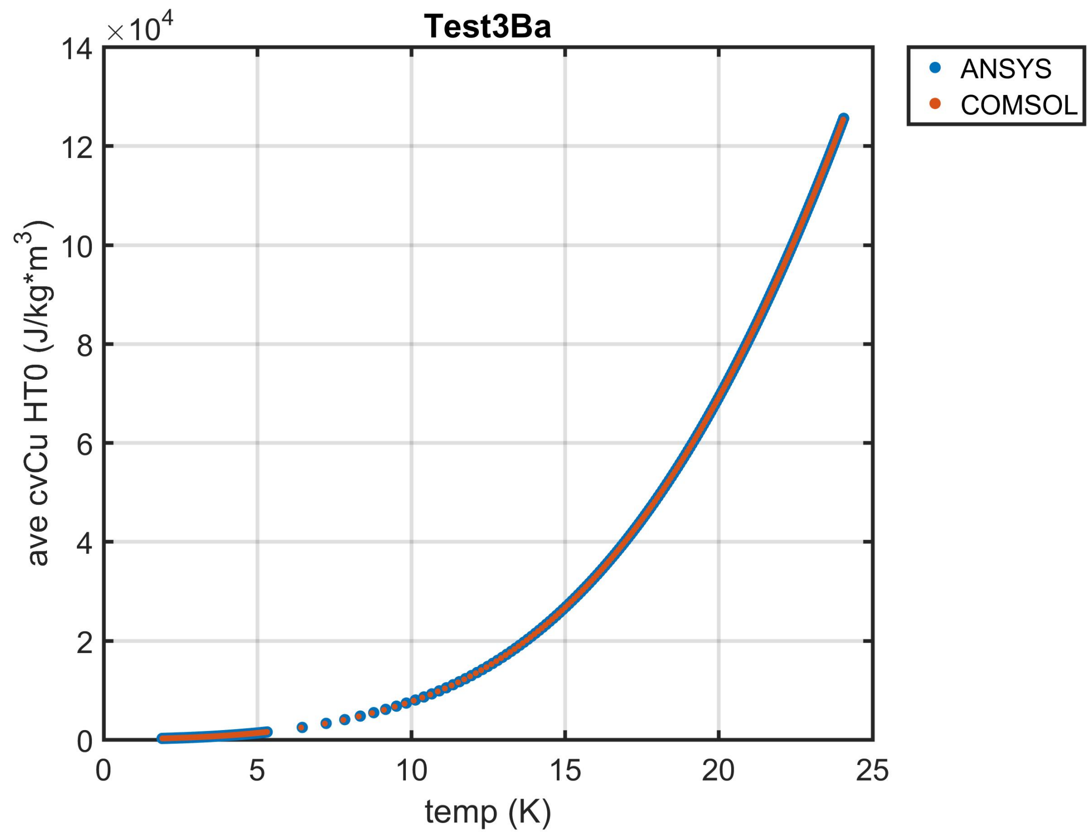
This test is designed to test the temperature dependence of the heat capacity fits and also the field dependence (quench) for Nb_3Sn. A constant heat load is applied on the turns, which are then allowed to heat up. Thermal Conductivity should not play a role as the heat load is uniform, but is output as a check of the fits between codes. This test is run for three different background fields labeled a, b, and c.

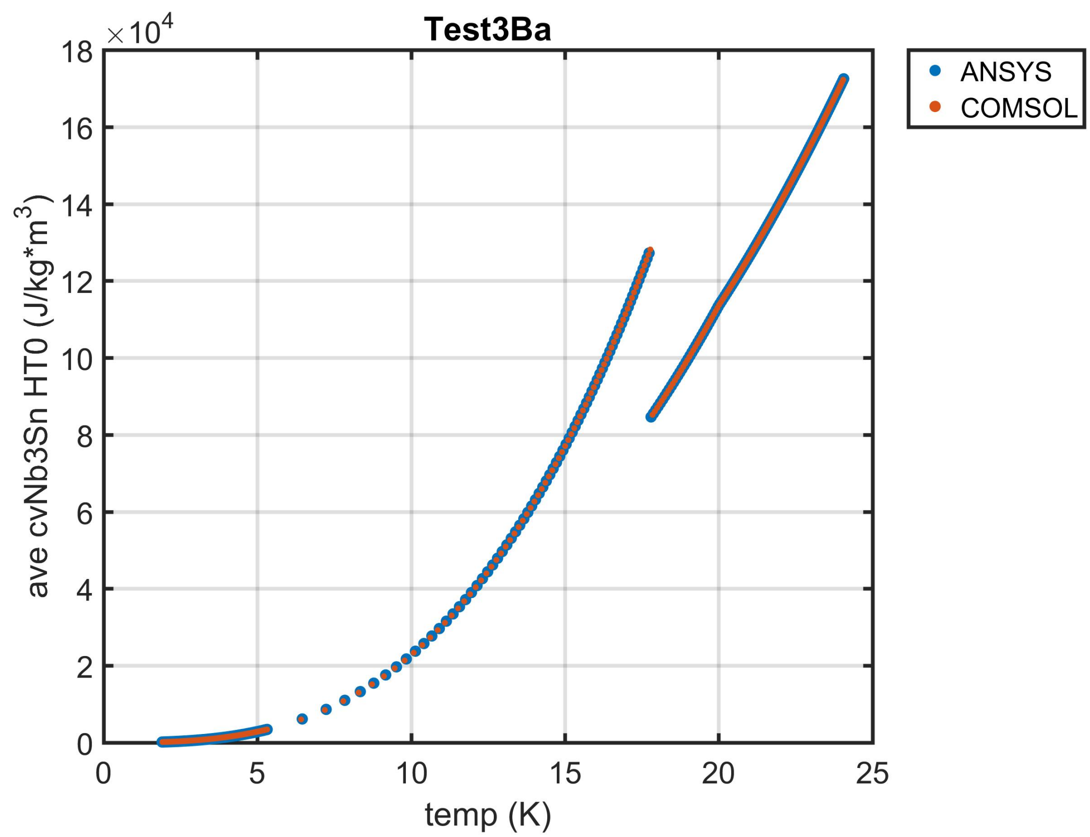
Active physics	TH
Coil initial temp	a=1.9 [K]
Input applied background field	a=0.0 [T], b=5 [T], c=10 [T]
Cable insulation material	None
Cable voids filling material	GLASS FIBER
External loads	Uniform heat load of 1e6 W/m^3, t=(0,1) [s], Δt=suff. for conv.
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
Output	T_{aveHT0} [K]
	$C_{v-cuHT0}$ [J/(kg*m^3)]
	$C_{v-Nb3SnHT0}$ [J/(kg*m^3)]
	$C_{v-G10HT0}$ [J/(kg*m^3)]
	$C_{v-mixHT0}$ [J/(kg*m^3)]
	k_{cuHT0} [W/(mK)]
	k_{mixHT0} [W/(mK)]

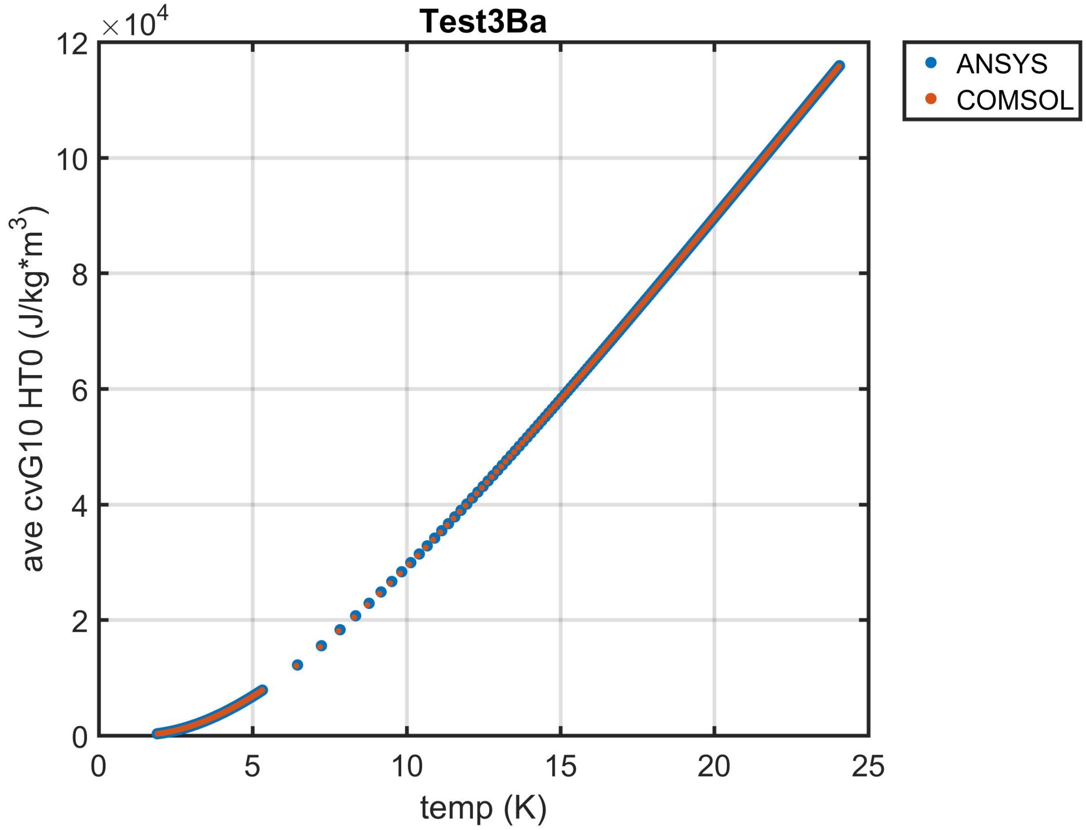
A plot of the Nb_3Sn Cv vs. temp for each case is shown first which demonstrates the Cv jump at quench for the different magnetic field levels.

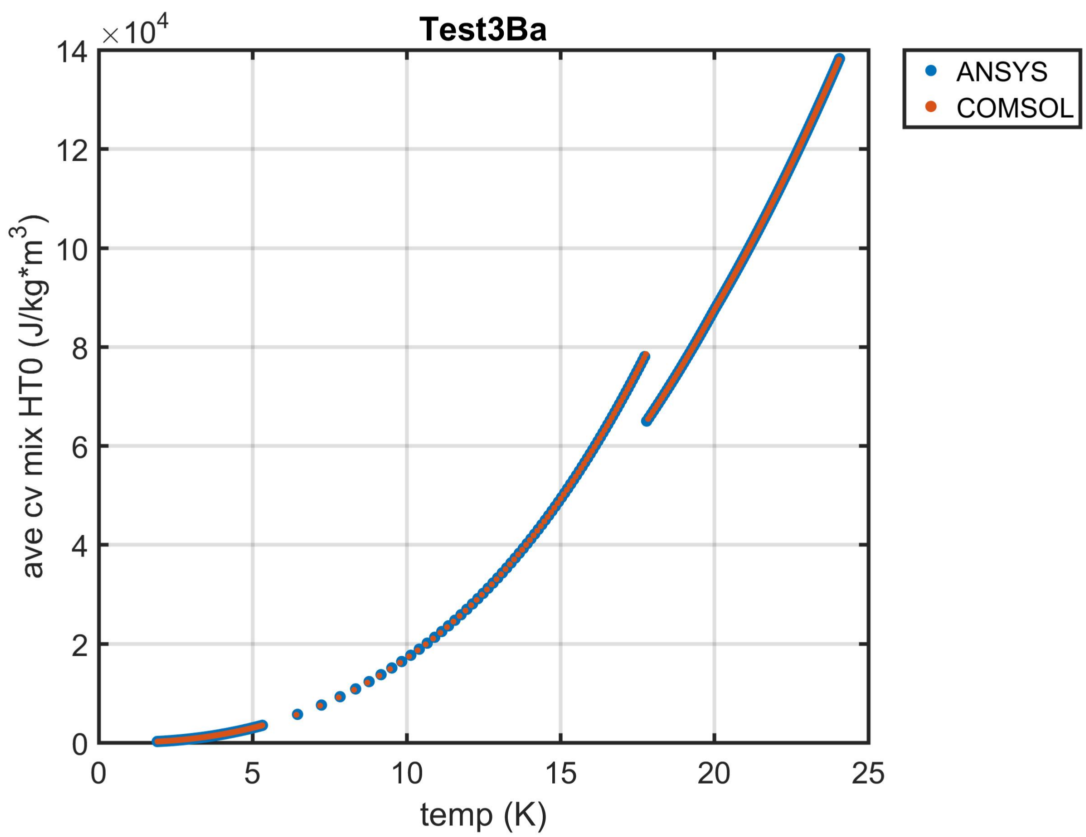

Test3B compare 0,5,10 T
×10^5
ave cvNb3Sn HT0 (J/kg*m^3)
temp (K)
B=0 ANSYS
B=5 ANSYS
B=10 ANSYS
B=0 COMSOL
B=5 COMSOL
B=10 COMSOL

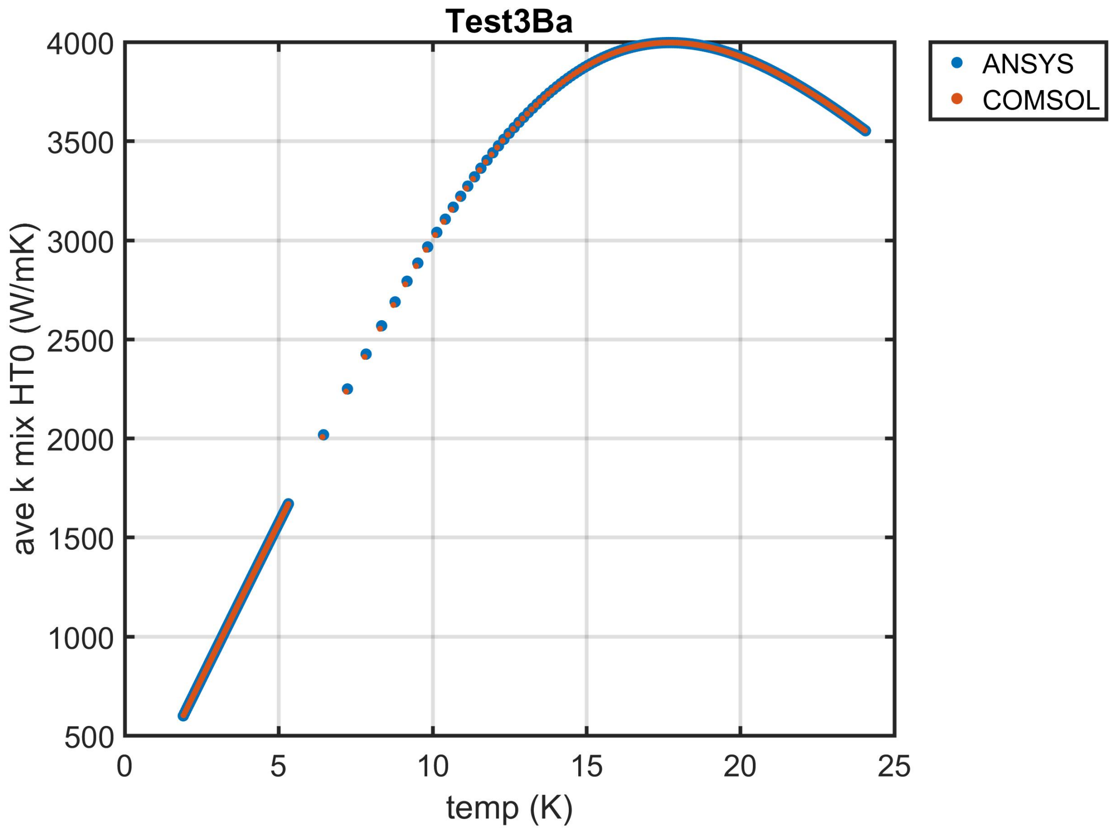

Test3Ba
ave temp HT0 (K)
tm (s)
ANSYS
COMSOL

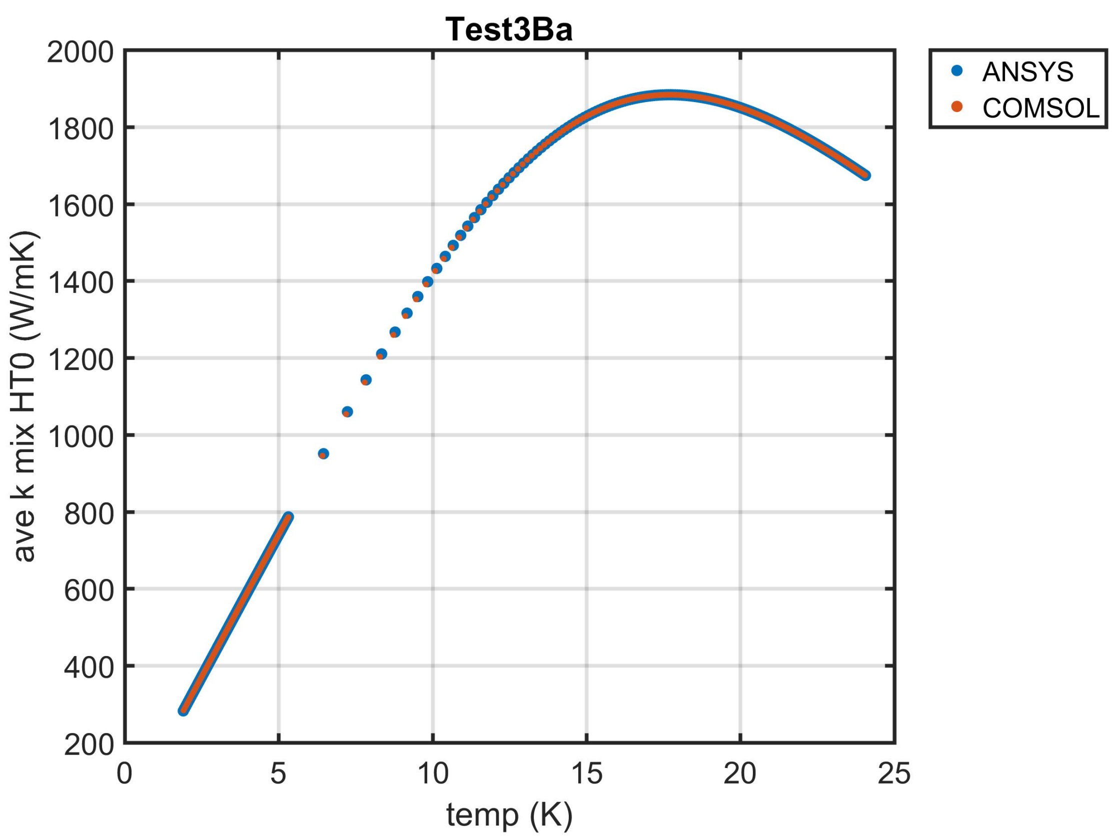

Test3Ba
×10^4
ave cvCu HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
14
0
5
10
15
20
25

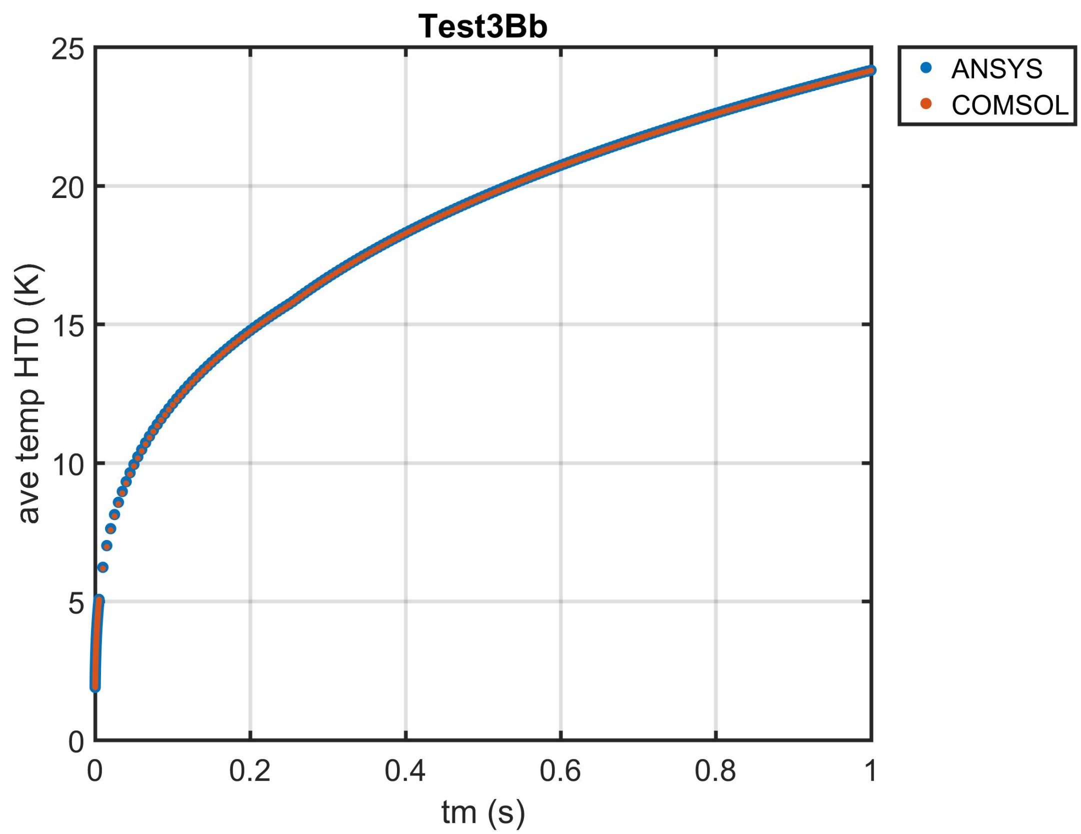

Test3Ba
×10^4
ave cvNb3Sn HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25

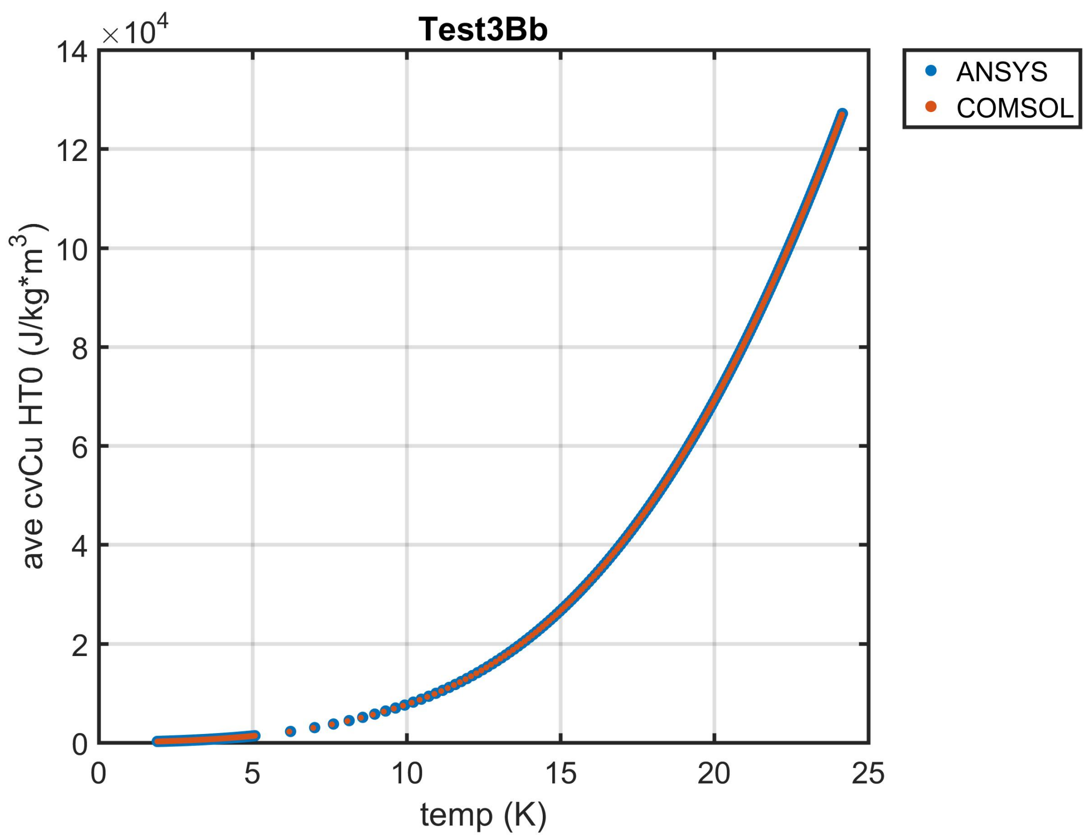

Test3Ba
×10^4
ave cvG10 HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
0
5
10
15
20
25

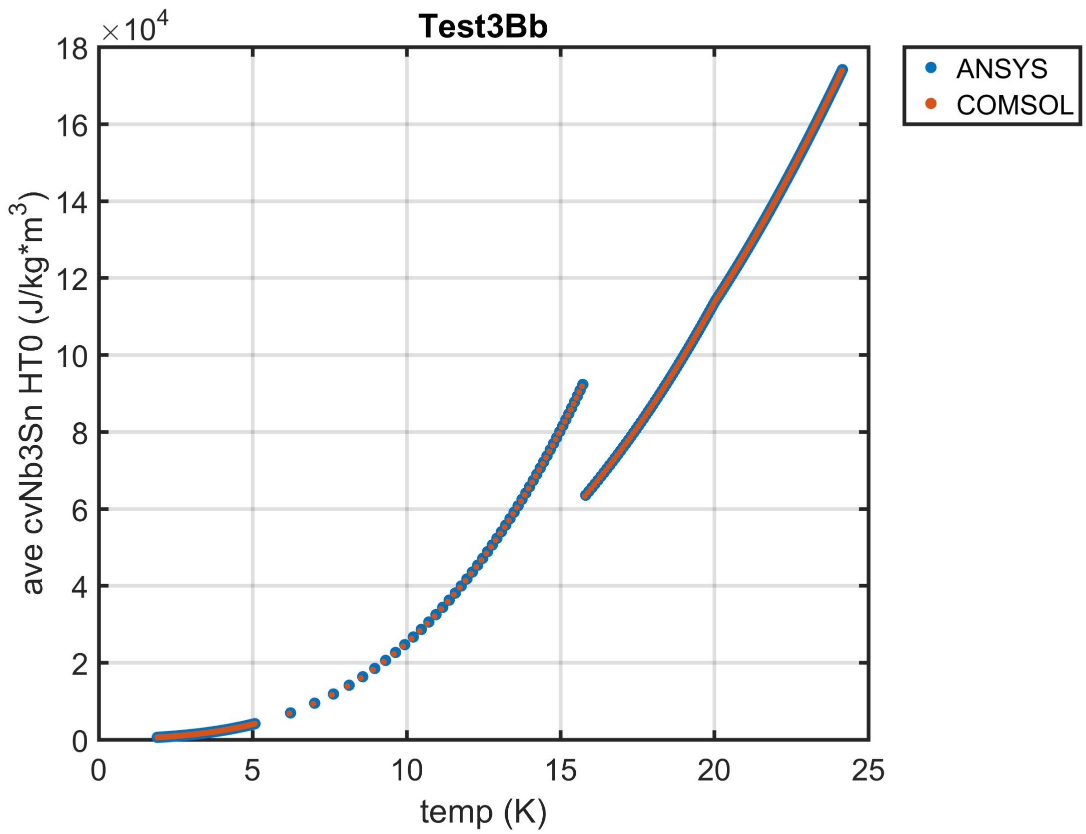

Test3Ba
×10^4
ave cv mix HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
14
0
5
10
15
20
25

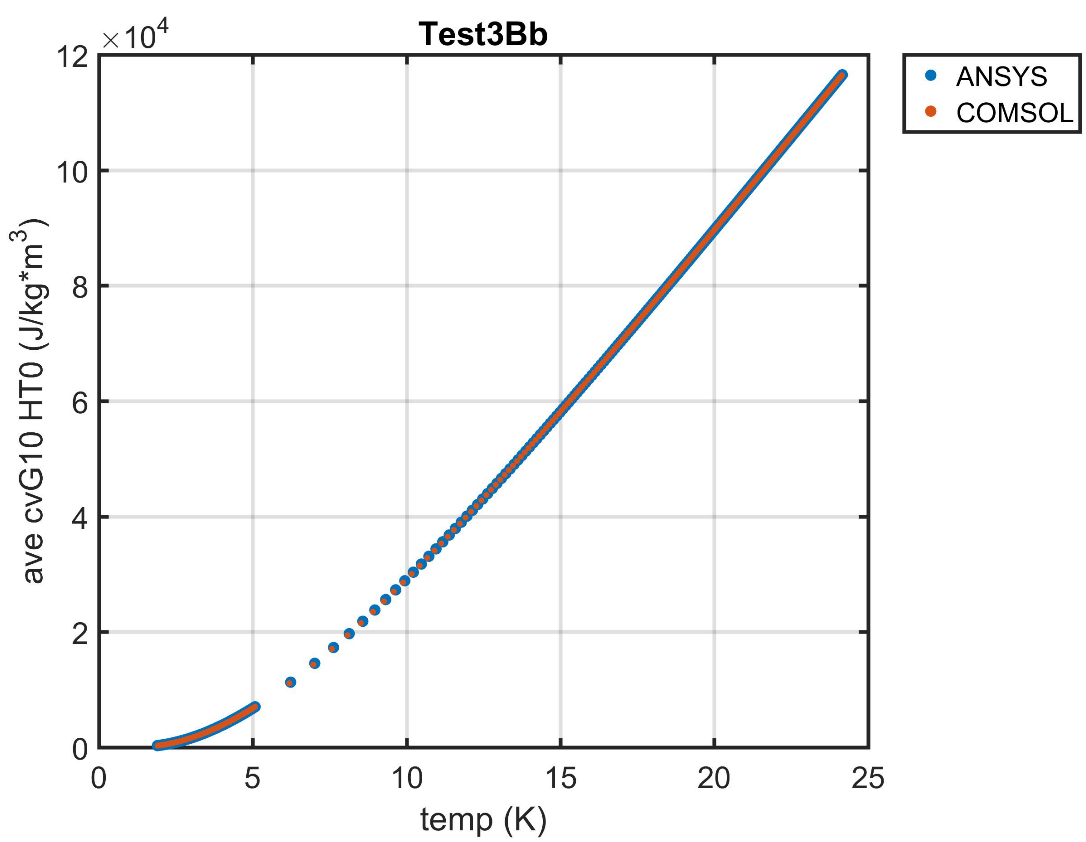

Test3Ba
ave k mix HT0 (W/mK)
temp (K)
ANSYS
COMSOL
4000
3500
3000
2500
2000
1500
1000
500
0
5
10
15
20
25

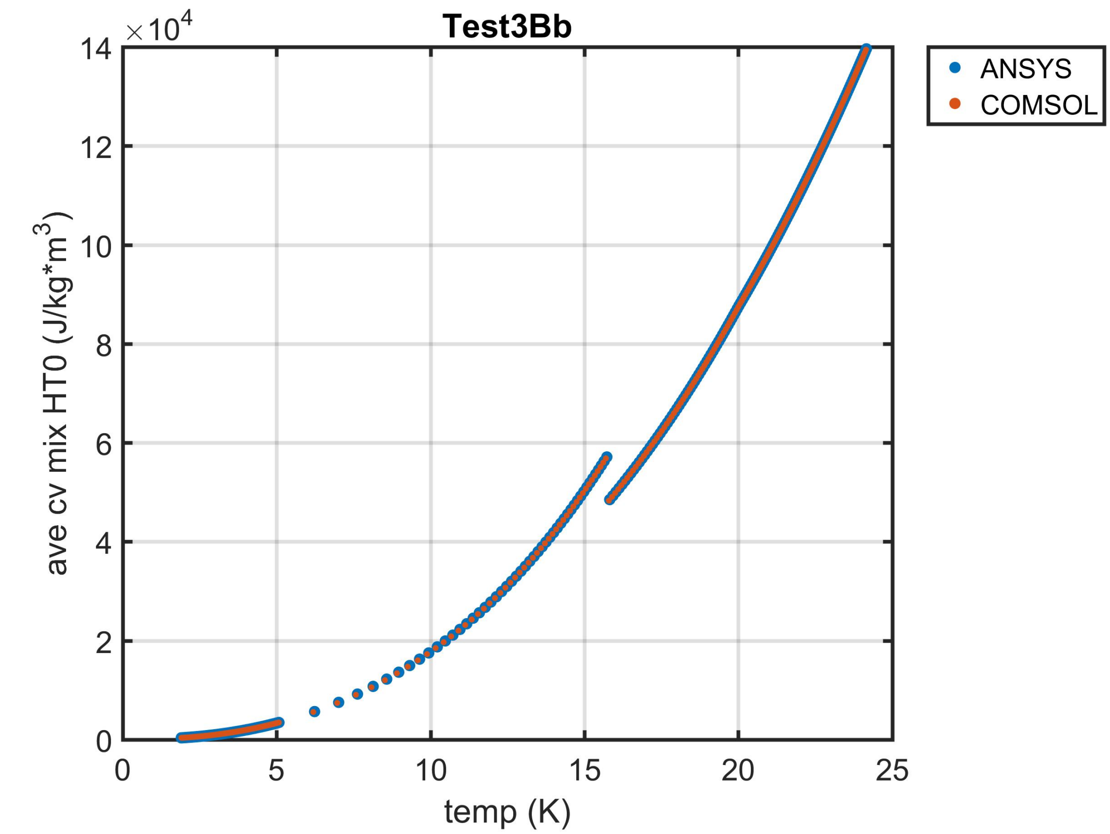

Test3Ba
ave k mix HT0 (W/mK)
temp (K)
ANSYS
COMSOL
2000
1800
1600
1400
1200
1000
800
600
400
200
0
5
10
15
20
25

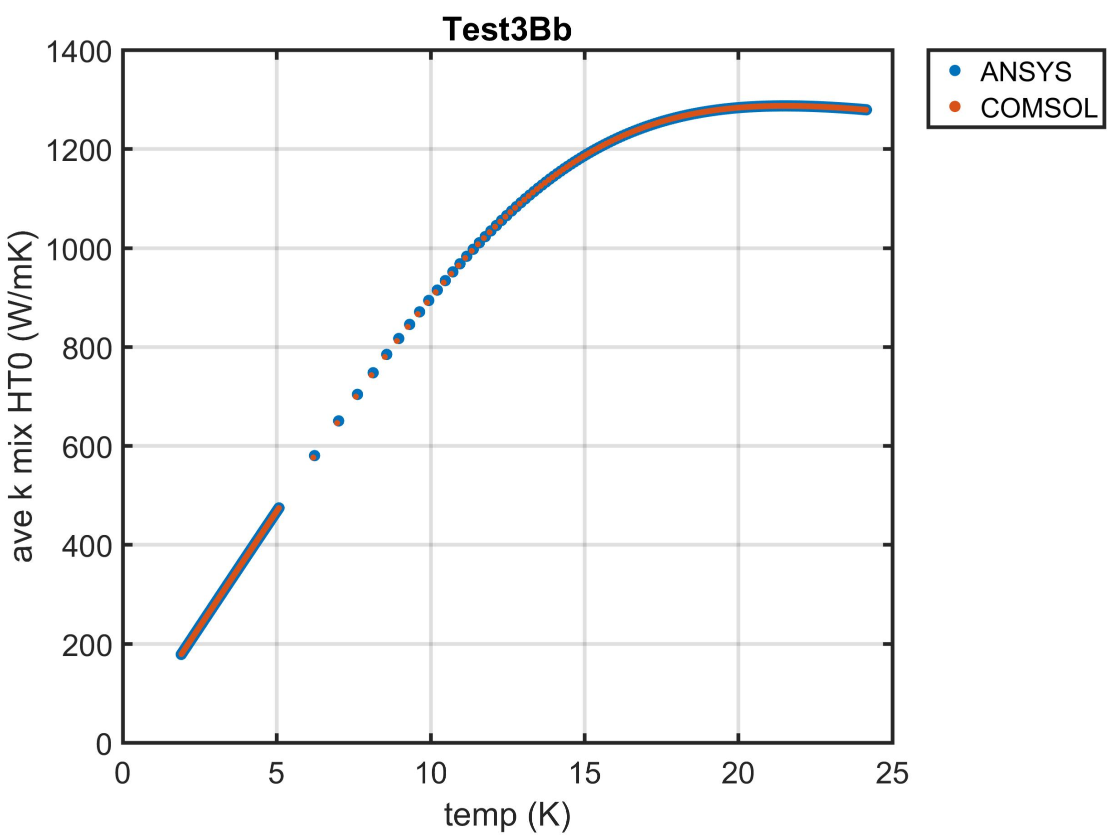

Test3Bb
ANSYS
COMSOL
ave temp HT0 (K)
tm (s)
0
5
10
15
20
25
0
0.2
0.4
0.6
0.8
1

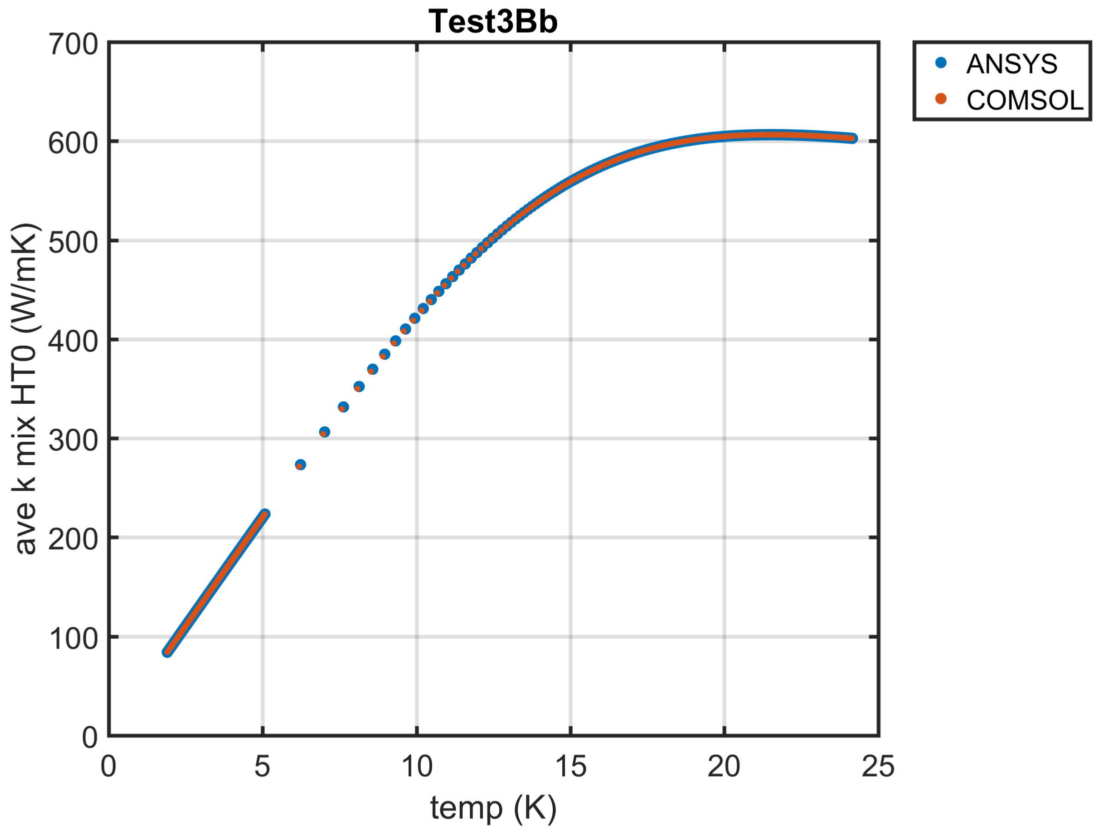

Test3Bb
ANSYS
COMSOL
$\times 10^4$
ave cvCu HT0 (J/kg*m^3)
temp (K)
0
2
4
6
8
10
12
14
0
5
10
15
20
25

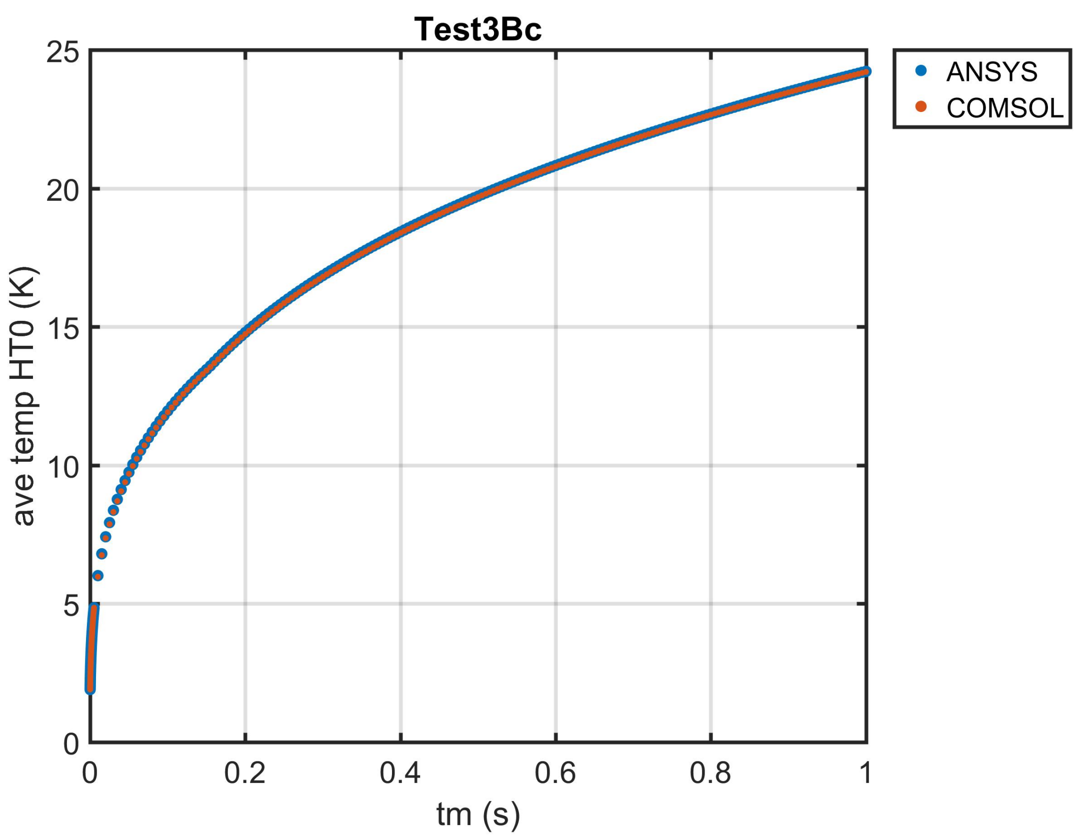

Test3Bb
×10^4
ave cvNb3Sn HT0 (J/kg*m^3)
temp (K)
0
2
4
6
8
10
12
14
16
18
0
5
10
15
20
25
ANSYS
COMSOL

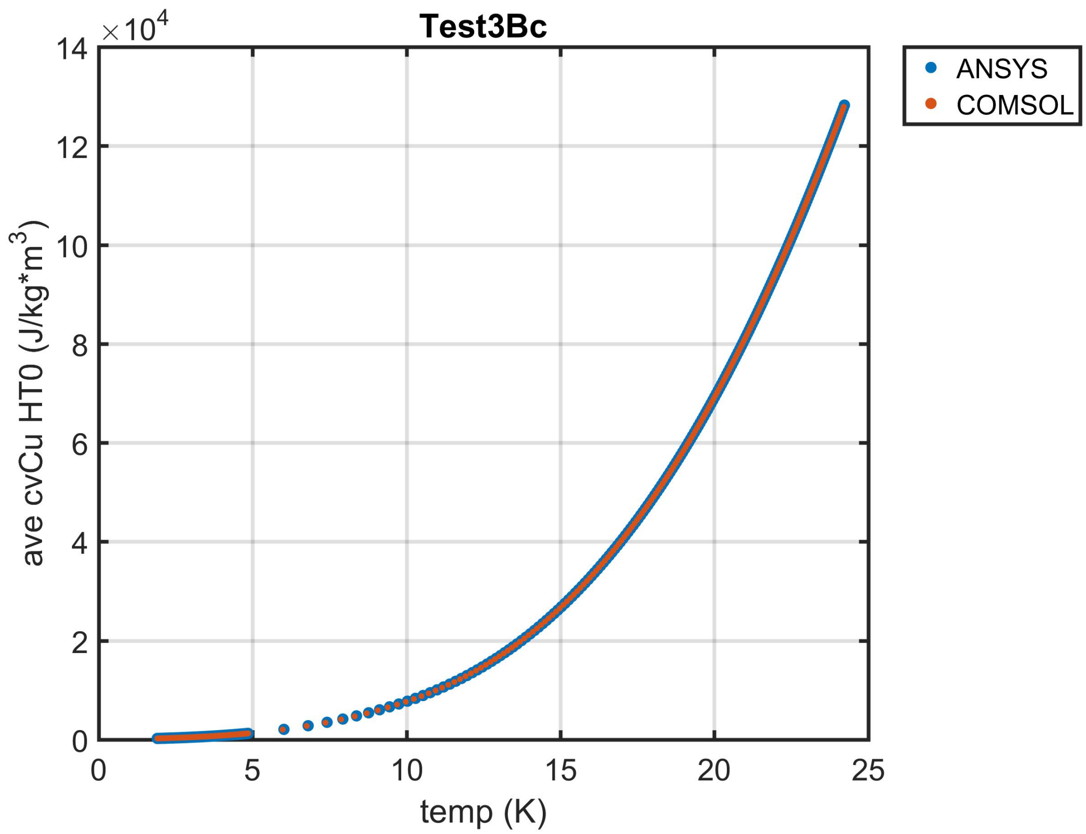

Test3Bb
×10^4
ave cvG10 HT0 (J/kg*m^3)
temp (K)
0
2
4
6
8
10
12
0
5
10
15
20
25
ANSYS
COMSOL

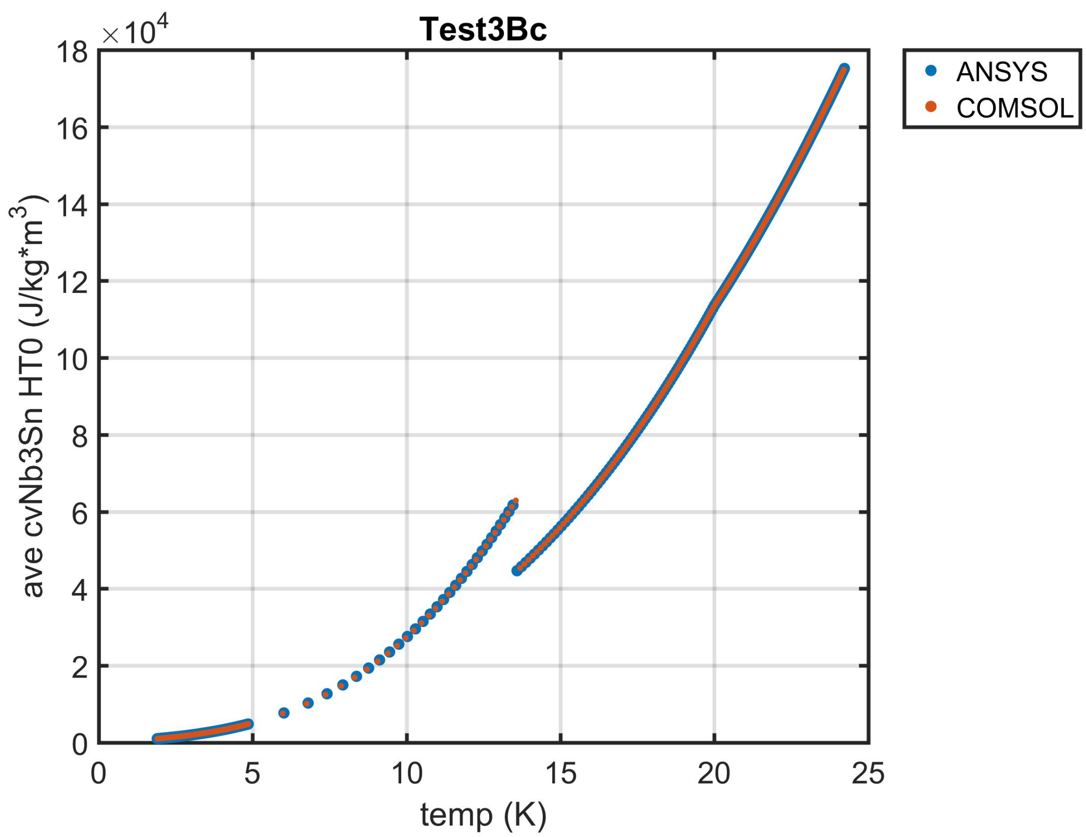

Test3Bb
×10^4
ave cv mix HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
14
0
5
10
15
20
25

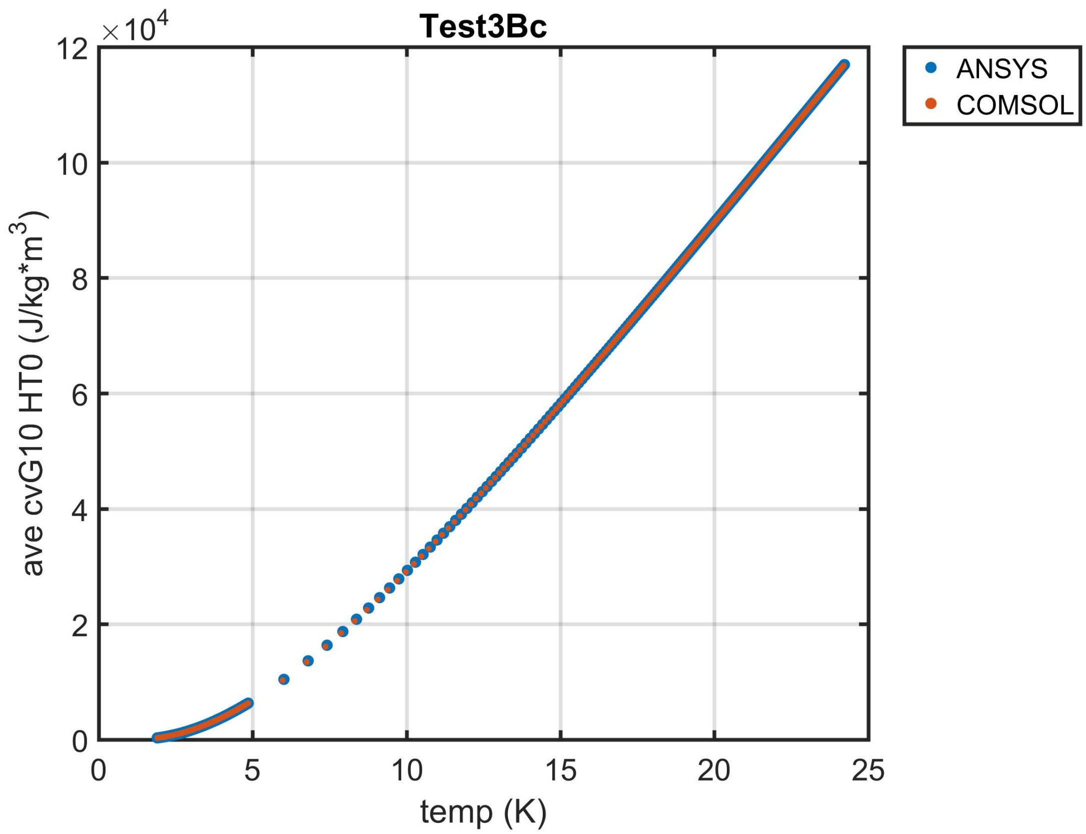

Test3Bb
ave k mix HT0 (W/mK)
temp (K)
ANSYS
COMSOL
0
200
400
600
800
1000
1200
1400
0
5
10
15
20
25

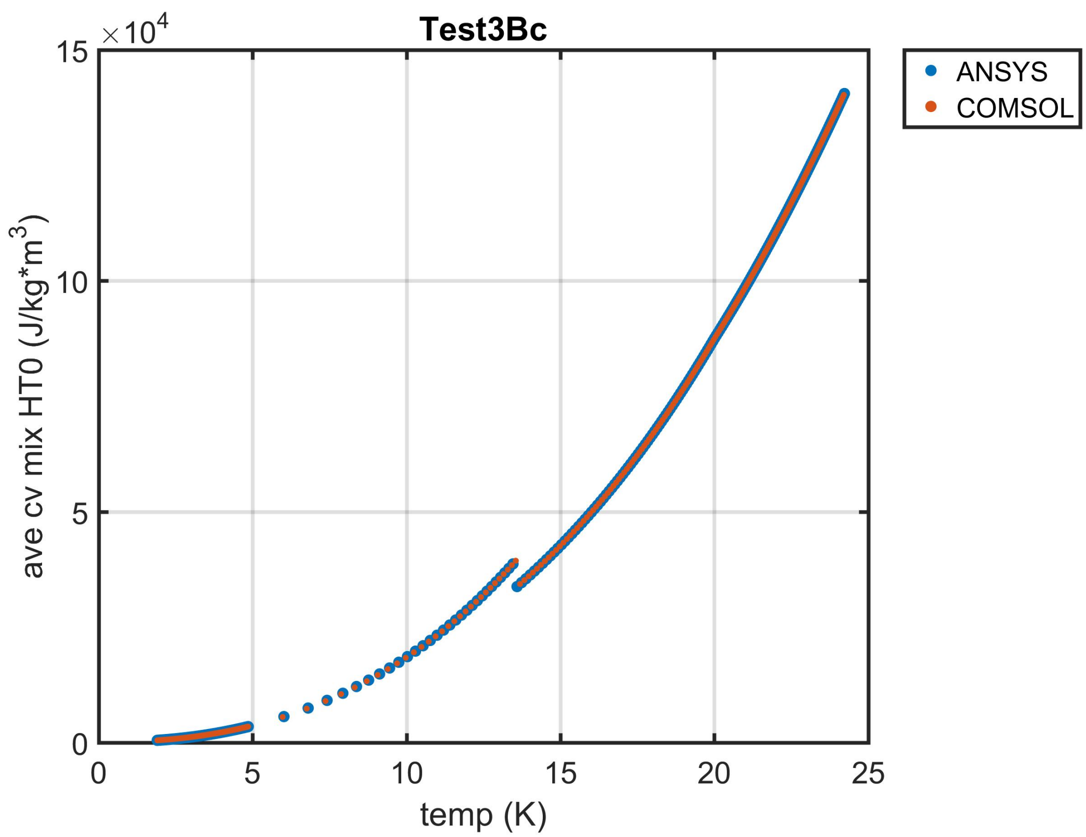

Test3Bb
ANSYS
COMSOL
ave k mix HT0 (W/mK)
temp (K)
0
100
200
300
400
500
600
700
0
5
10
15
20
25

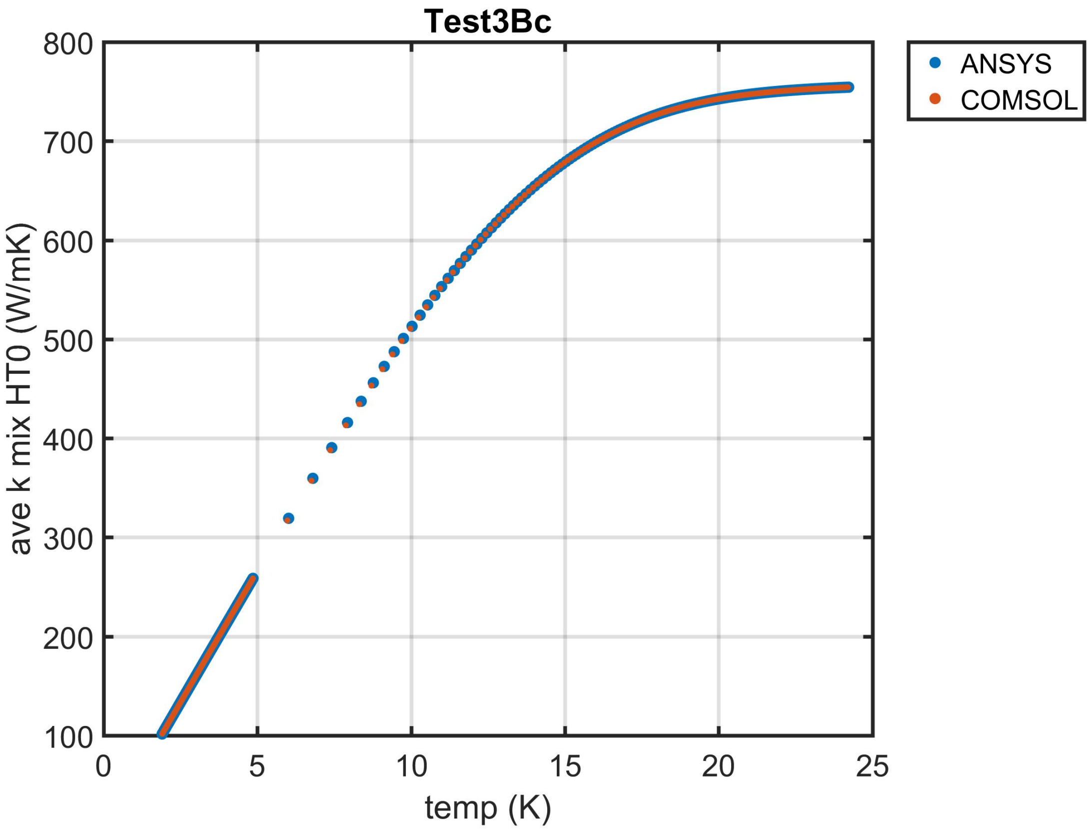

Test3Bc
ANSYS
COMSOL
ave temp HT0 (K)
tm (s)
0
5
10
15
20
25
0
0.2
0.4
0.6
0.8
1

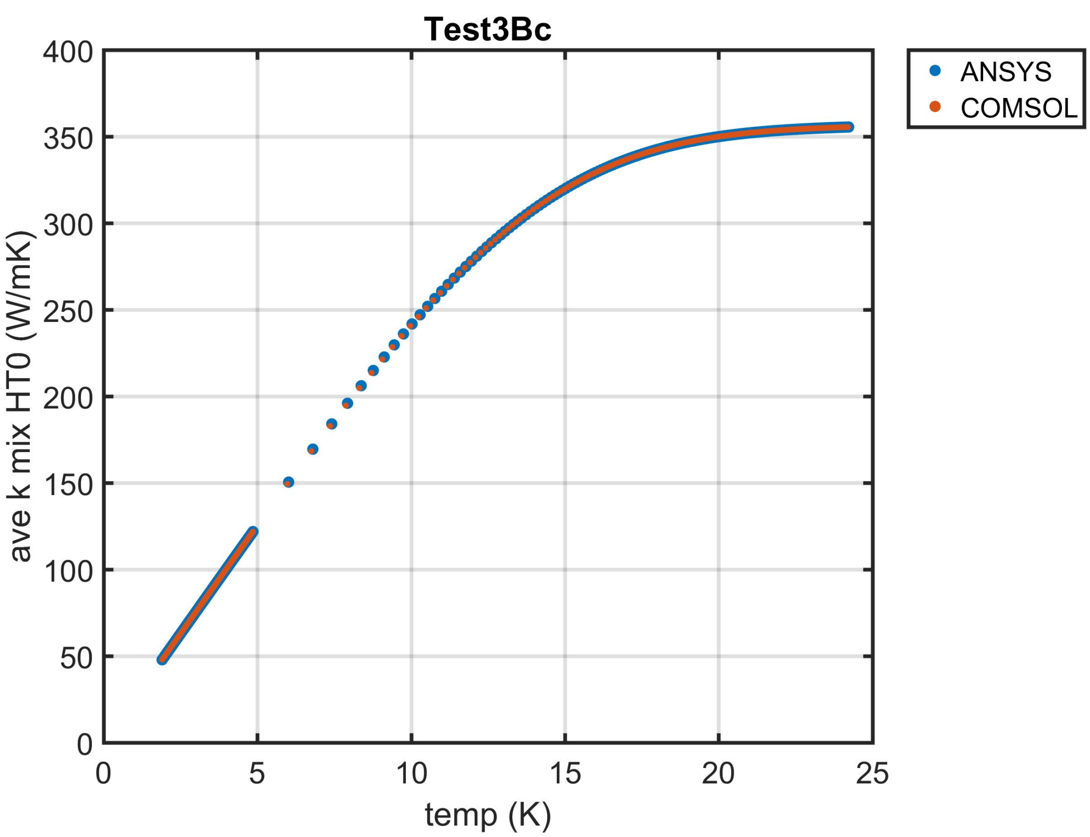

Test3Bc
×10^4
14
12
10
8
6
4
2
0
ave cvCu HT0 (J/kg*m^3)
0
5
10
15
20
25
temp (K)
ANSYS
COMSOL


Test3Bc
×10^4
18
16
14
12
10
8
6
4
2
0
ave cvNb3Sn HT0 (J/kg*m^3)
0
5
10
15
20
25
temp (K)
ANSYS
COMSOL


Test3Bc
×10^4
ave cvG10 HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
2
4
6
8
10
12
0
5
10
15
20
25

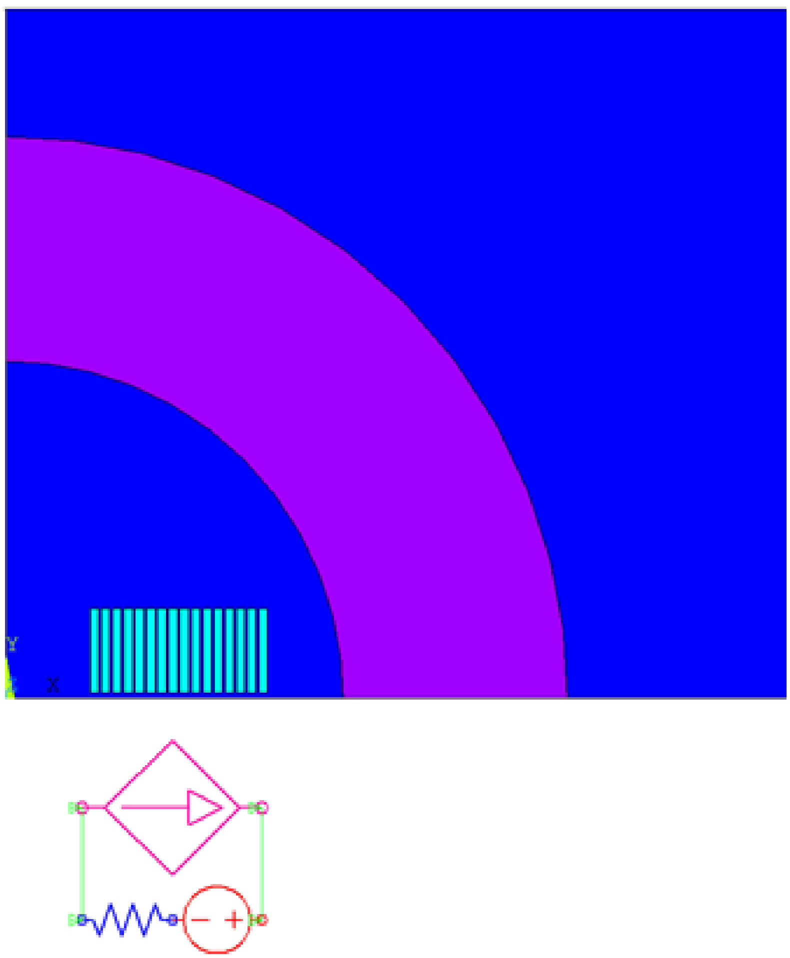

Test3Bc
×10^4
ave cv mix HT0 (J/kg*m^3)
temp (K)
ANSYS
COMSOL
0
5
10
15
0
5
10
15
20
25


Test3Bc
800
700
600
500
400
300
200
100
0
5
10
15
20
25
ave k mix HT0 (W/mK)
temp (K)
ANSYS
COMSOL


Test3Bc
400
350
300
250
200
150
100
50
0
0
5
10
15
20
25
ave k mix HT0 (W/mK)
temp (K)
ANSYS
COMSOL

4 Single Layer Tests With Circuit Coupling

A series of comparison tests are added which build up the effects included for a single simulation including circuit coupling. The finite element region is assumed to be coupled to a simple dump resistor and power supply circuit. A voltage source is used to apply the desired current before extraction is triggered. At 5.0 ms the voltage source is ramped down to zero over 0.1 ms which acts like a switch to allow for the decay of the magnet in series with the dump resistor. This circuit is shown in the figure below. The parameters I0 and Rdump are used as the initial current in the circuit (steady state before 5.0 ms) and the dump resistance. Two length scaling factors are used. L_c is the coil length which can be scaled to match the resistive voltage between 2D and 3D models, and L_i is a similar factor but for matching the inductive voltage. These four parameters will be added to the table for each simulation. For the following comparisons, a current of nearly 90% of short sample and a dump resistor which keeps the magnet voltage from exceeding 500 V were chosen.

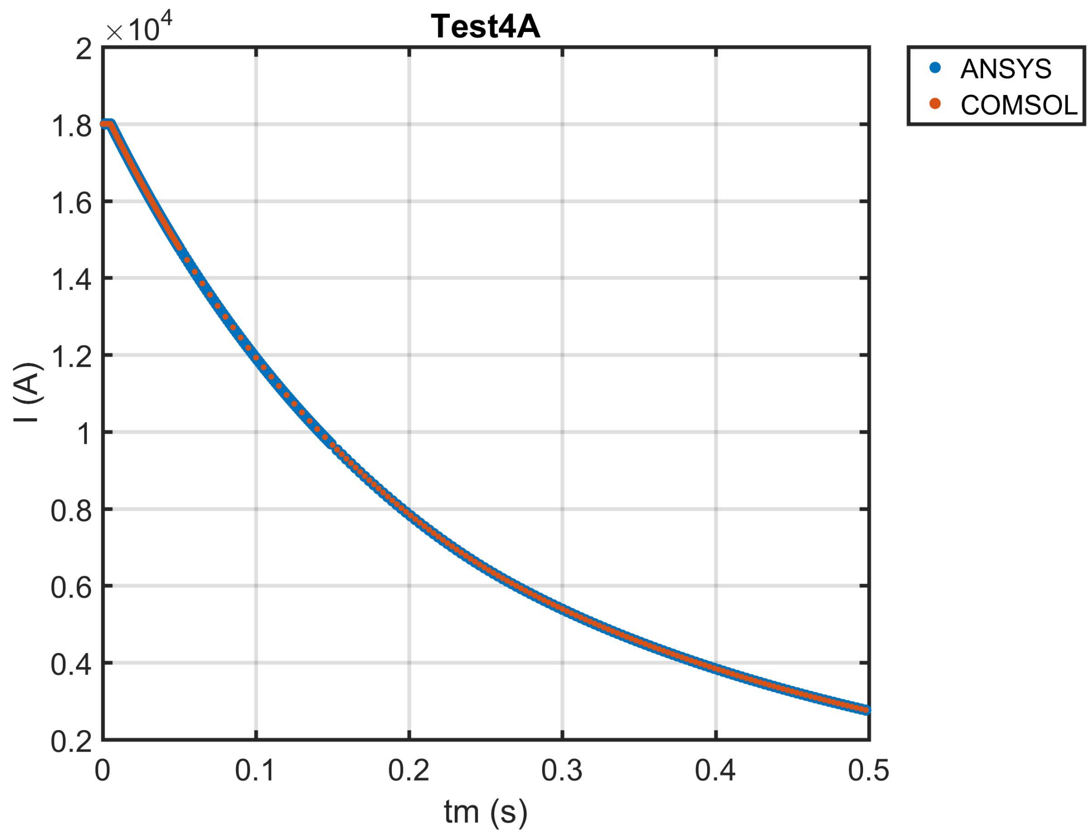


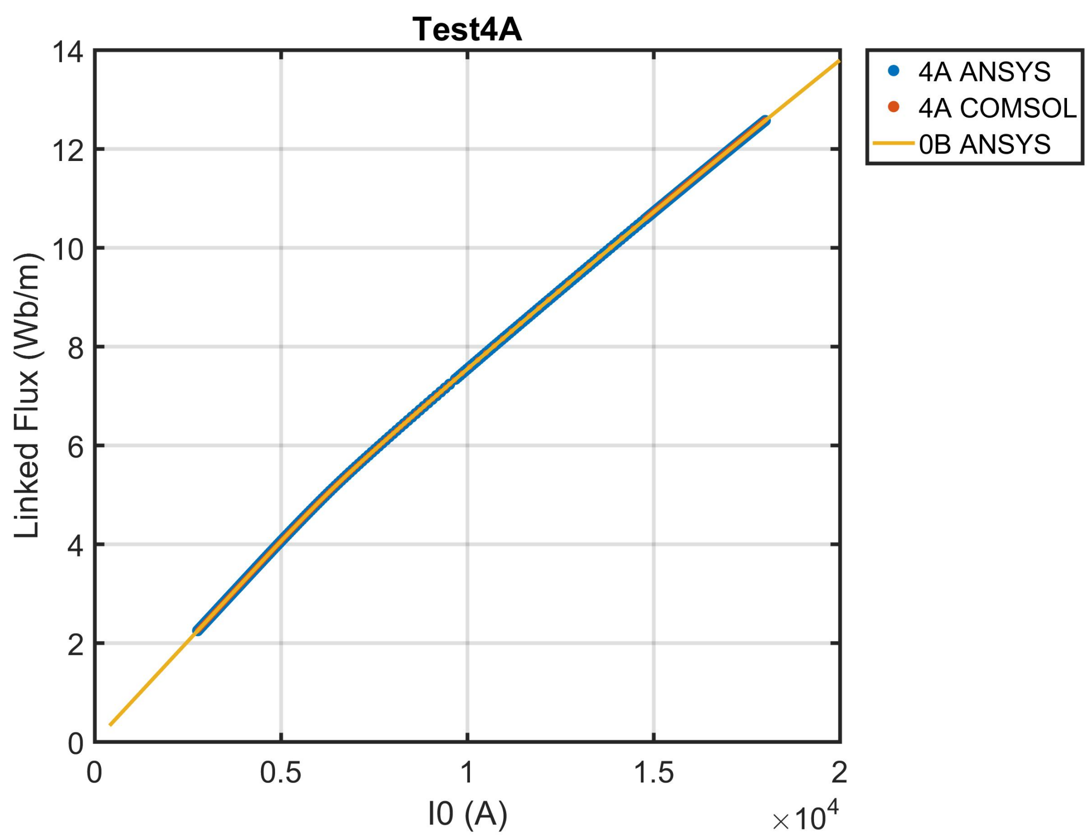
4.1 Test 4.A LR Decay With No Losses

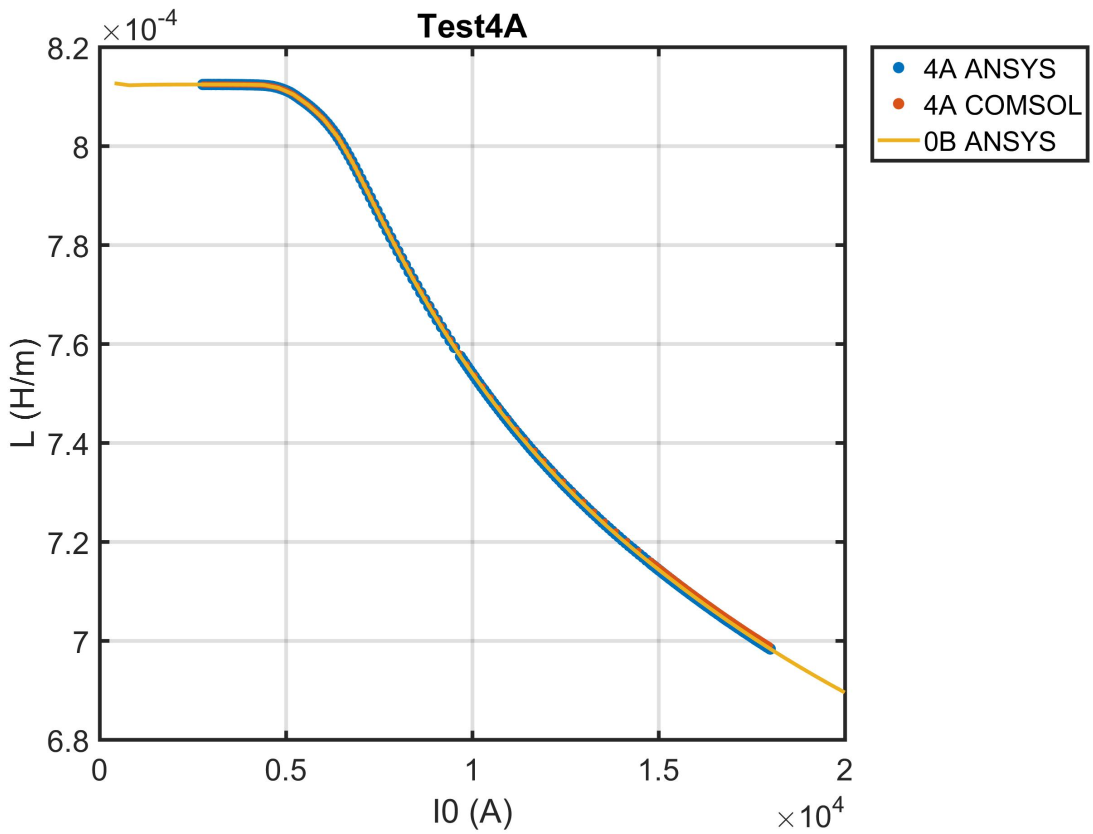
This first simulation is intended to test the circuit coupling with the coil only contributing inductive voltage. Interfilament coupling currents and quench are turned off so there are no losses outside of the dump resistor. Since there are no heating terms, thermal coupling is not needed and the coil will stay superconducting and at the initial temperature of 4.5 K. I like to track energy, and for this case its a good check that 100% is dissipated in the dump. The length L_i is the effective magnet length used for inductive voltage. Note that both the linked flux and inductance can be checked against Test0B if plotted vs current.

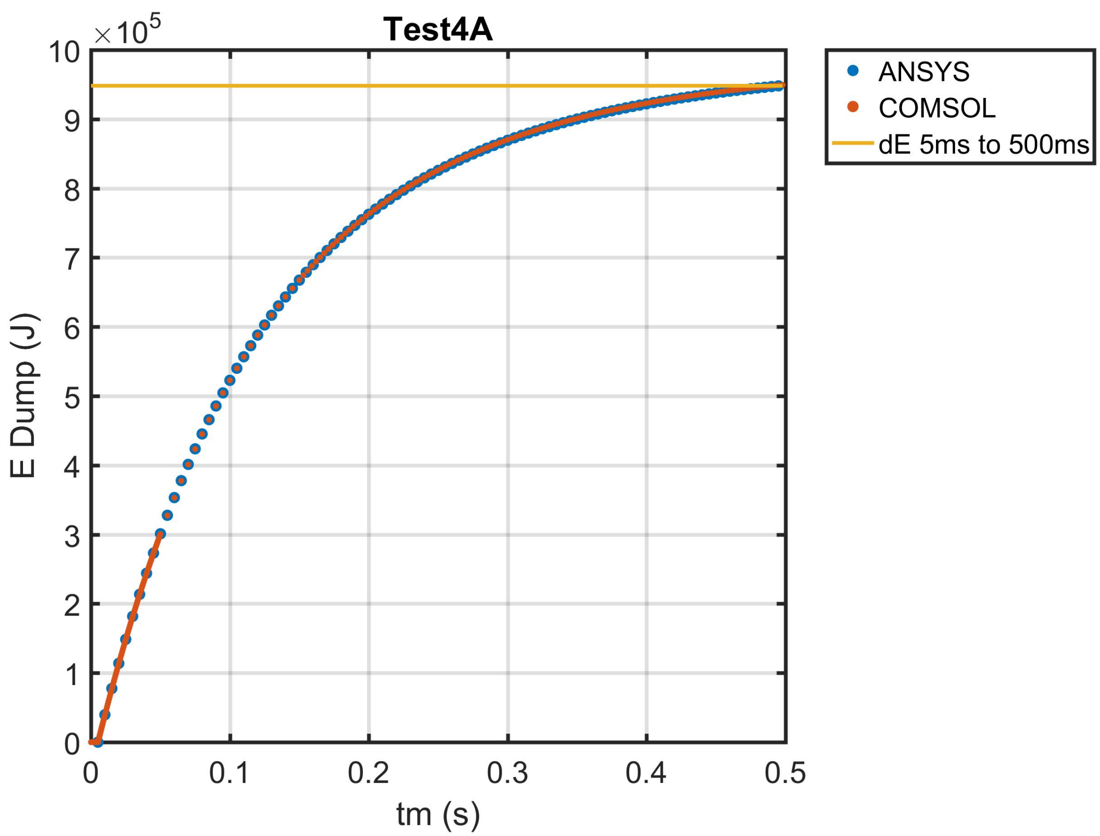
Active physics	EM, CIRCU
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	18.0 kA
Rdump	25 mΩ
L_c	N/A
L_i	9.20 m
Output	I(t) [A]
	Coil magnetic flux ϕ [Wb/m]
	Flux inductance as L = ϕ/i [H/m] (finite difference)
	E-dump(t) [J]

ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	976.77 kJ
Stored Energy at 500ms	28.61 kJ
ΔE	948.16 kJ
Edump	948.58 kJ (100% of ΔE)


Test4A
×10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
I (A)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL


Test4A
14
12
10
8
6
4
2
0
Linked Flux (Wb/m)
0
0.5
1
1.5
2
I0 (A)
×10^4
4A ANSYS
4A COMSOL
0B ANSYS


Test4A
$\times 10^{-4}$
8.2
8
7.8
7.6
7.4
7.2
7
6.8
L (H/m)
0
0.5
1
1.5
2
I0 (A)
$\times 10^{4}$
4A ANSYS
4A COMSOL
0B ANSYS

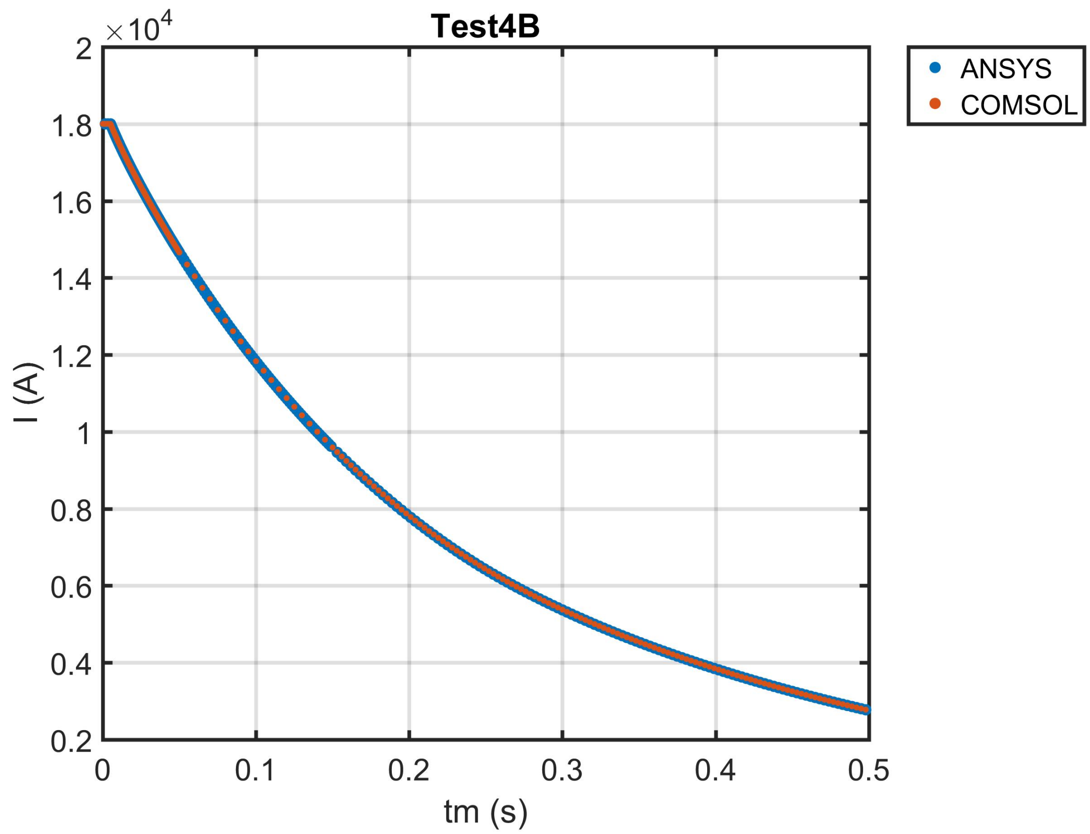

Test4A
$\times 10^{5}$
10
9
8
7
6
5
4
3
2
1
0
E Dump (J)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL
dE 5ms to 500ms

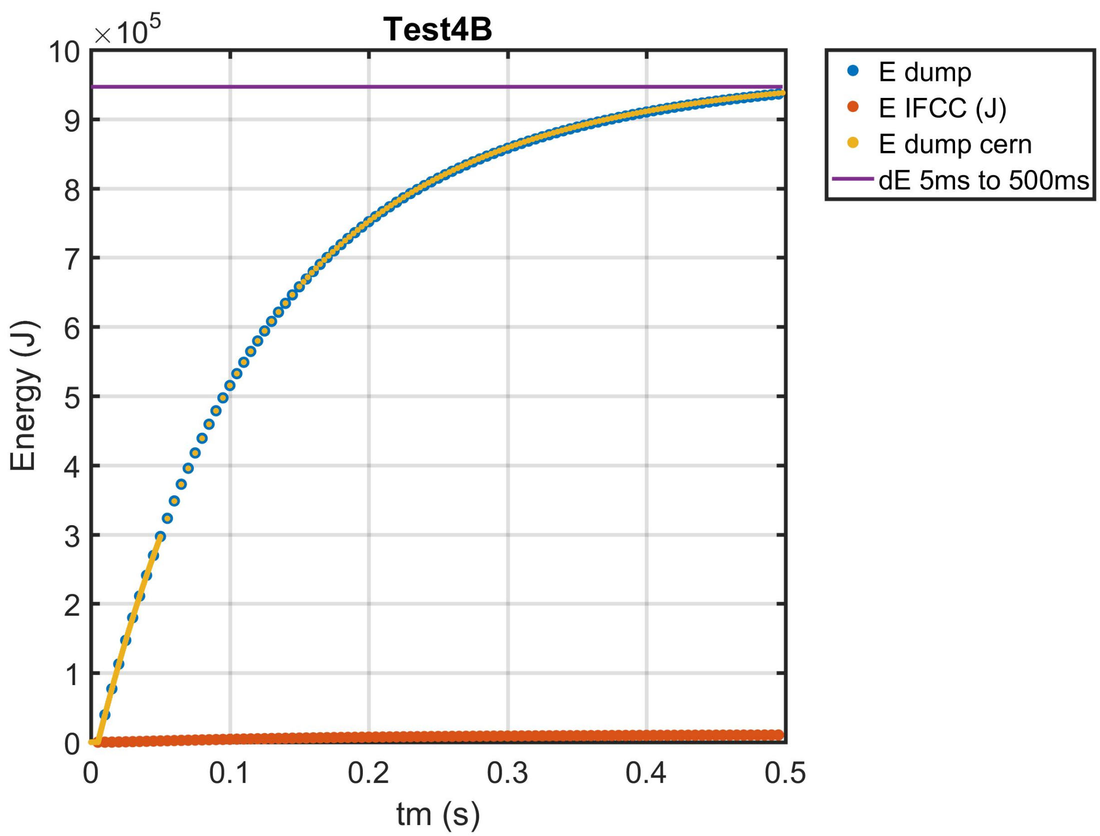
4.2 Test 4.B LR Decay With IFCC Losses

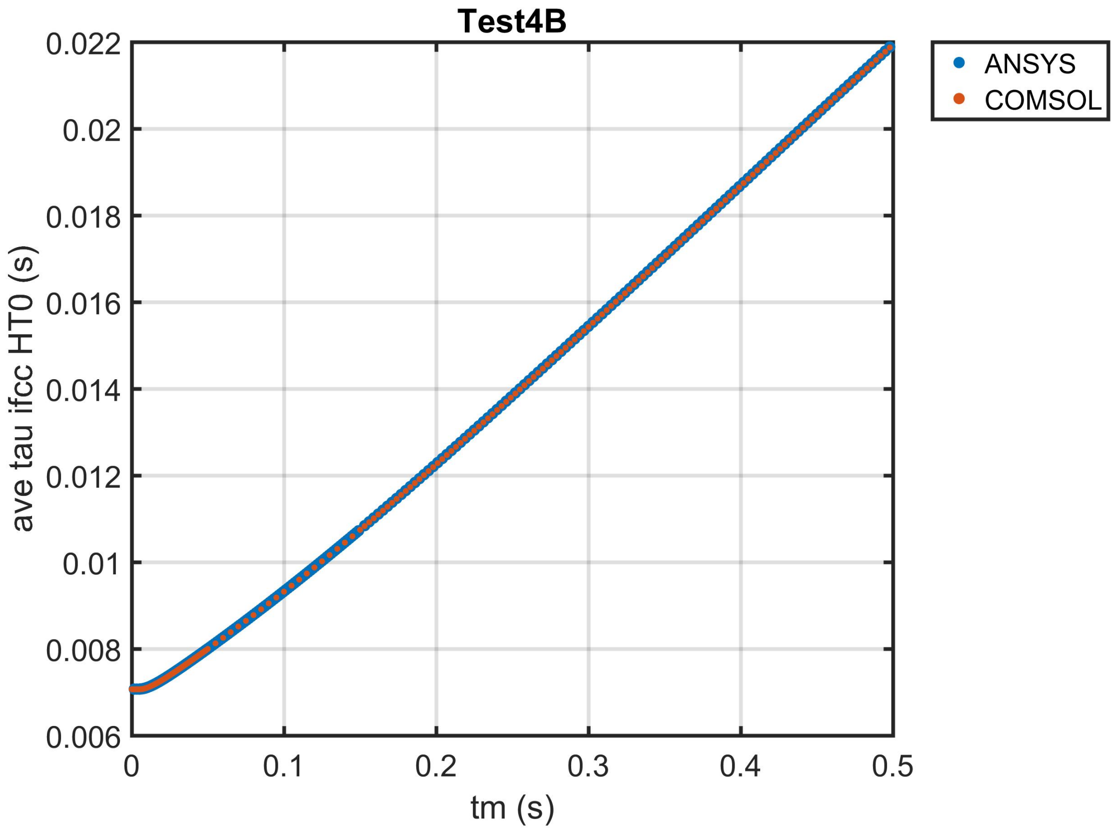
The previous simulation is repeated with inter-filament coupling current losses added, but kept at fixed temperature. This test checks the effect of IFCC on the current decay as some of the stored energy is now dissipated as IFCC loss.

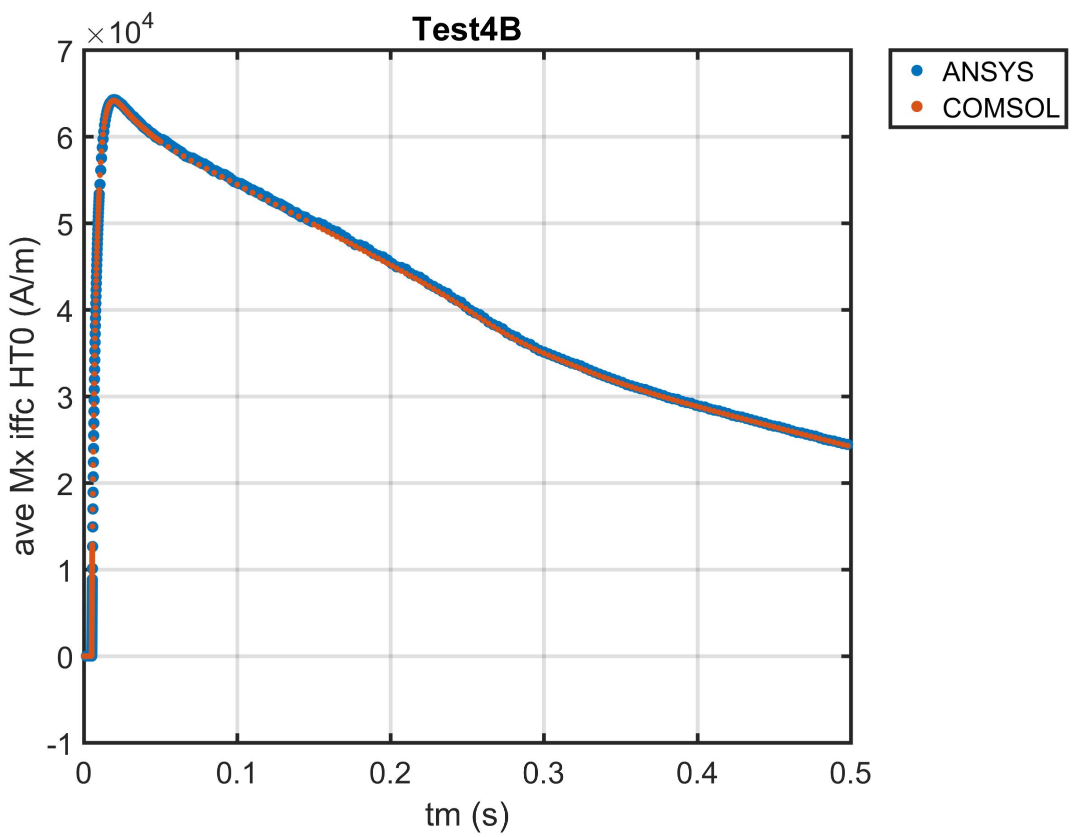
Active physics	EM, CIRCU
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Always SC
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	18.0 kA
Rdump	25 mΩ
L_c	N/A
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I(t) [A]
	E-dump(t) [J]
	Tau-IFCC$_{aveHT0}$ [s]
	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W/m] (per quad)
	Q-IFCC$_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]

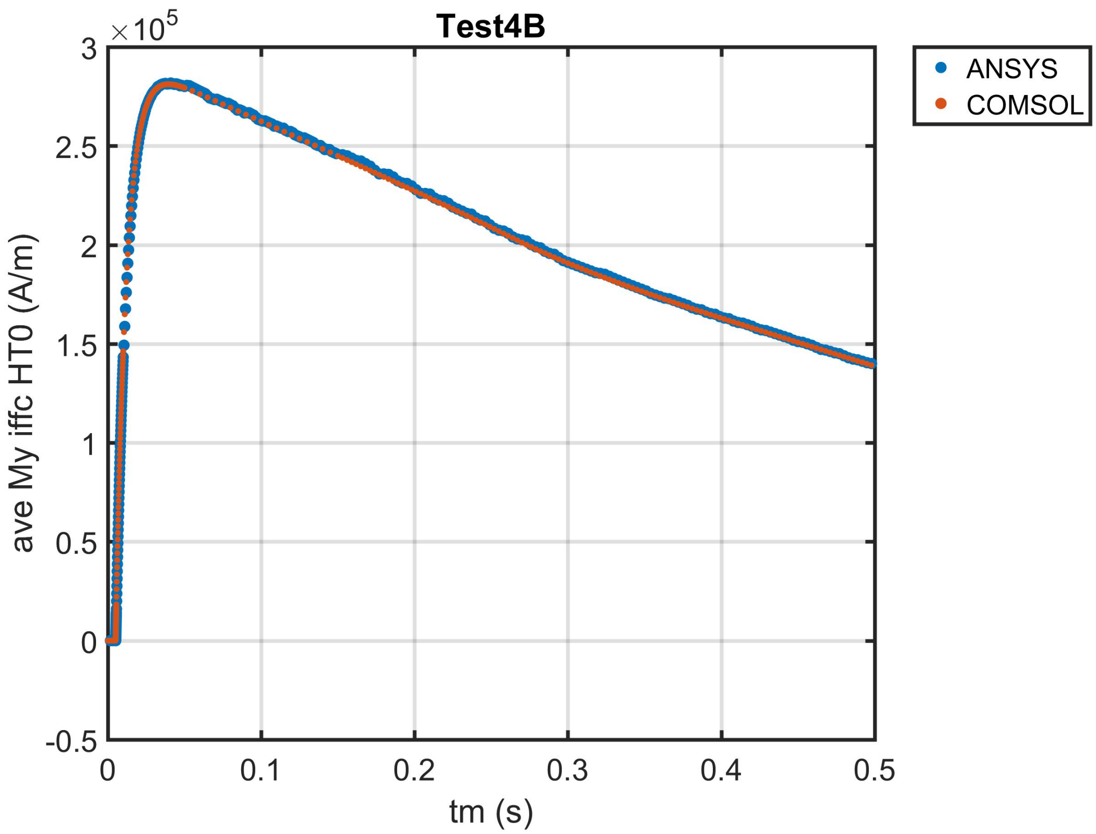
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	976.77 kJ
Stored Energy at 500ms	30.05 kJ
ΔE	946.72 kJ
Edump	936.59 kJ (98.96% of ΔE)
Eifcc	10.37 kJ (1.10% of ΔE)

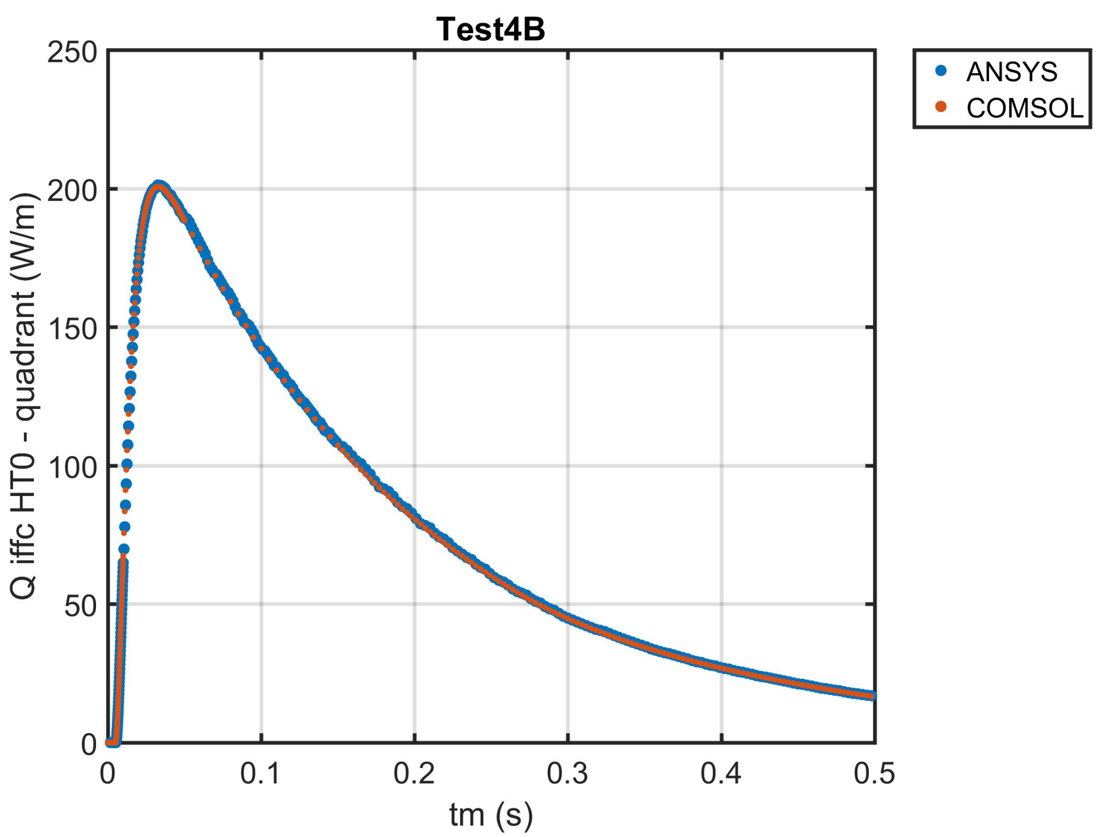

Test4B
×10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
I (A)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

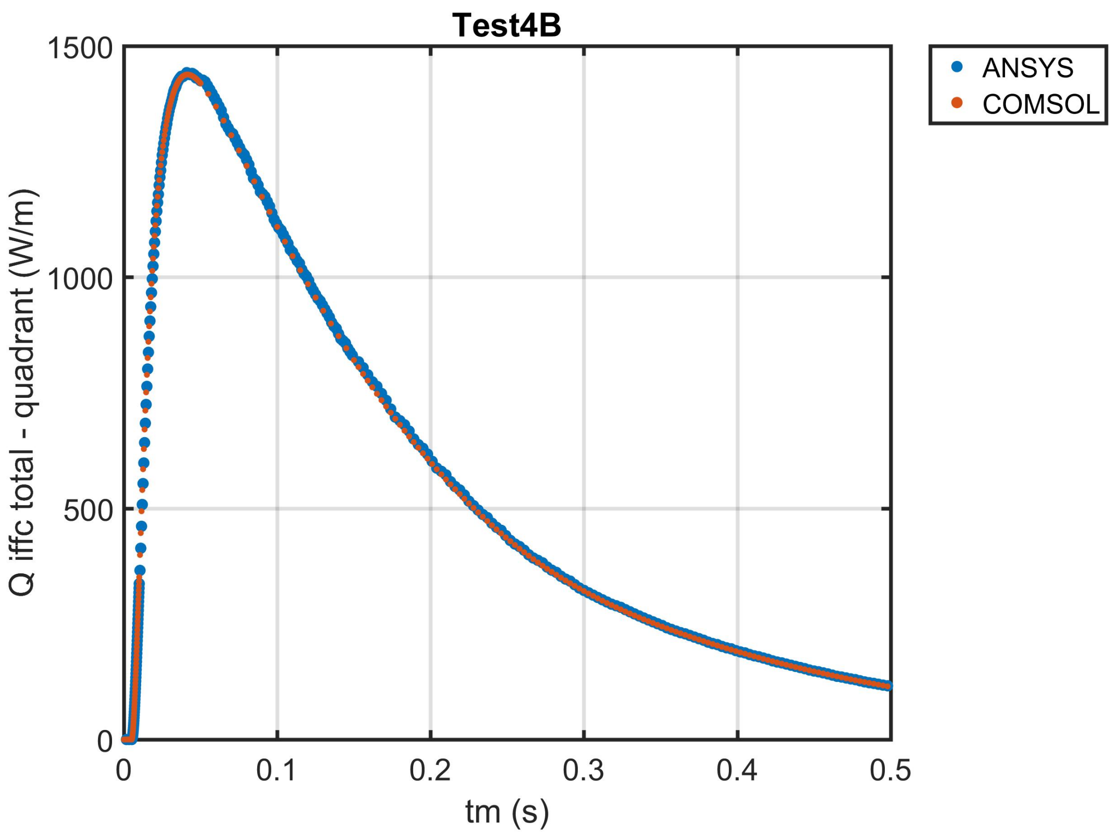

Test4B
×10^5
10
9
8
7
6
5
4
3
2
1
0
Energy (J)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
E dump
E IFCC (J)
E dump cern
dE 5ms to 500ms


Test4B
ave tau ifcc HT0 (s)
tm (s)
ANSYS
COMSOL
0.022
0.02
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0
0.1
0.2
0.3
0.4
0.5


Test4B
$\times 10^4$
ave Mx iffc HT0 (A/m)
tm (s)
ANSYS
COMSOL
7
6
5
4
3
2
1
0
-1
0
0.1
0.2
0.3
0.4
0.5


Test4B
×10^5
3
2.5
2
1.5
1
0.5
0
-0.5
ave My iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL


Test4B
250
200
150
100
50
0
Q iffc HT0 - quadrant (W/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

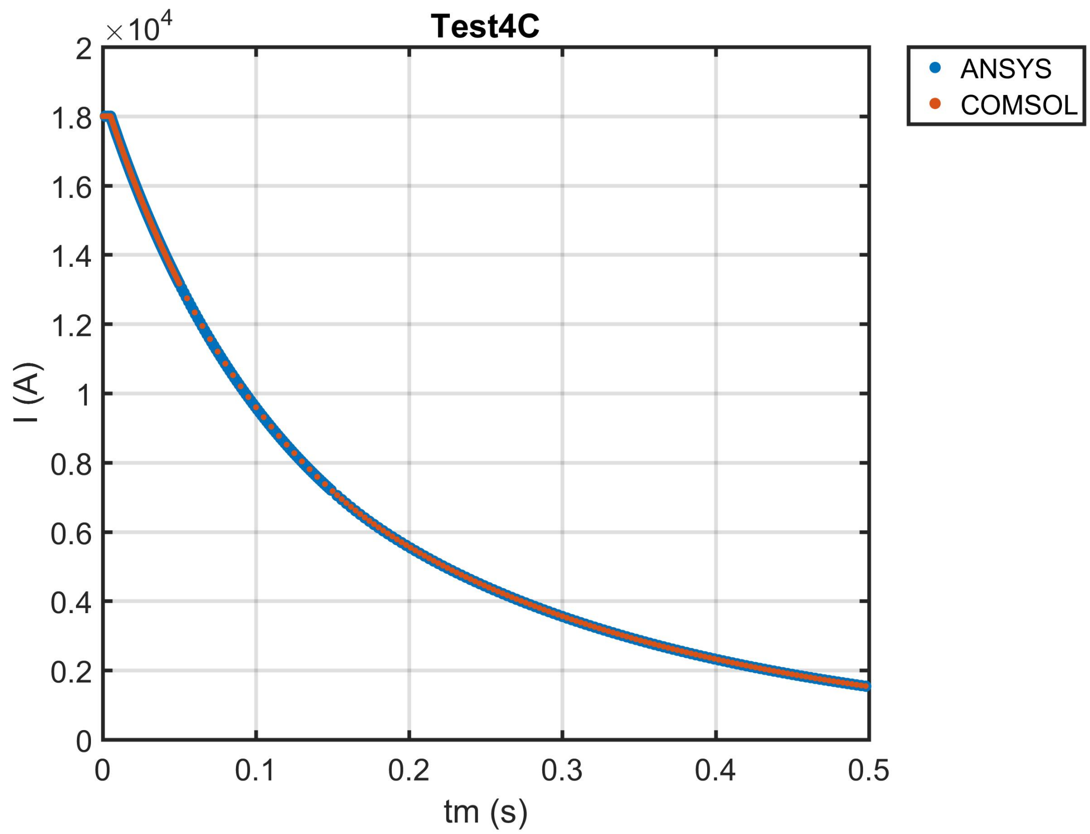

Test4B
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
tm (s)
Q iffc total - quadrant (W/m)
ANSYS
COMSOL

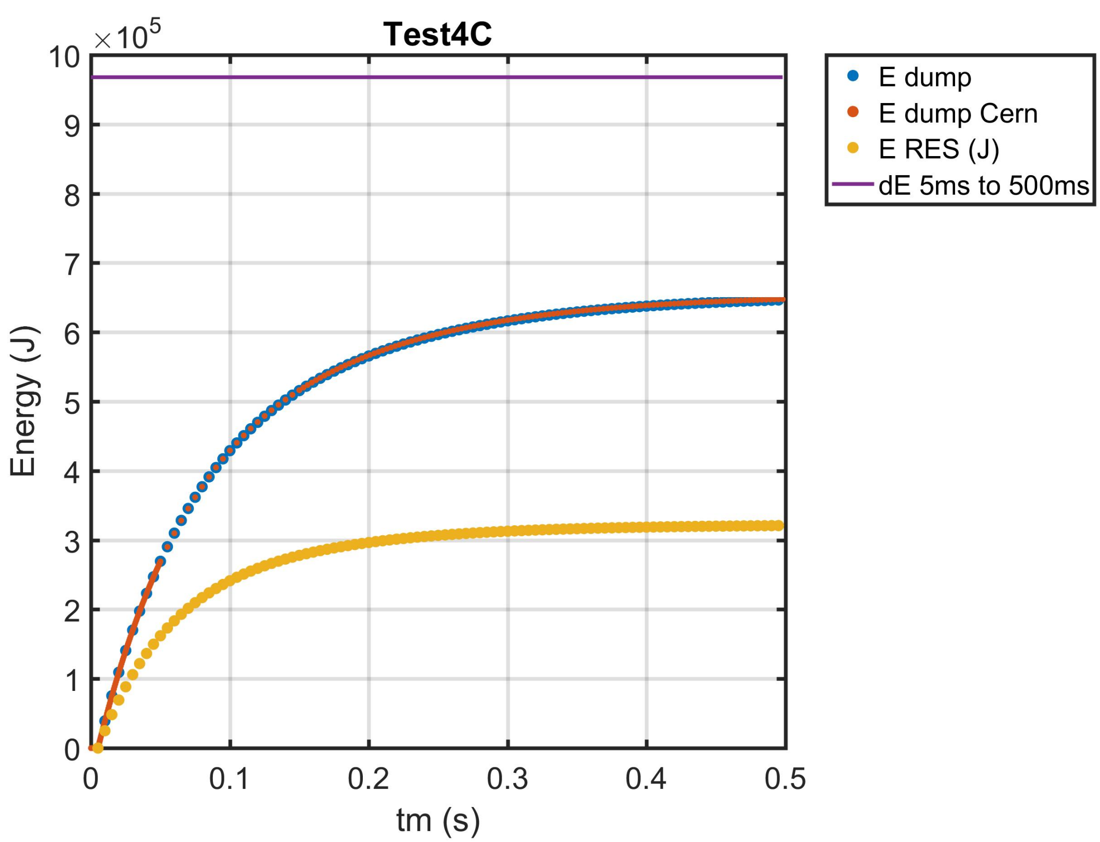
4.3 Test 4.C LR Decay With Coil Forced Quenched

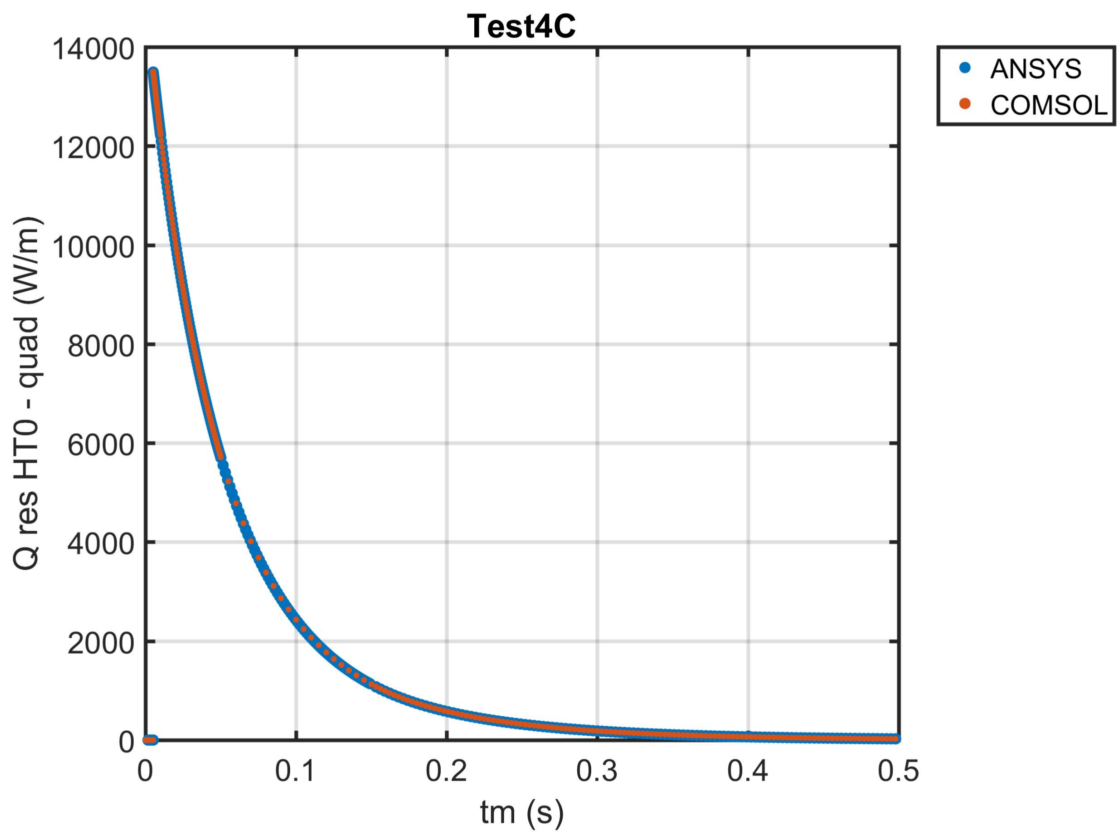
In this simulation IFCC is again turned off, but now the coil is forced to quench at a certain time. In this case we choose right when the supply voltage is dropped (5.1 ms). This adds the coil resistance to the decay seen in test 4A. Note an effective coil length for resistance is now included as L_c. As before, no heating is allowed. In this case the temperature is kept fixed and coil resistance only changes due to magneto resistivity.

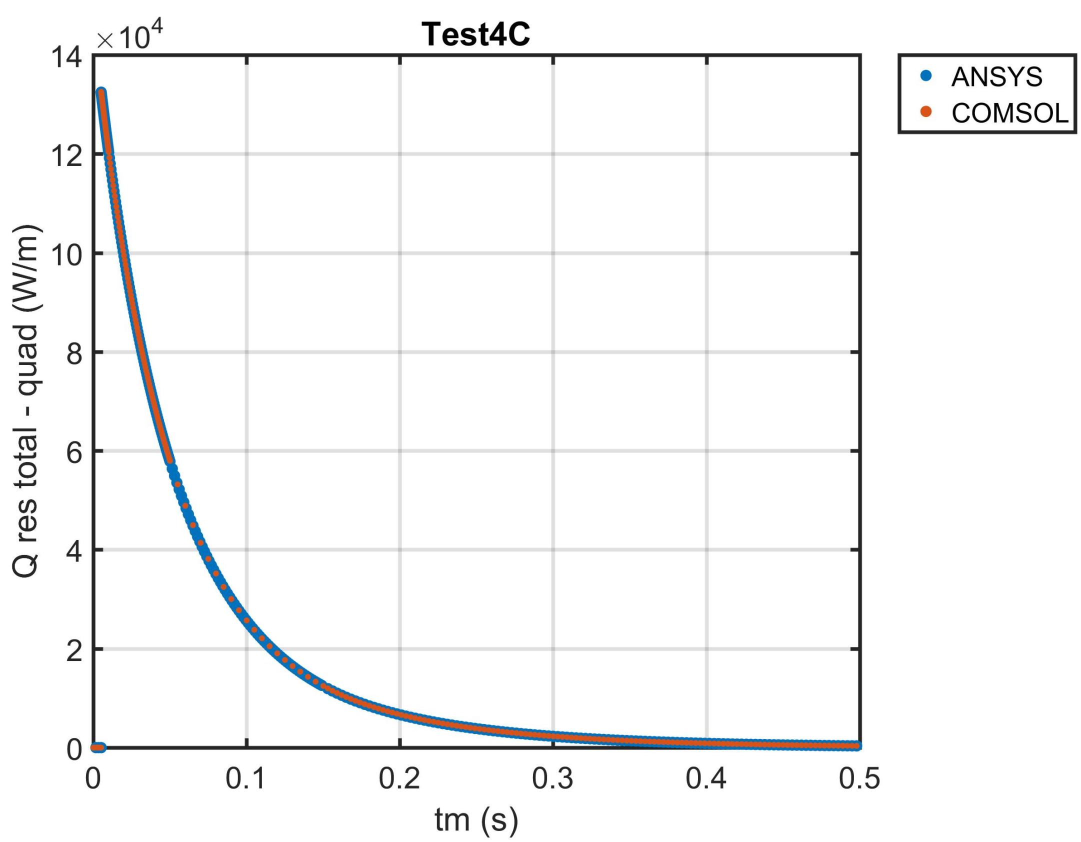
Active physics	EM, CIRCU
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	NO
Quench state	Fully Quenched at 5.1 ms
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	18.0 kA
Rdump	25 mΩ
L_c	10.11 m
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
Output	I(t) [A]
	E-dump(t) [J]
	Q-Ohm$_{totHT0}$ [W/m] (per quad)
	Q-Ohm$_{totcoil}$ [W/m] (per quad)
	R-coil(t) [Ω]
	E-Ohm(t) [J]

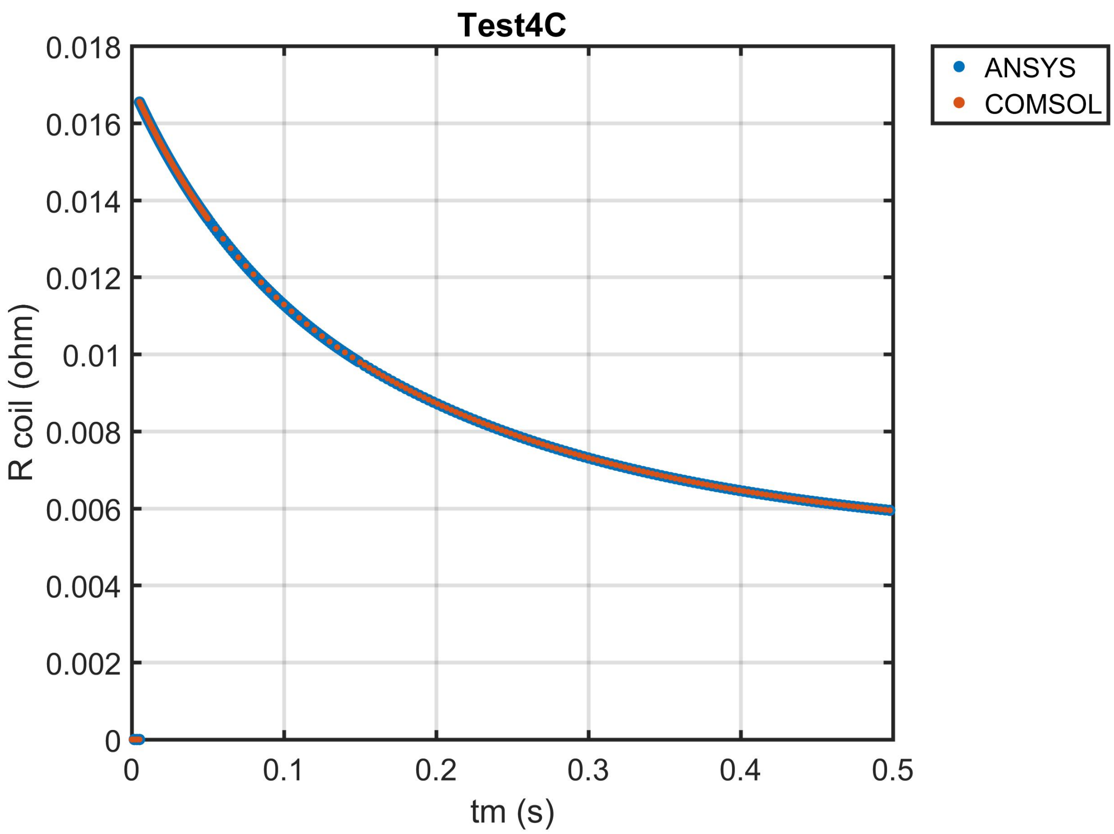
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	976.77 kJ
Stored Energy at 500ms	8.89 kJ
ΔE	967.88 kJ
Edump	646.63 kJ (66.81% of ΔE)
Eohm	320.97 kJ (33.16% of ΔE)


Test4C
×10^4
I (A)
tm (s)
ANSYS
COMSOL
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0.1
0.3
0.5


Test4C
×10^5
Energy (J)
tm (s)
E dump
E dump Cern
E RES (J)
dE 5ms to 500ms
0
1
2
3
4
5
6
7
8
9
10
0.1
0.2
0.3
0.4
0.5


Test4C
14000
12000
10000
8000
6000
4000
2000
0
Q res HT0 - quad (W/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL


Test4C
×10^4
14
12
10
8
6
4
2
0
Q res total - quad (W/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

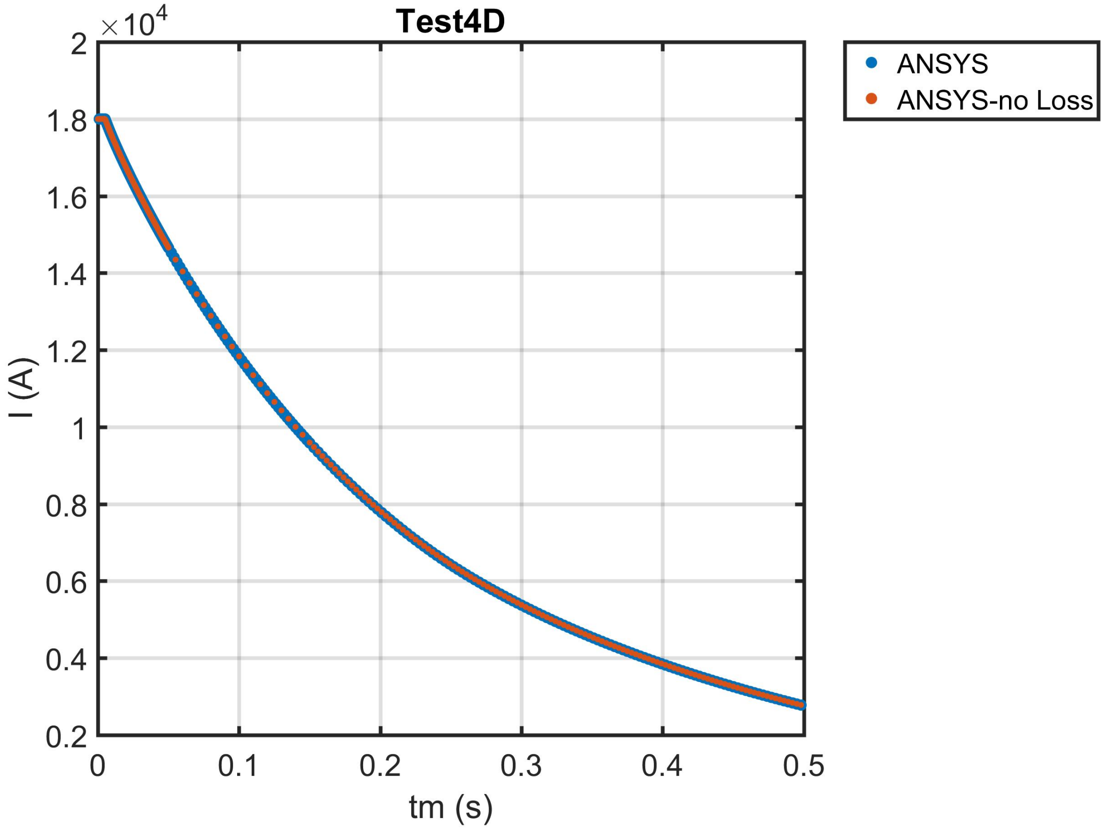

Test4C
0.018
0.016
0.014
0.012
0.01
0.008
0.006
0.004
0.002
0
R coil (ohm)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

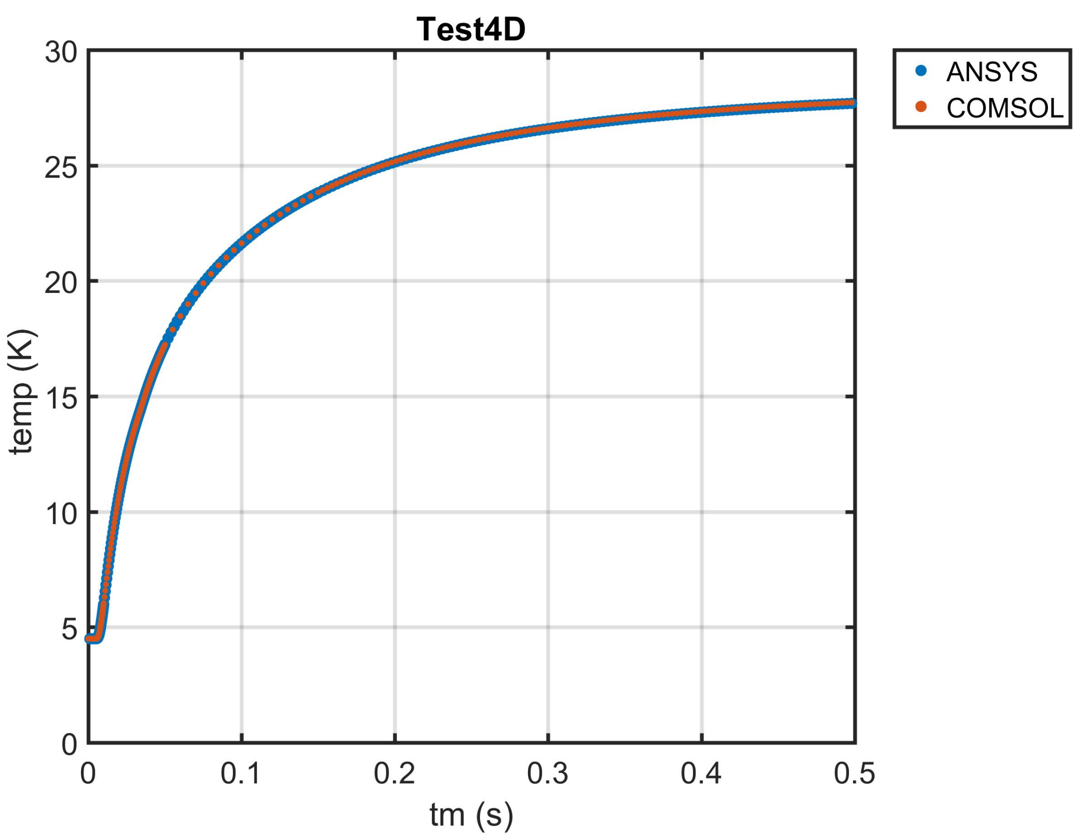
4.4 Test 4.D LR Decay With IFCC Loss and Thermal

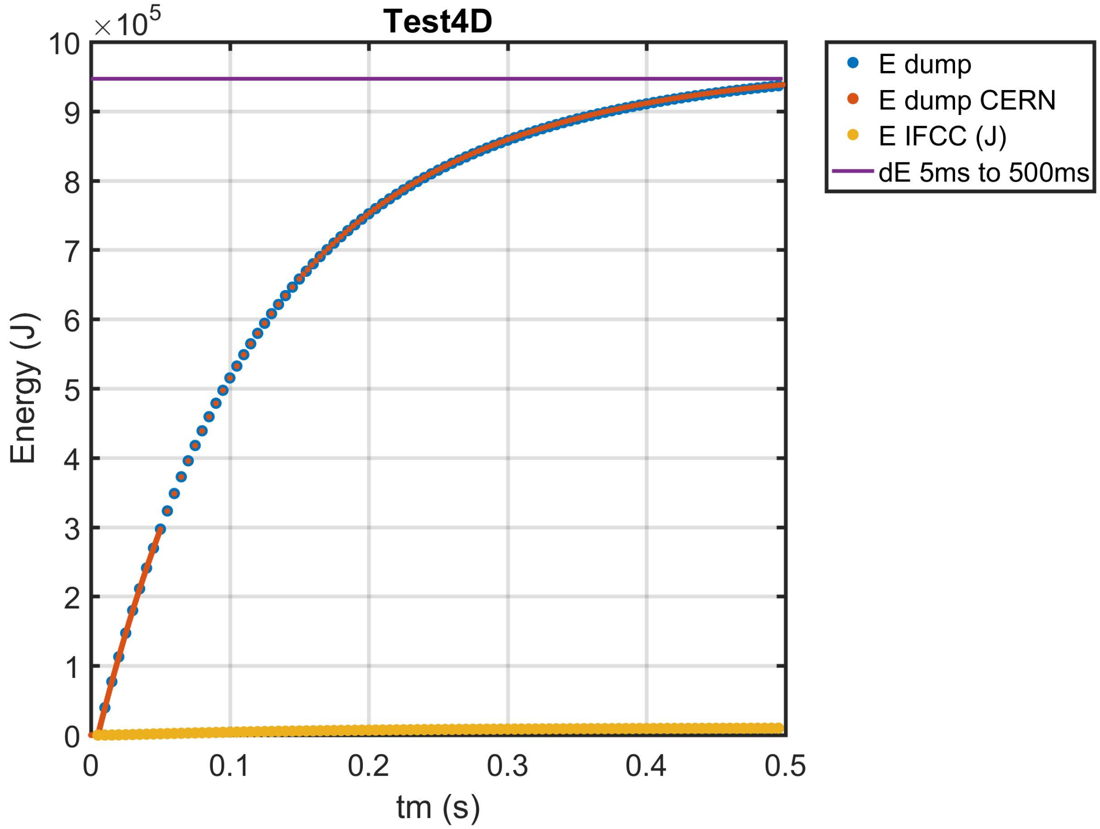
Test 4B is repeated with coupling to thermal. This allows the conductor to heat up due to the IFCC losses with the variation of material properties with temperature and field included. This is the first step towards a fully coupled case of both IFCC losses and quench.

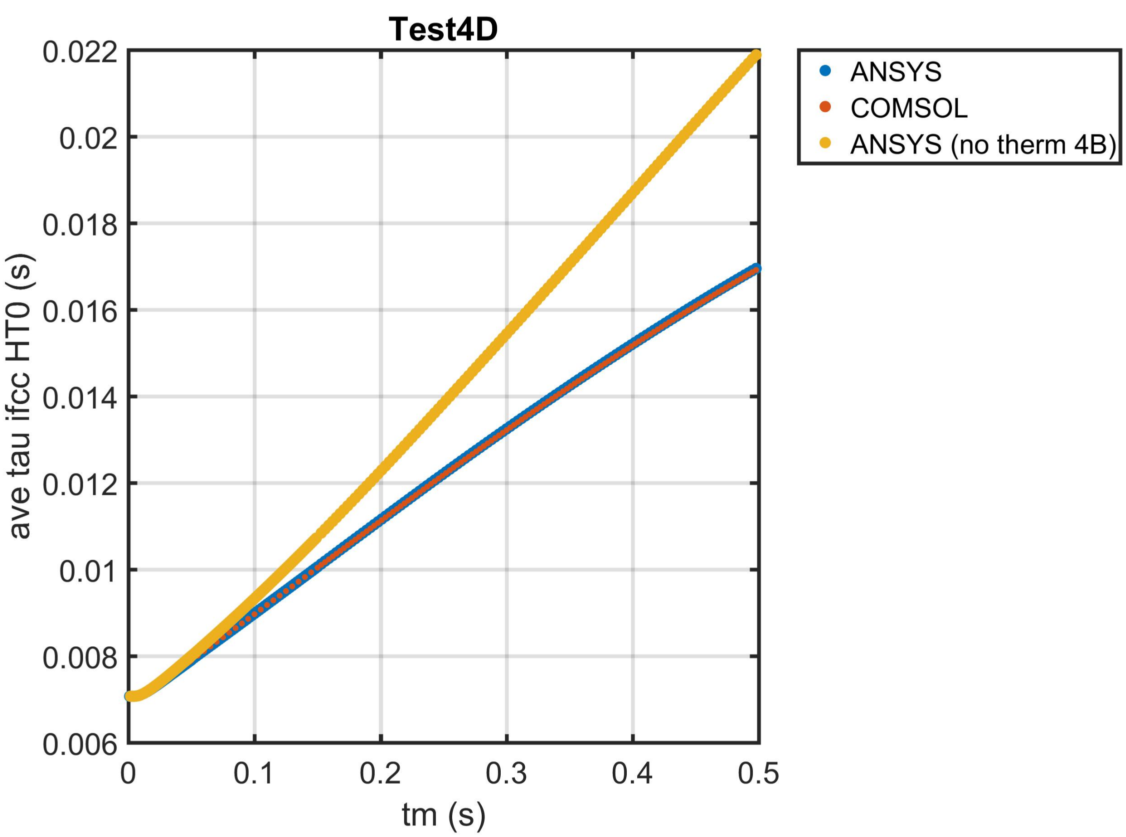
Active physics	EM, CIRCU, THERM
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	GLASS FIBER
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	18.0 kA
Rdump	25 mΩ
L_c	N/A
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I(t) [A]
	T_{aveHT0} [K]
	E-dump(t) [J]
	Tau-IFCC$_{aveHT0}$ [s]
	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W/m] (per quad)
	Q-IFCC$_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]

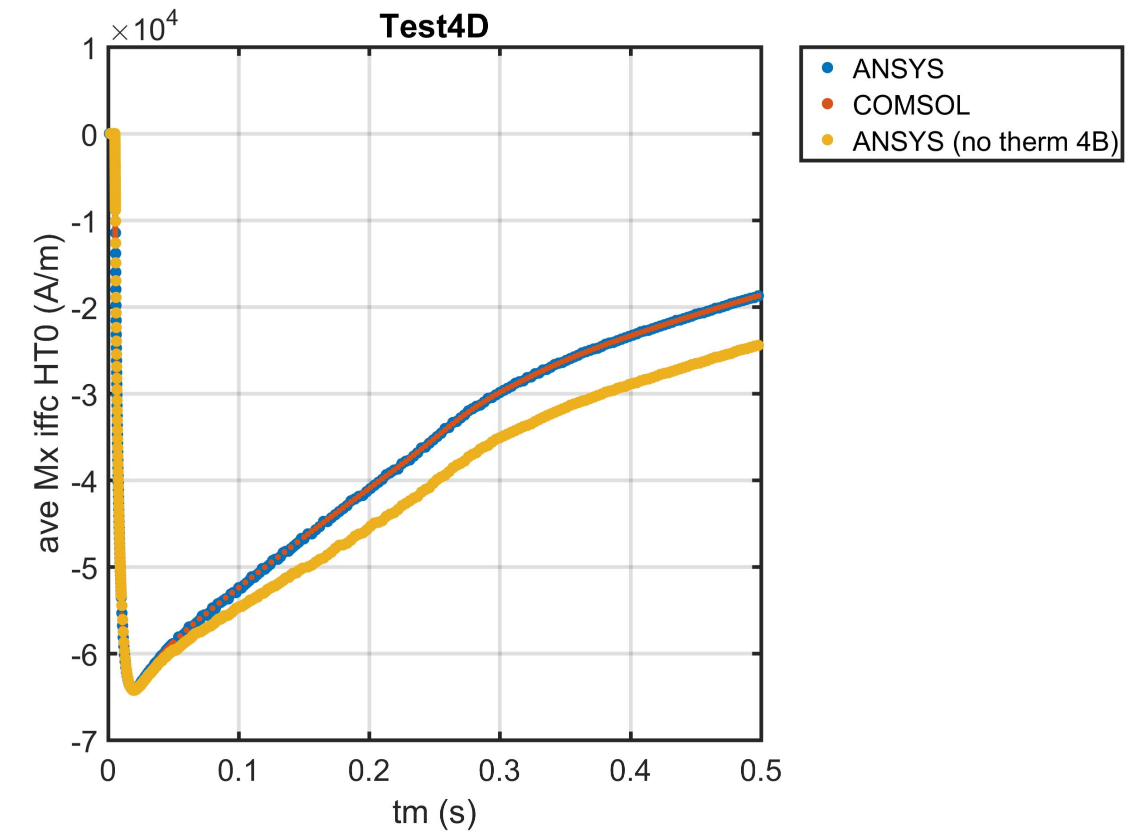
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	976.77 kJ
Stored Energy at 500ms	29.92 kJ
ΔE	946.85 kJ
Edump	937.39 kJ (99.00% of ΔE)
Eifcc	9.91 kJ (1.05% of ΔE)

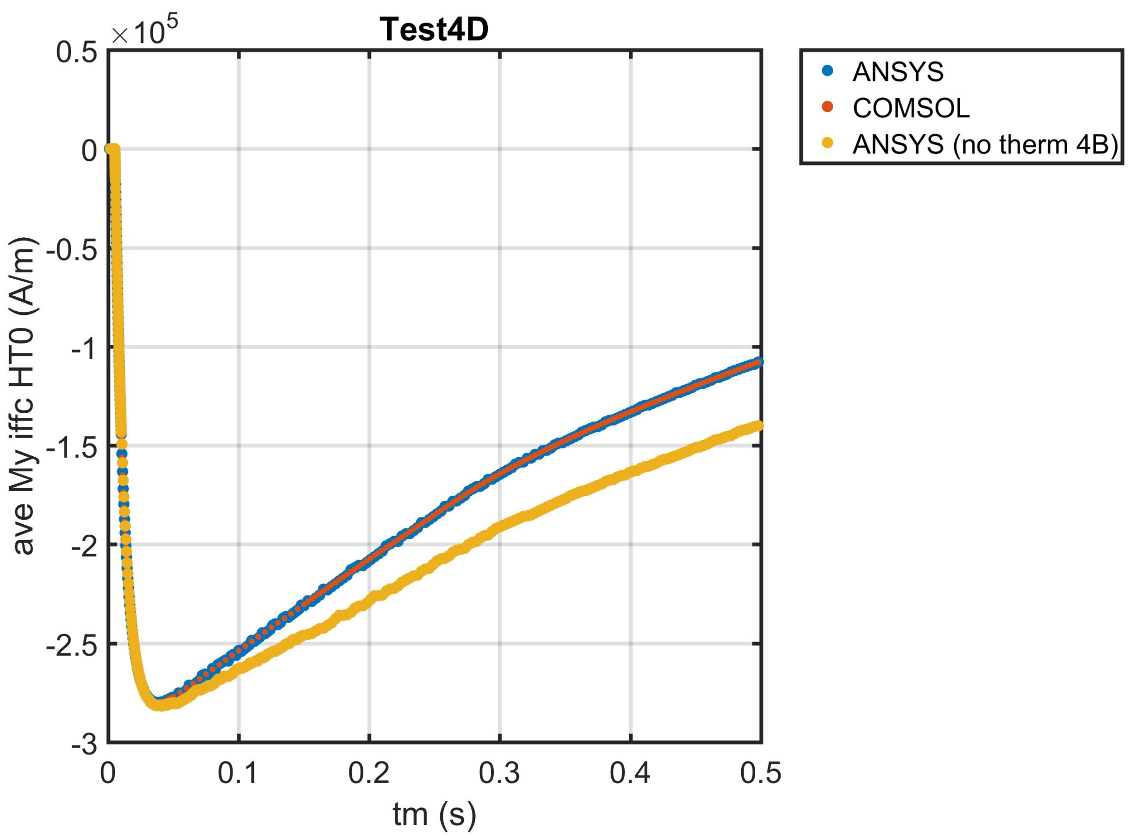

Test4D
×10^4
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
I (A)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
ANSYS-no Loss

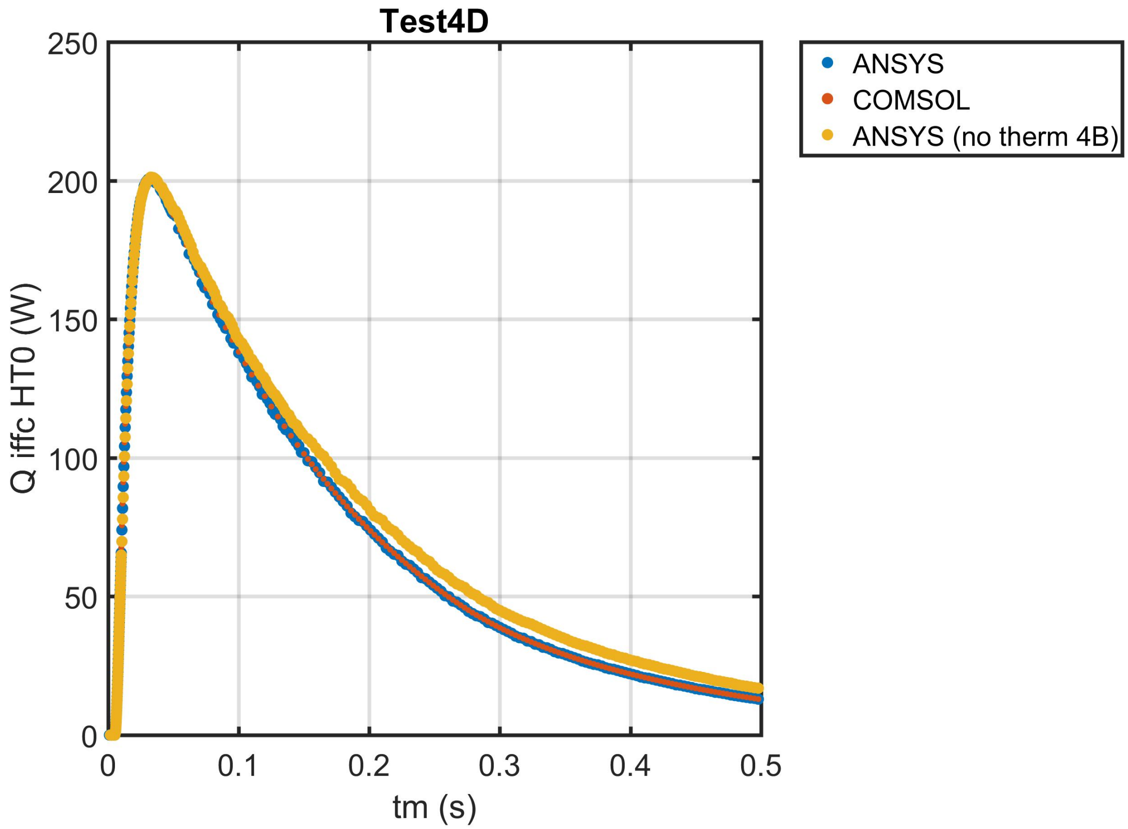

Test4D
30
25
20
15
10
5
0
temp (K)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

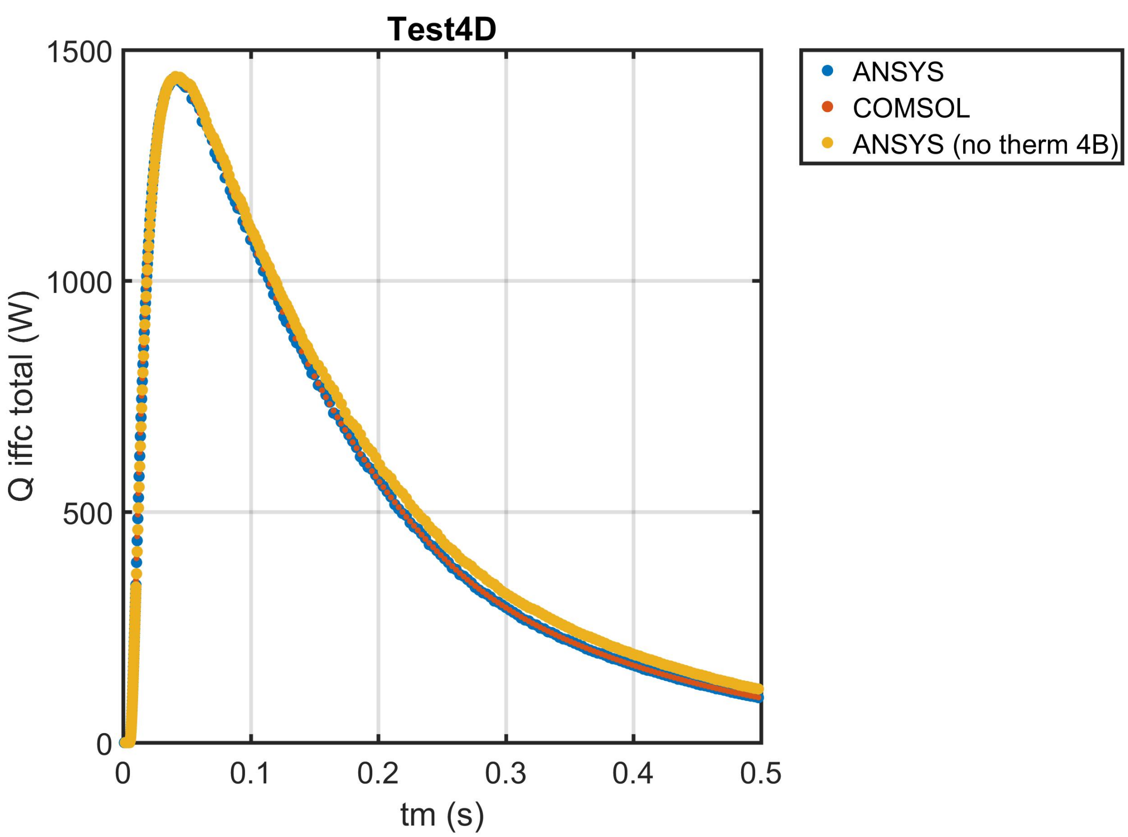

Test4D
×10^5
Energy (J)
tm (s)
E dump
E dump CERN
E IFCC (J)
dE 5ms to 500ms
0
1
2
3
4
5
6
7
8
9
10
0.1
0.2
0.3
0.4
0.5


Test4D
ave tau ifcc HT0 (s)
tm (s)
ANSYS
COMSOL
ANSYS (no therm 4B)
0.006
0.008
0.01
0.012
0.014
0.016
0.018
0.02
0.022
0
0.1
0.2
0.3
0.4
0.5


Test4D
×10^4
1
0
-1
-2
-3
-4
-5
-6
-7
ave Mx iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL
ANSYS (no therm 4B)


Test4D
×10^5
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
ave My iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL
ANSYS (no therm 4B)


Test4D
Q iffc HT0 (W)
tm (s)
ANSYS
COMSOL
ANSYS (no therm 4B)
0
50
100
150
200
250
0
0.1
0.2
0.3
0.4
0.5

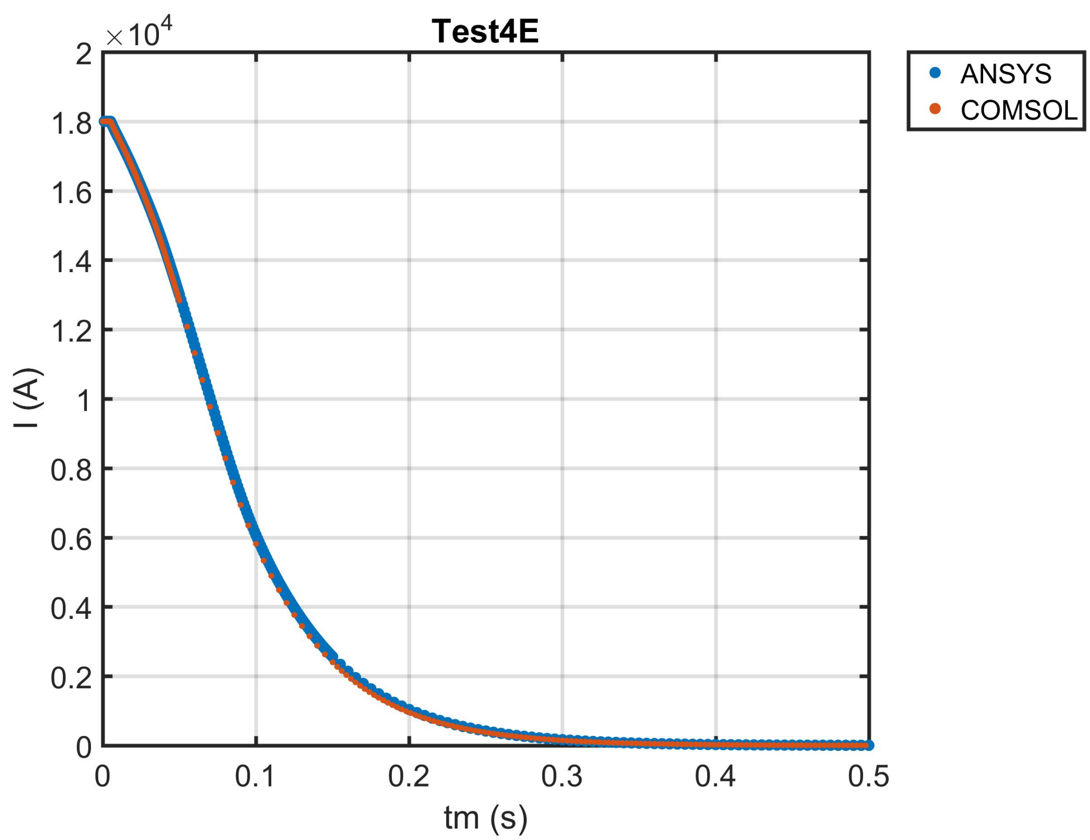

Test4D
Q iffc total (W)
tm (s)
ANSYS
COMSOL
ANSYS (no therm 4B)
0
500
1000
1500
0
0.1
0.2
0.3
0.4
0.5

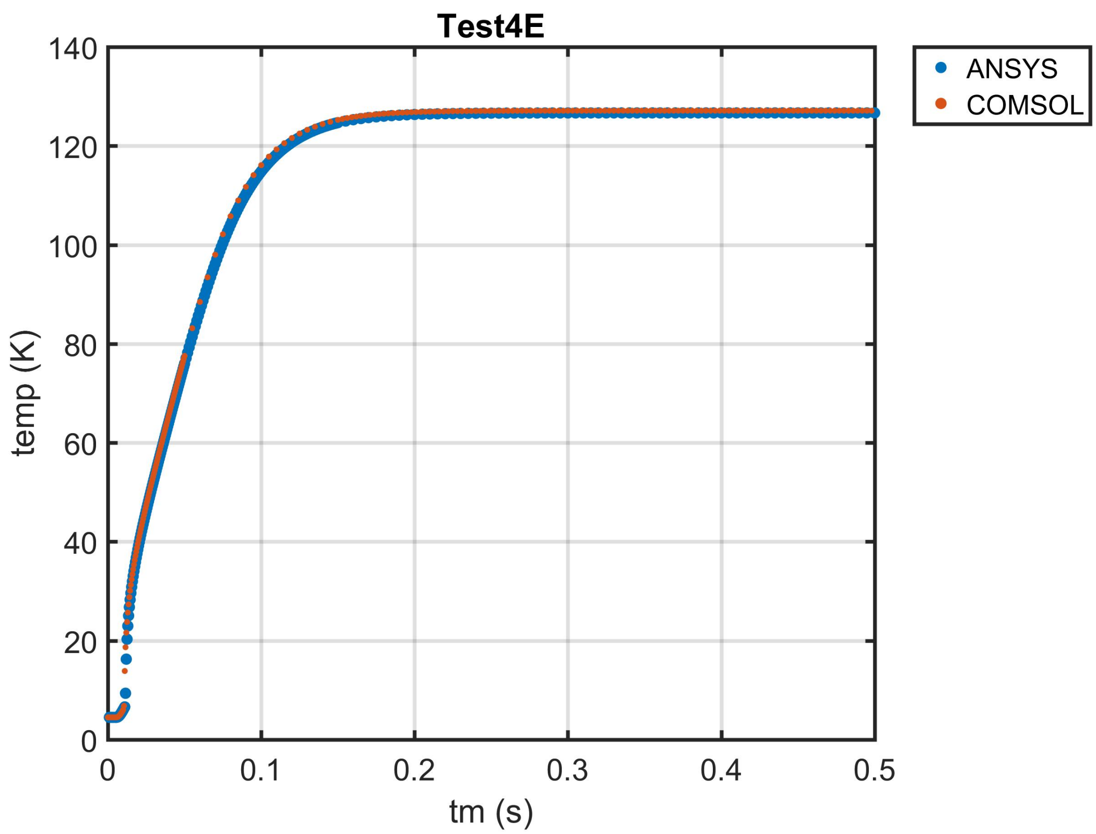
4.5 Test 4.E LR Decay With IFCC Induced Quench Back

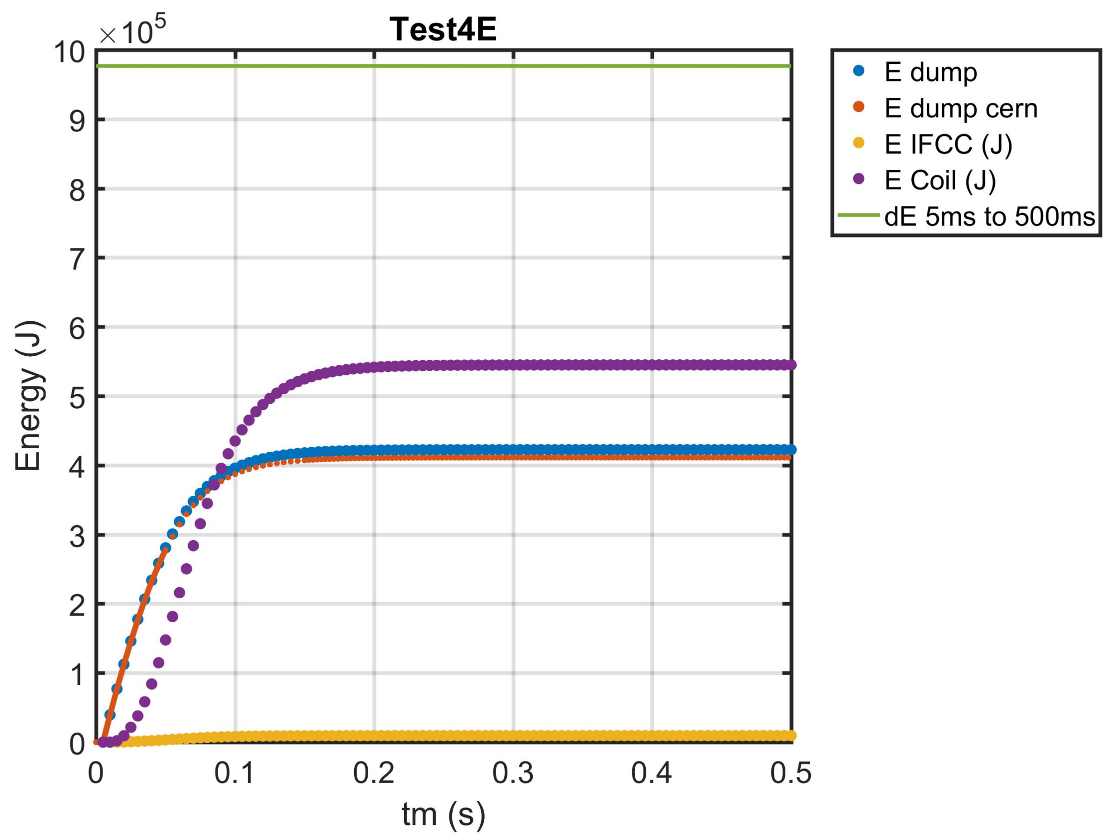
This is the first case where all the effects are combined for a quench back scenario. The high dB/dt due to the dump resistor extraction initiates IFCC losses which heats the coil to the point of quench. Then the coil resistance grows quickly and dominates the decay.

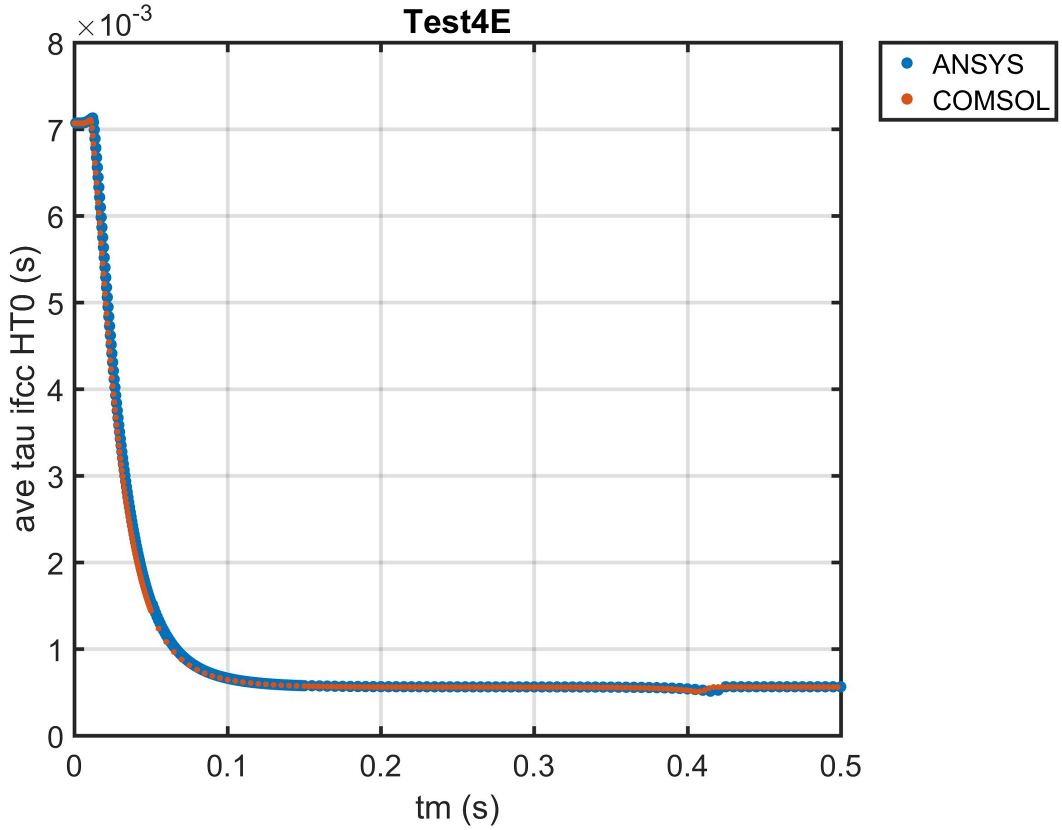
Active physics	EM, CIRCU, THERM
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Allow Quench with no Current Sharing
Cable insulation material	None
Cable voids filling material	GLASS FIBER
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	18.0 kA
Rdump	25 mΩ
L_c	10.11 m
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I(t) [A]
	T_{aveHT0} [K]
	E-dump(t) [J]
	Tau-IFCC$_{aveHT0}$ [s]
	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W/m] (per quad)
	Q-IFCC$_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]
	Q-Ohm$_{totHT0}$ [W/m] (per quad)
	Q-Ohm$_{totcoil}$ [W/m] (per quad)
	R-coil(t) [Ω]
	E-Ohm(t) [J]

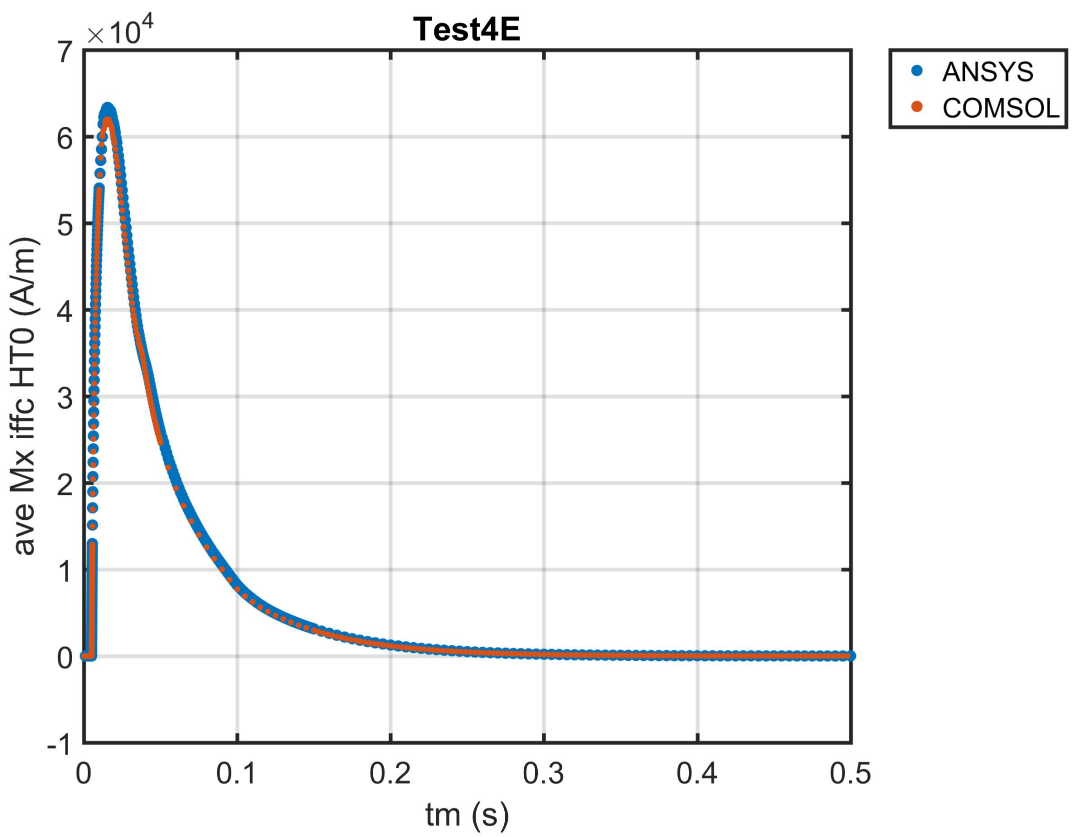
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	976.77 kJ
Stored Energy at 500ms	0.00 kJ
ΔE	976.77 kJ
Edump	422.51 kJ (43.26% of ΔE)
Eifcc	9.41 kJ (0.96% of ΔE)
Eohm	544.98 kJ (55.79% of ΔE)

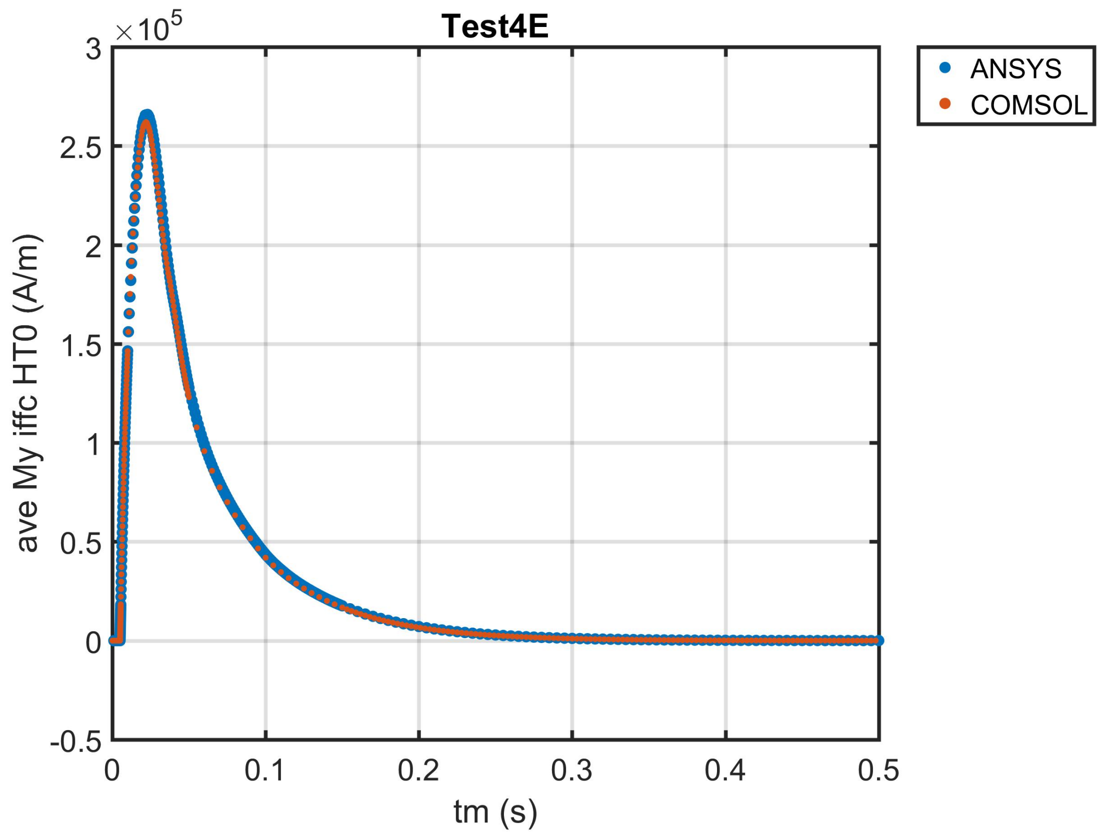


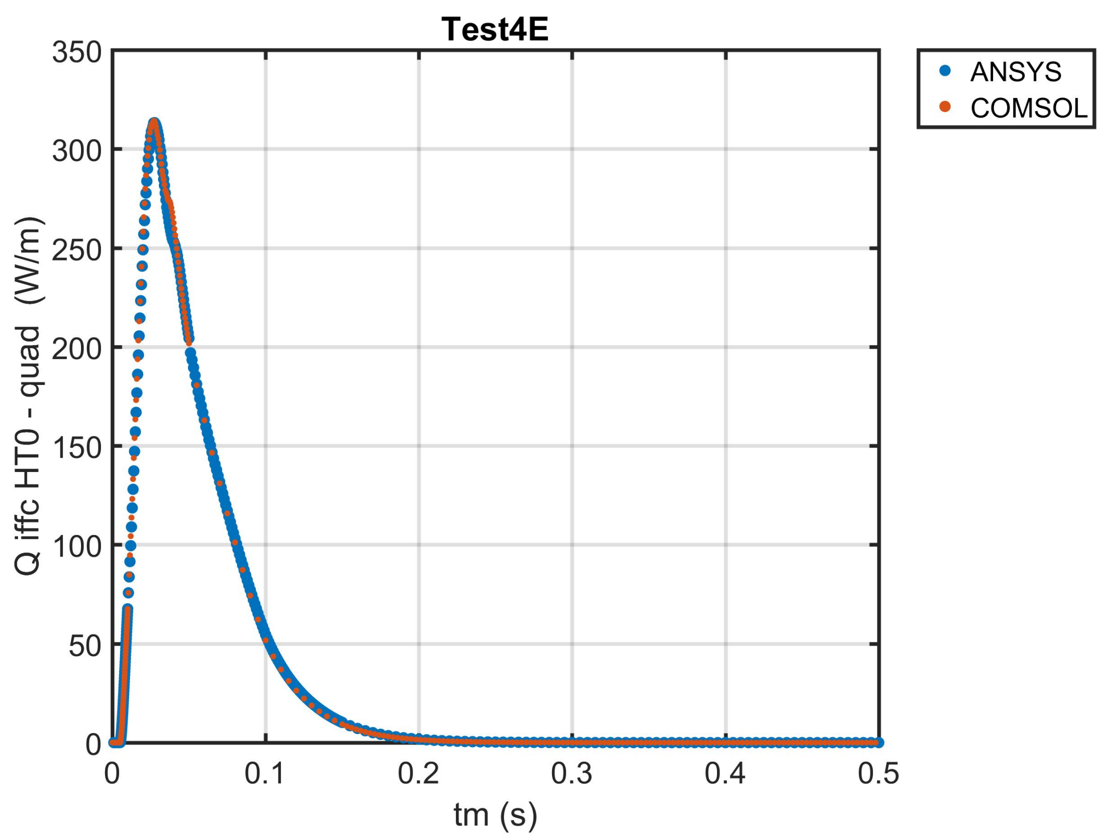

Test4E
ANSYS
COMSOL
temp (K)
tm (s)
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5

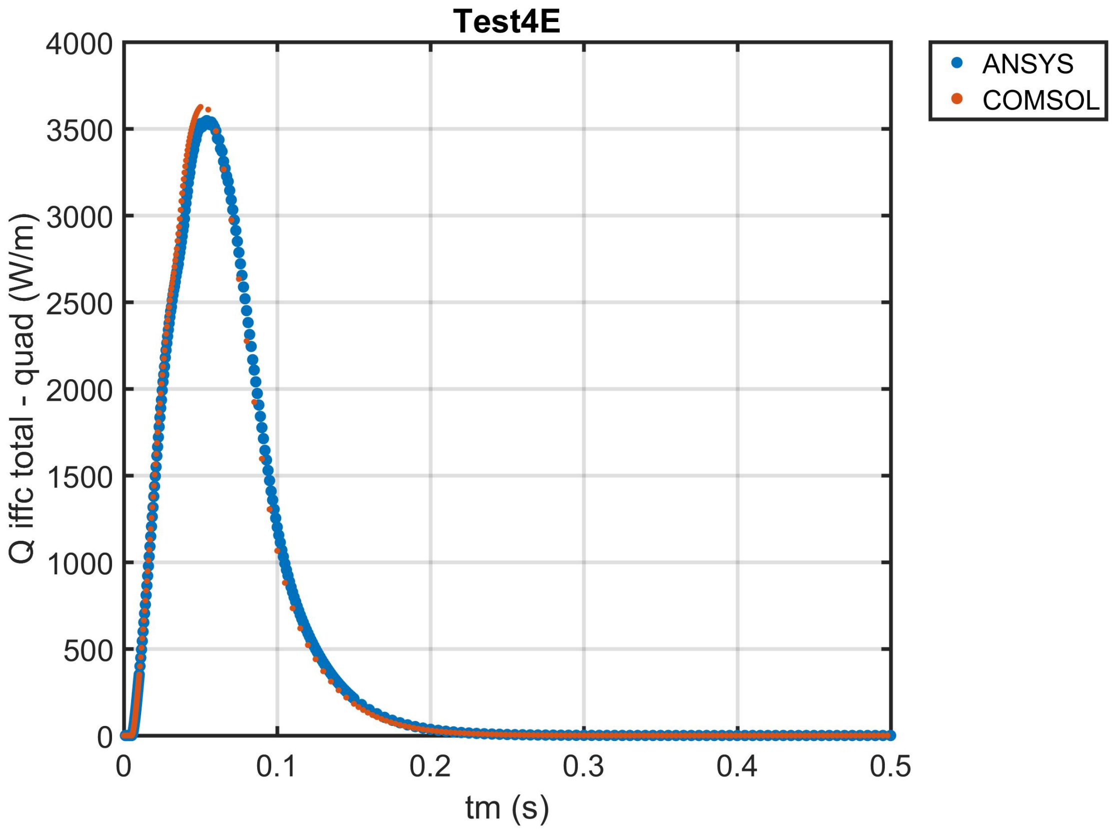

Test4E
$\times 10^5$
E dump
E dump cern
E IFCC (J)
E Coil (J)
dE 5ms to 500ms
Energy (J)
tm (s)
0
1
2
3
4
5
6
7
8
9
10
0
0.1
0.2
0.3
0.4
0.5

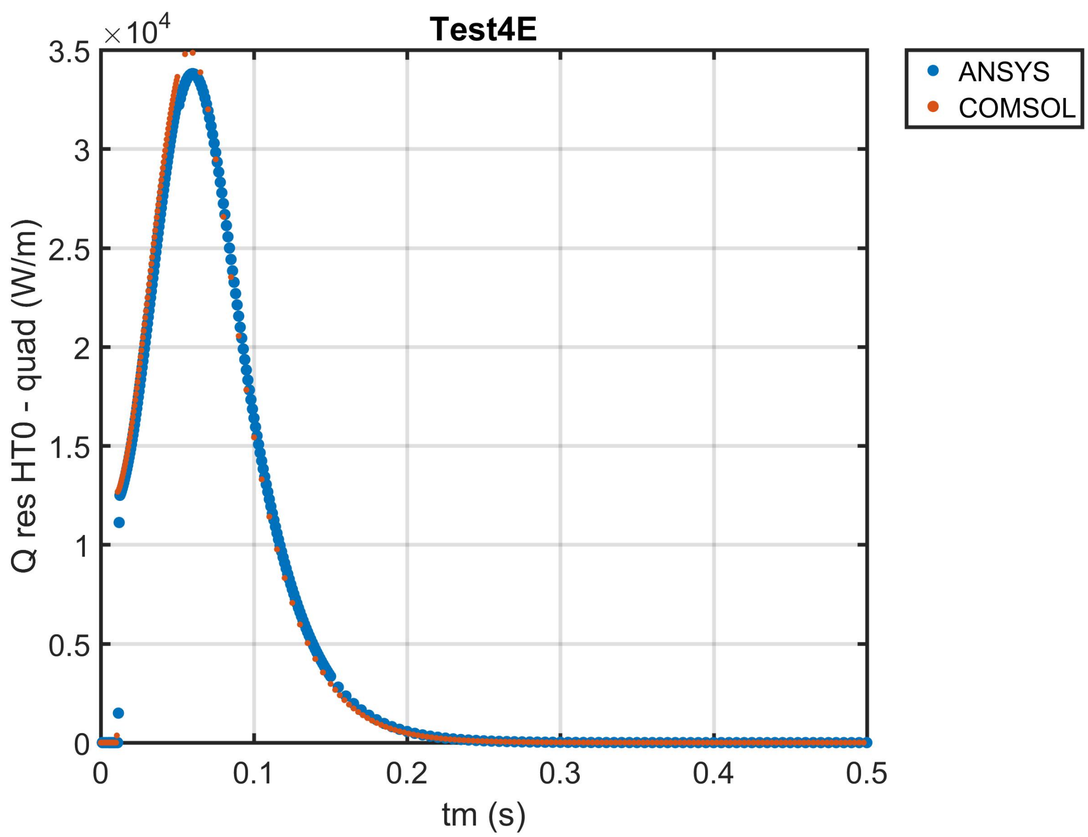

Test4E
$\times 10^{-3}$
8
7
6
5
4
3
2
1
0
ave tau ifcc HT0 (s)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

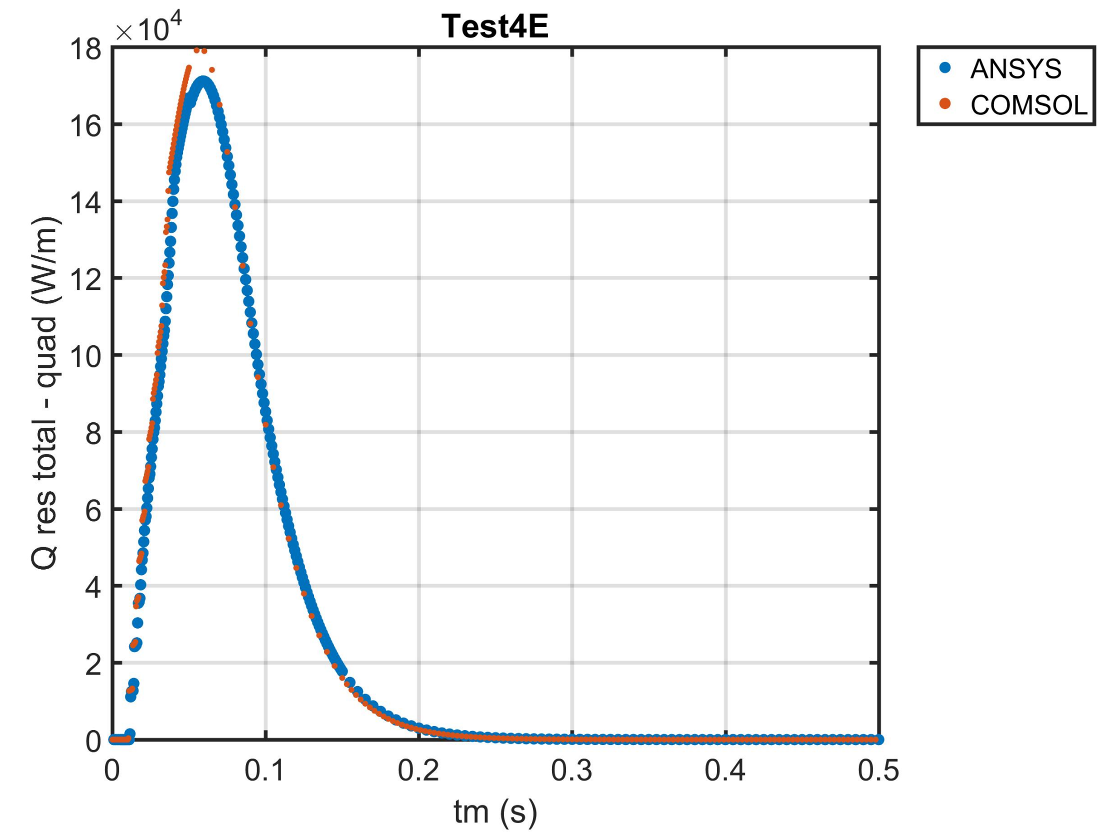

Test4E
$\times 10^{4}$
7
6
5
4
3
2
1
0
-1
ave Mx iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

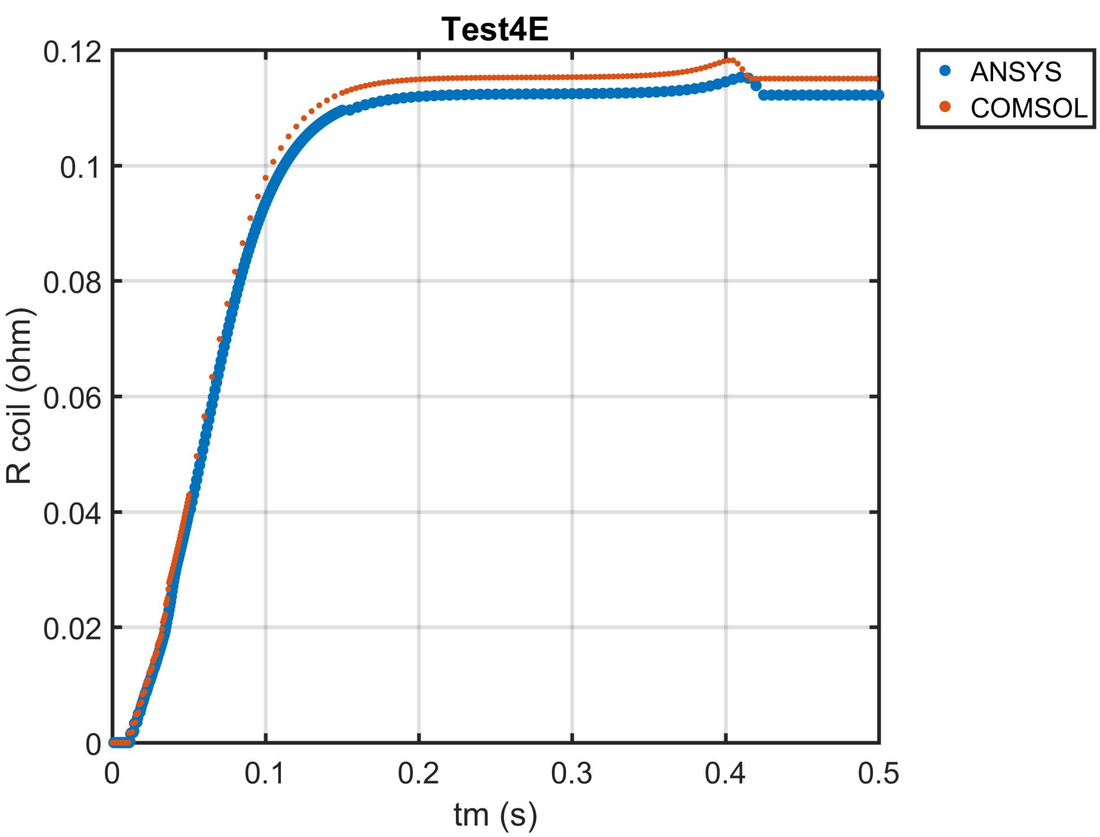

Test4E
ANSYS
COMSOL
×10^5
ave My iffc HT0 (A/m)
tm (s)
3
2.5
2
1.5
1
0.5
0
-0.5
0
0.1
0.2
0.3
0.4
0.5


Test4E
ANSYS
COMSOL
Q iffc HT0 - quad (W/m)
tm (s)
350
300
250
200
150
100
50
0
0
0.1
0.2
0.3
0.4
0.5


Test4E
4000
3500
3000
2500
2000
1500
1000
500
0
0
0.1
0.2
0.3
0.4
0.5
tm (s)
Q iffc total - quad (W/m)
ANSYS
COMSOL


Test4E
×10^4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.1
0.2
0.3
0.4
0.5
tm (s)
Q res HT0 - quad (W/m)
ANSYS
COMSOL


Test4E
×10^4
18
16
14
12
10
8
6
4
2
0
Q res total - quad (W/m)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

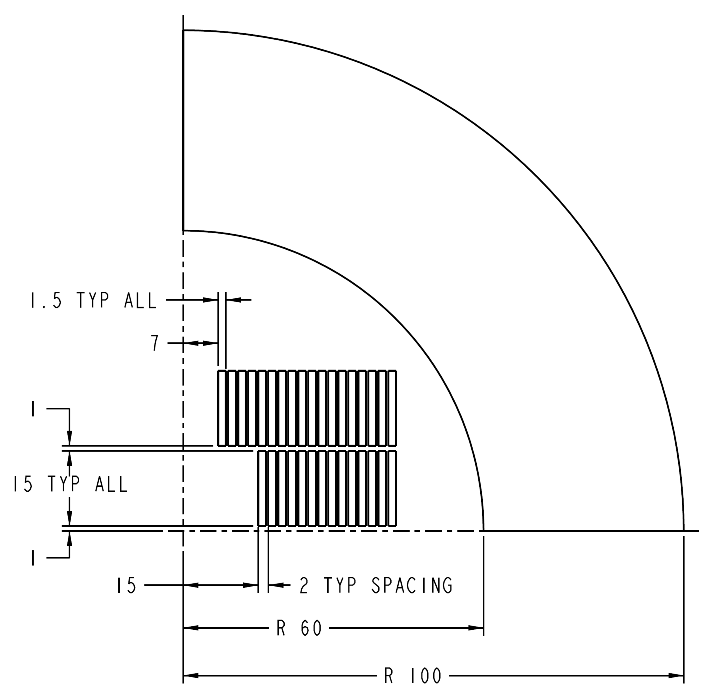

Test4E
0.12
0.1
0.08
0.06
0.04
0.02
0
R coil (ohm)
0
0.1
0.2
0.3
0.4
0.5
tm (s)
ANSYS
COMSOL

5 A Double Layer Nb_3Sn Dipole Model

5.1 Model and Geometry

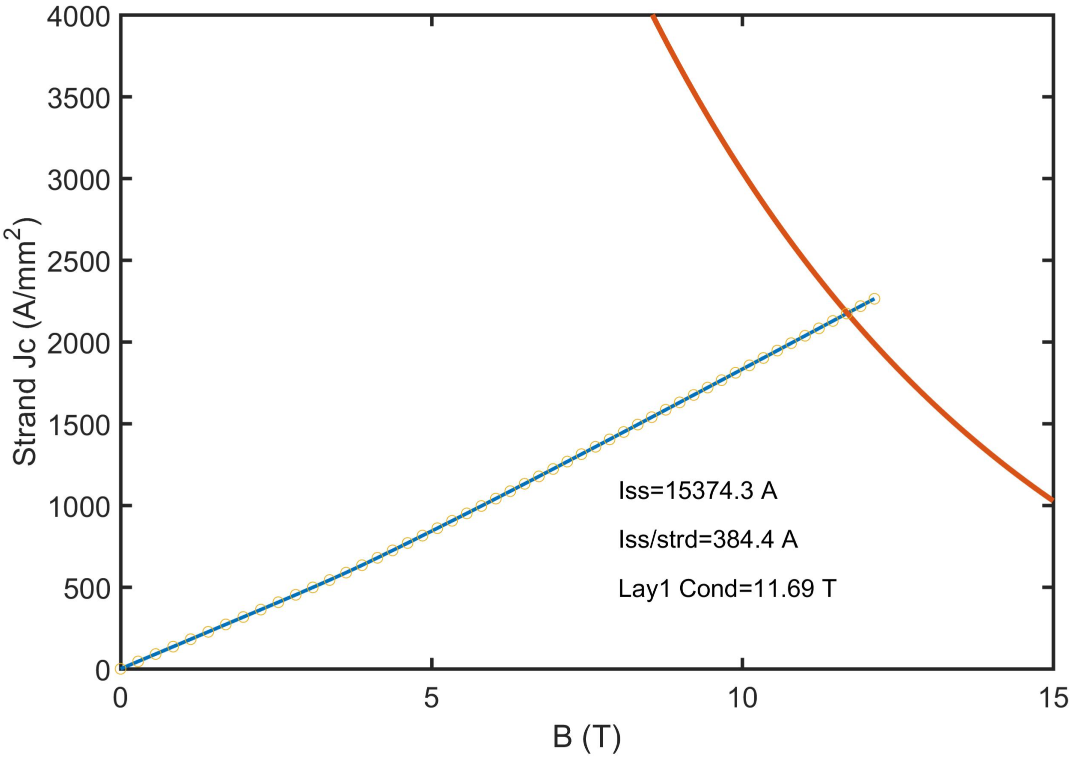
A dipole model with two layers (to allow for layer-layer CLIQ tests) was designed in a current and field regime representative of realistic Nb_3Sn accelerator magnets. This model consists of two, block-like conductor layers surrounded by a cylindrical iron yoke. The inner layer contains 14 turns and the outer layer has 18 turns. The figure below details the model dimensions (with units of millimeters), and a list of high level model parameters are given in the table. The cable and conductor properties are given in Appendices A and B. The non-linear BH curve for the iron yoke can be found in Appendix D. The outer, radial boundary conditions are assumed to be far enough from the coil and yoke to no longer have an impact on the results. There are also .stp and .dxf CAD files (named "geo2") included. In many cases the compared results are averaged over the first half turn labeled "HT0". This is the cable nearest to the aperture in the inner layer (farthest left of the 14).

Inner layer turns (per quad.)	14	
Outer layer turns (per quad.)	18	
Nb_3Sn J_c (4.5 K, 12 T)	2040	A/mm^2
Short-sample current (4.5 K)	15.4	kA
Short-sample cond. field (4.5 K)	11.7	T
Lc: effective res. coil length	10.11	m
Li: effective ind. coil length	9.2	m



5.2 Short-Sample

The strand and cable parameters in Appendix A, load line with iron (from Test5A), and J_c fit found in Appendix B were used to calculate the short-sample for the double layer model with iron. As seen in the figure below, the short-sample conductor field is 11.7 T at a current of 15.37 kA when operating at a temperature of 4.5 K.

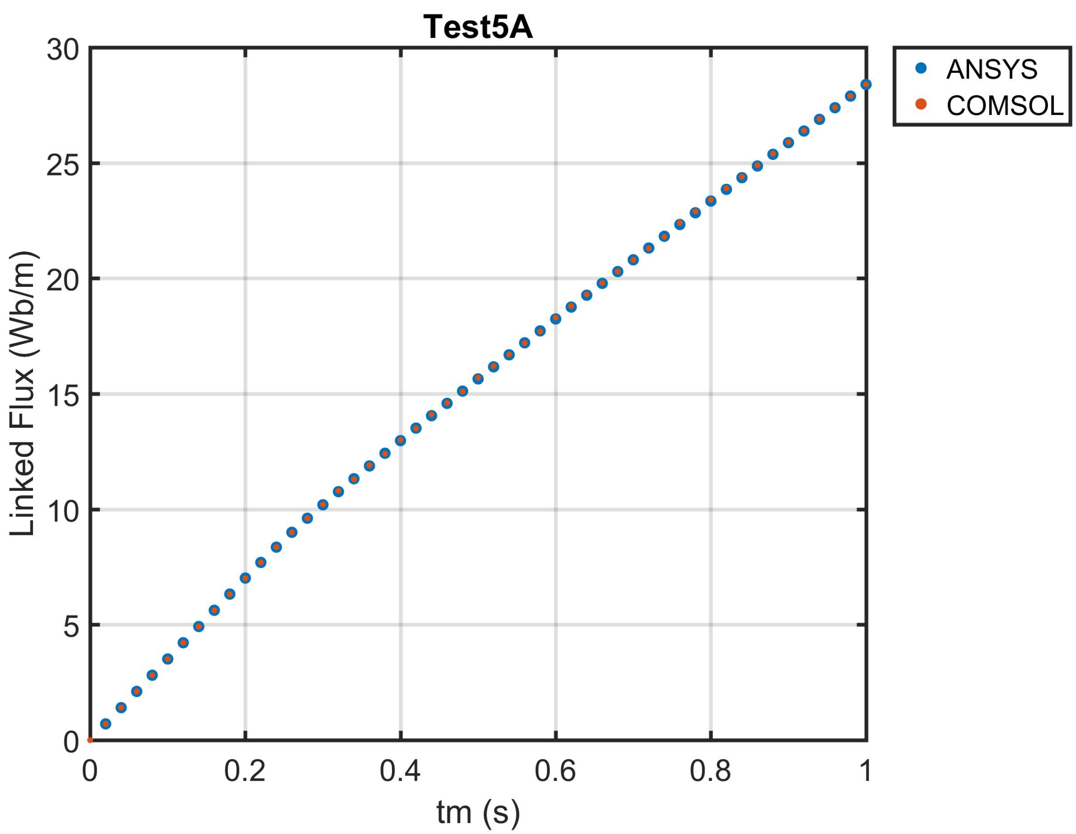


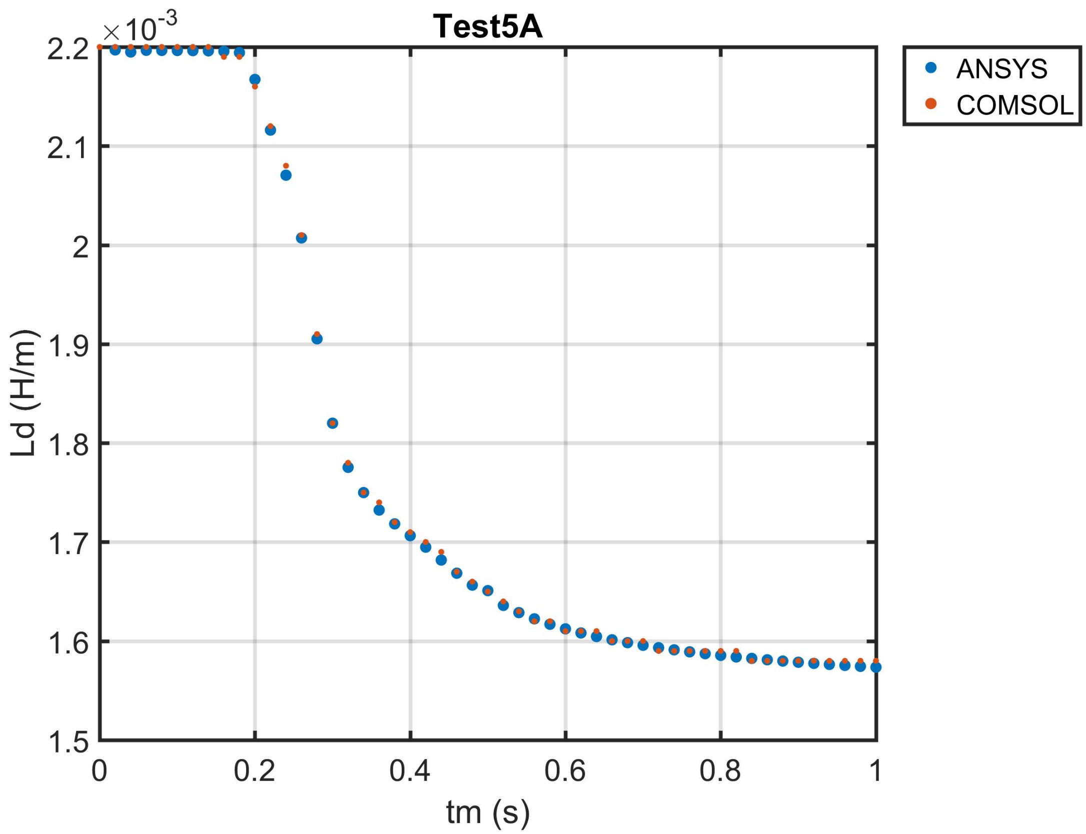
6 Double Layer LR Tests

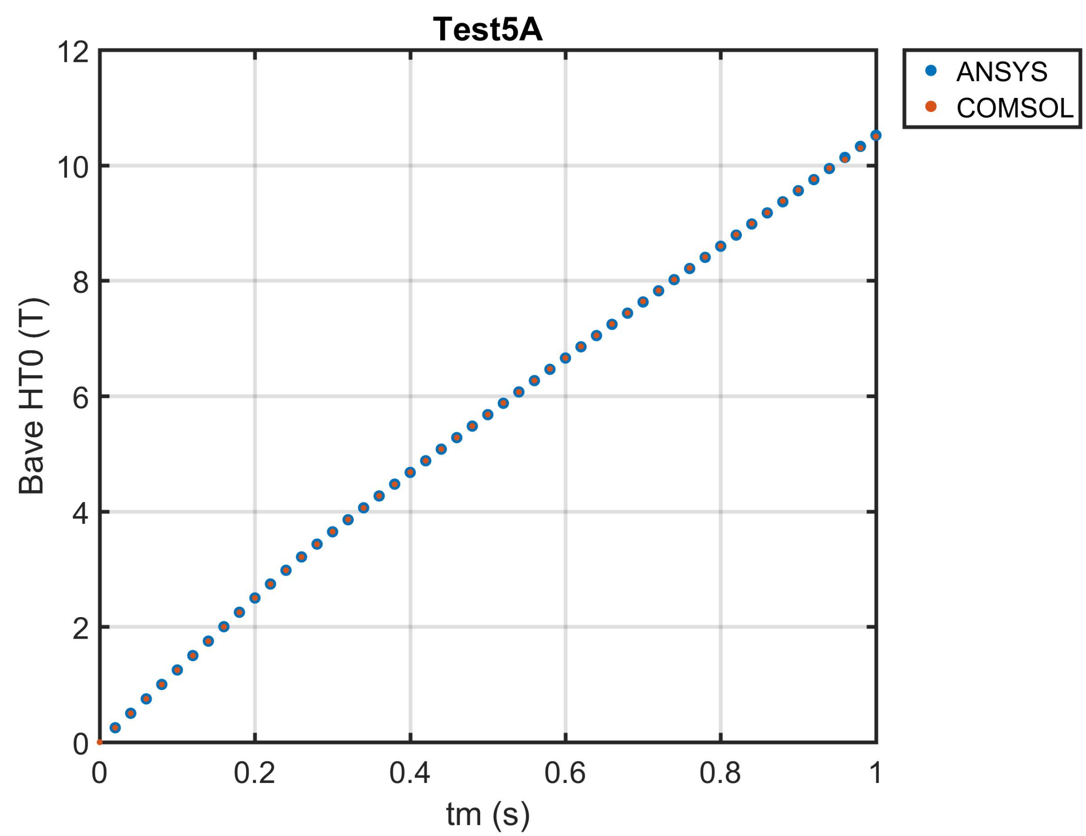
A set of tests is completed for a two layer model simulating dump resistor based extraction and a CLIQ discharge. These tests form the basis of the comparison published in [1]. With respect to previous tests, a second conductor layer is now included with the details given in Section 5. An initial test of the inductance is performed, similar to 0B, and then repeat of 4A, 4D, and 4E with the new geometry. This builds up a dump resistor extraction case to the point where quench back from IFCC losses is included. A final series of tests, 6A and 6B, simulate a CLIQ unit attached in a layer-layer configuration.

6.1 Test 5.A Differential Inductance (with iron yoke)

Active physics	EM
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	None
External loads	Linear ramp-up, t=(0,1) [s], Δt=20e-3 [s], i=(0,16) [kA]
Output	Coil magnetic flux ϕ [Wb/m]
	Differential inductance as $L_d = \Delta\phi/\Delta i$ [H/m] (finite difference)
	B_{aveHT0} [T]




Test5A
×10^-3
2.2
2.1
2
1.9
1.8
1.7
1.6
1.5
Ld (H/m)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

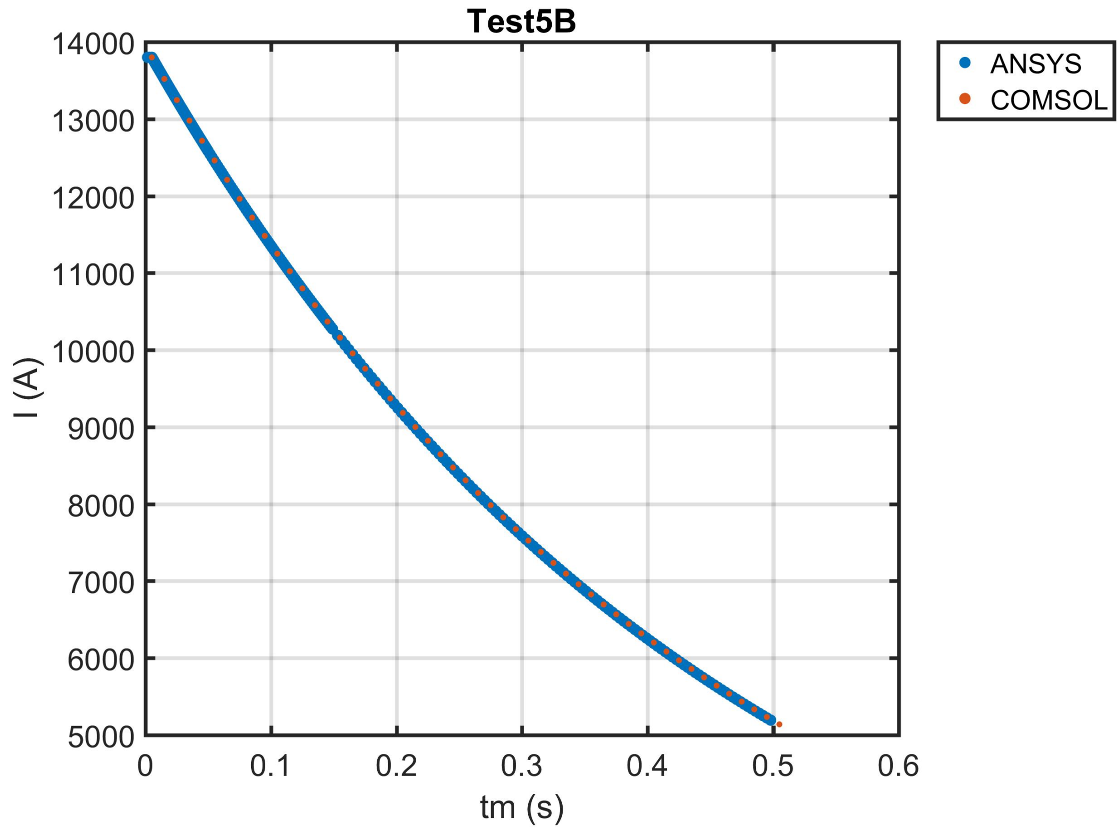

Test5A
12
10
8
6
4
2
0
Bave HT0 (T)
0
0.2
0.4
0.6
0.8
1
tm (s)
ANSYS
COMSOL

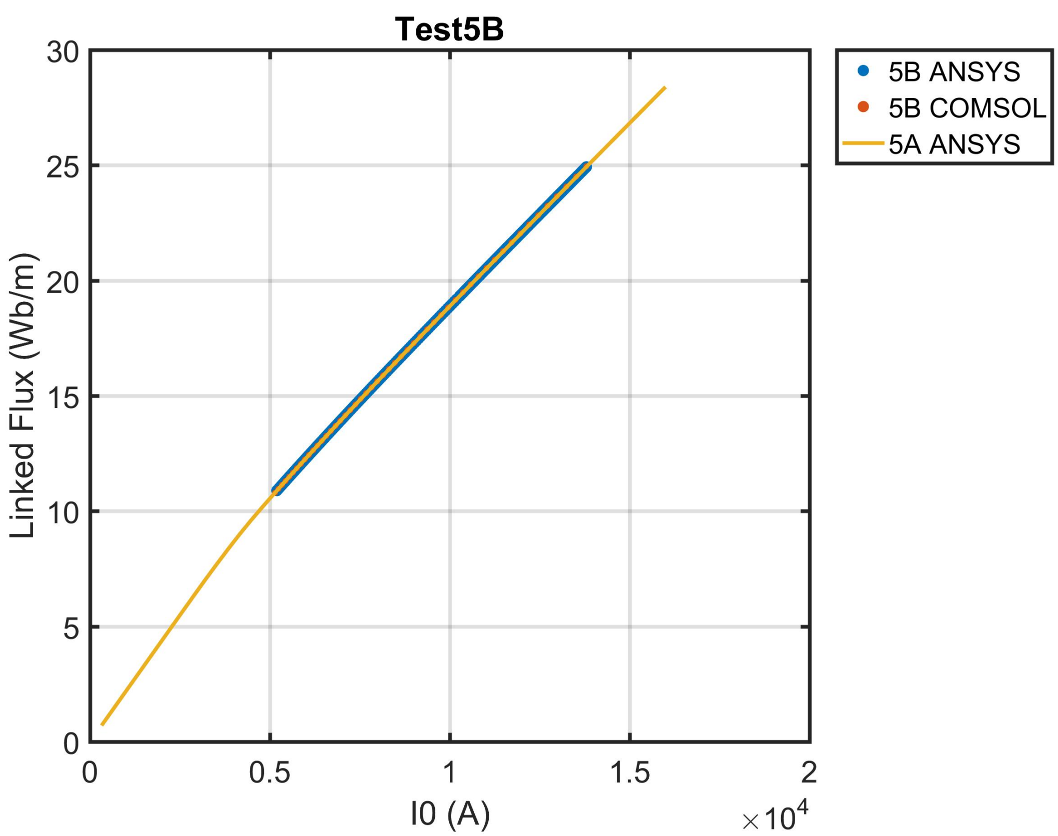
6.2 Test 5.B LR Decay With No Losses

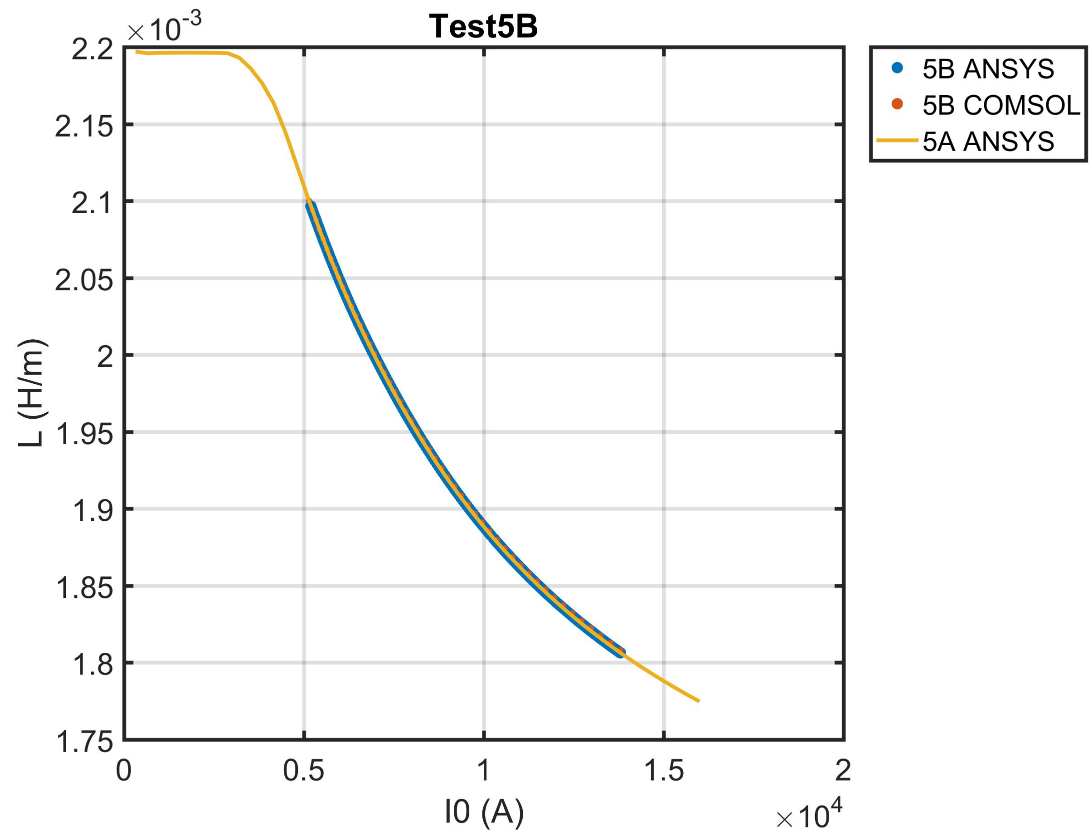
Tests 4A, 4D, and 4E are repeated with the new geometry to build up a dump resistor extraction case. The initial current is set to 90% of the short-sample for this new geometry (13.8 kA) and the dump resistor is increased to keep a similar voltage maximum. This first simulation is intended to test the circuit coupling with the coil only contributing inductive voltage. Interfilament coupling currents and quench are turned off so there are no losses outside of the dump resistor. Since there are no heating terms, thermal coupling is not needed and the coil will stay superconducting and at the initial temperature of 4.5 K. I like to track energy, and for this case its a good check that 100% is dissipated in the dump. The length L_i is the effective magnet length used for inductive voltage. Note that both the linked flux and inductance can be checked against Test5A if plotted vs current.

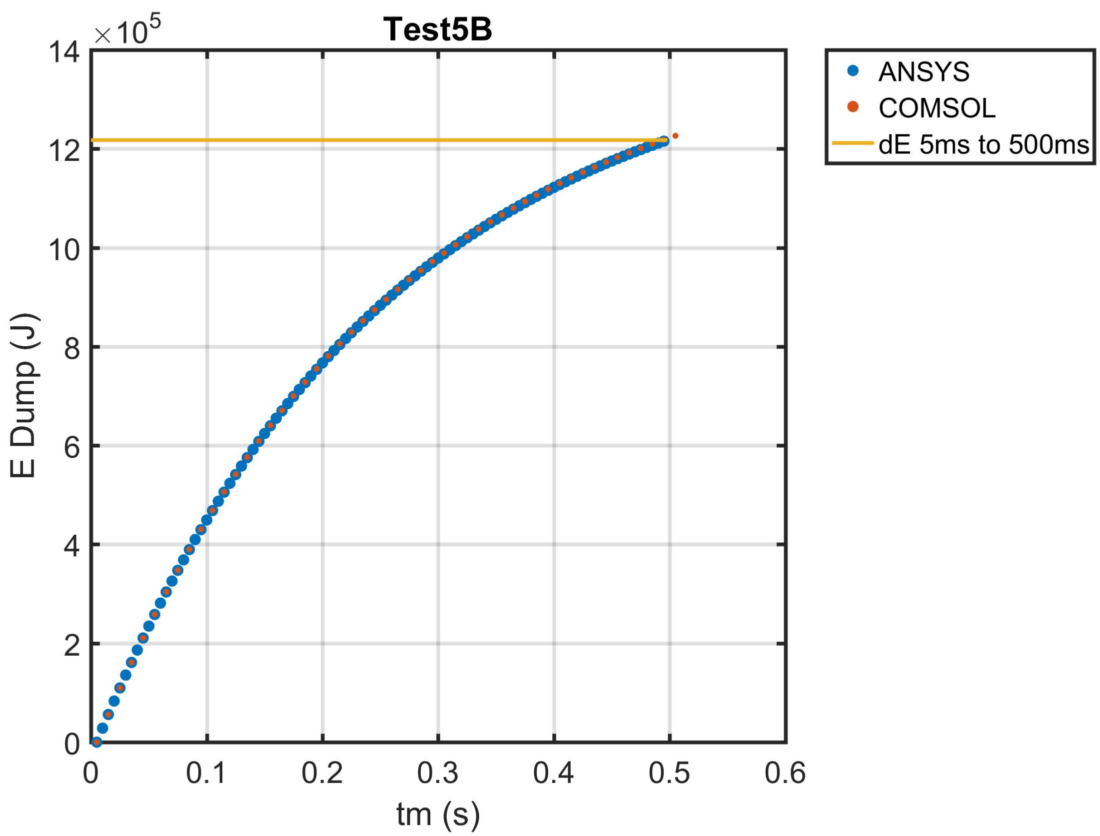
Active physics	EM, CIRCU
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	13.8 kA
Rdump	30 mΩ
L_c	N/A
L_i	9.20 m
Output	I(t) [A]
	Coil magnetic flux ϕ [Wb/m]
	Flux inductance as L = ϕ/i [H/m] (finite difference)
	E-dump(t) [J]

ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	1.469 MJ
Stored Energy at 500ms	0.251 MJ
ΔE	1.218 kJ
Edump	1.218 kJ (100% of ΔE)
Edump-CERN	1.218 kJ


Test5B
ANSYS
COMSOL
I (A)
tm (s)
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5B
5B ANSYS
5B COMSOL
5A ANSYS
Linked Flux (Wb/m)
I0 (A)
$\times 10^4$
30
25
20
15
10
5
0
0
0.5
1
1.5
2


Test5B
$\times 10^{-3}$
2.2
2.15
2.1
2.05
2
1.95
1.9
1.85
1.8
1.75
L (H/m)
0
0.5
1
1.5
2
I0 (A)
$\times 10^{4}$
5B ANSYS
5B COMSOL
5A ANSYS

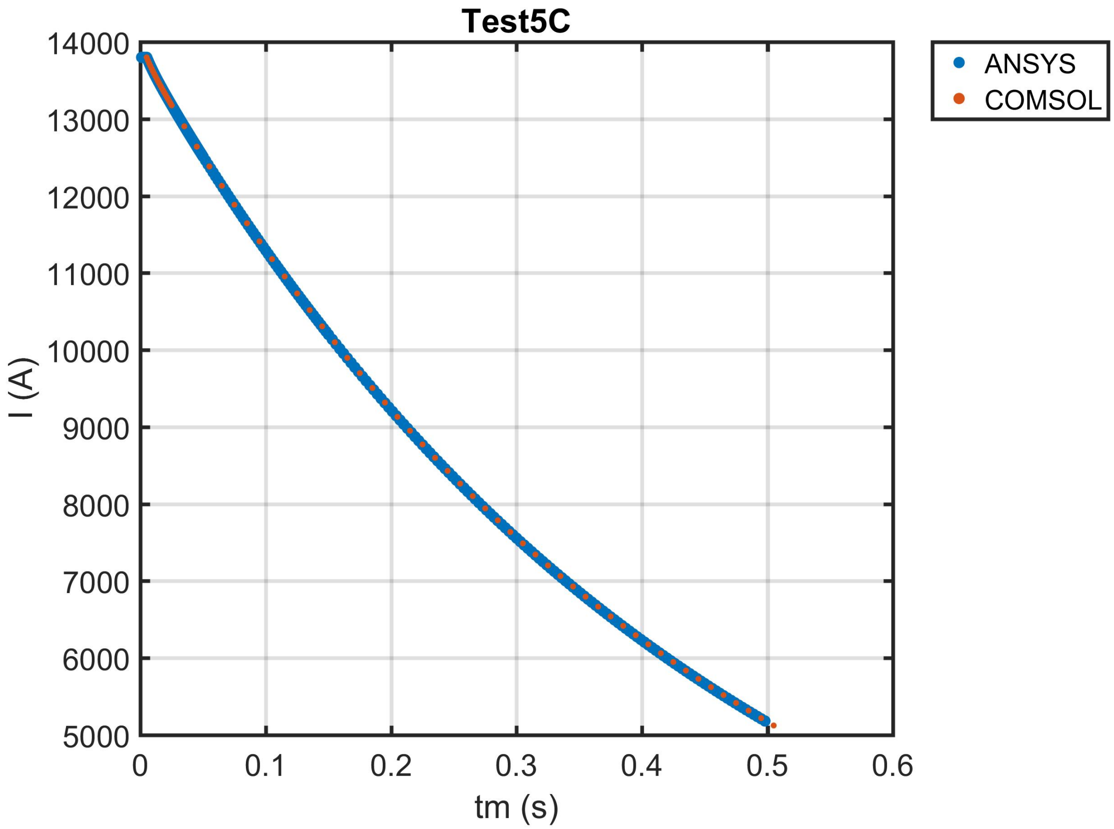

Test5B
$\times 10^{5}$
14
12
10
8
6
4
2
0
E Dump (J)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL
dE 5ms to 500ms

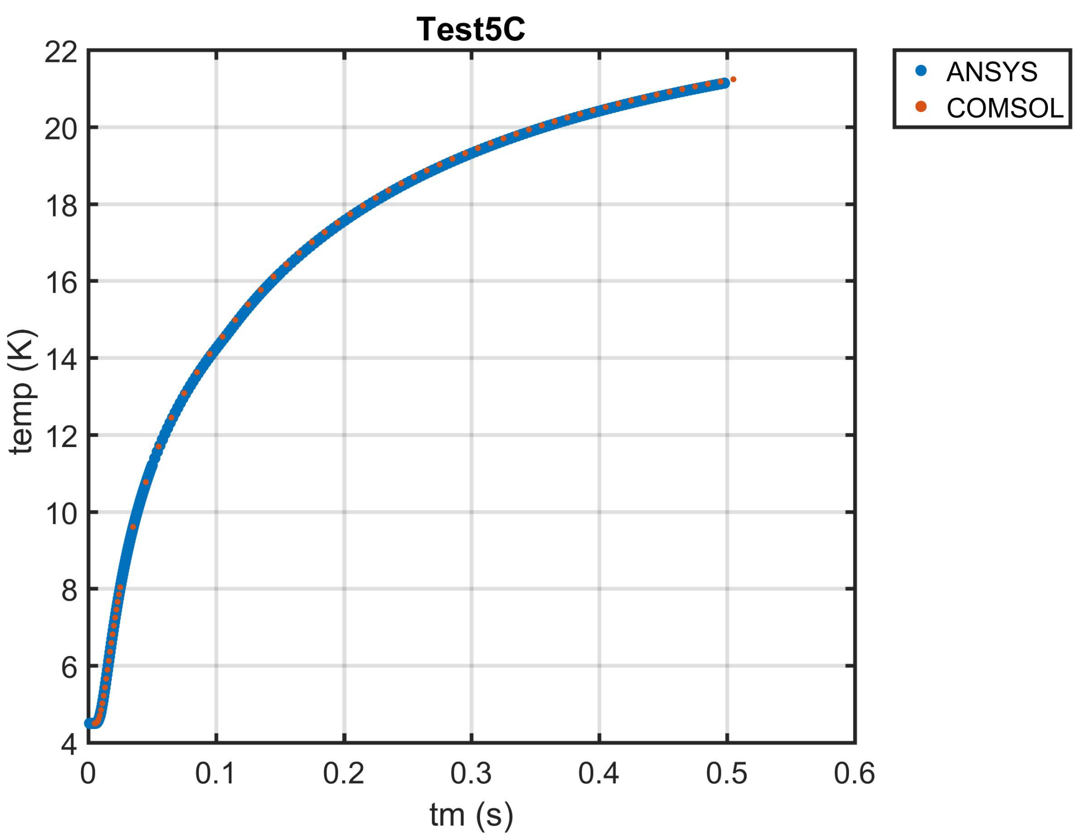
6.3 Test 5.C LR Decay With IFCC Loss and Thermal

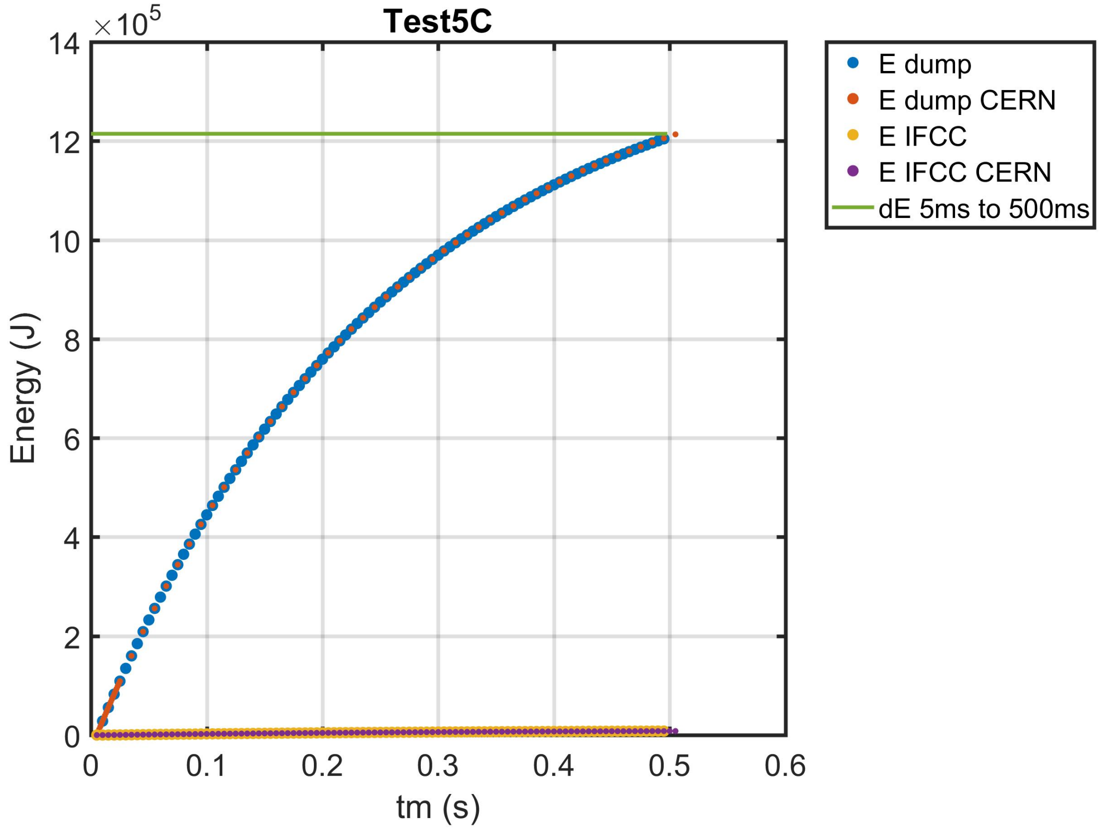
Test 5B is repeated with coupling to thermal. This allows the conductor to heat up due to the IFCC losses with the variation of material properties with temperature and field included. This is the first step towards a fully coupled case of both IFCC losses and quench.

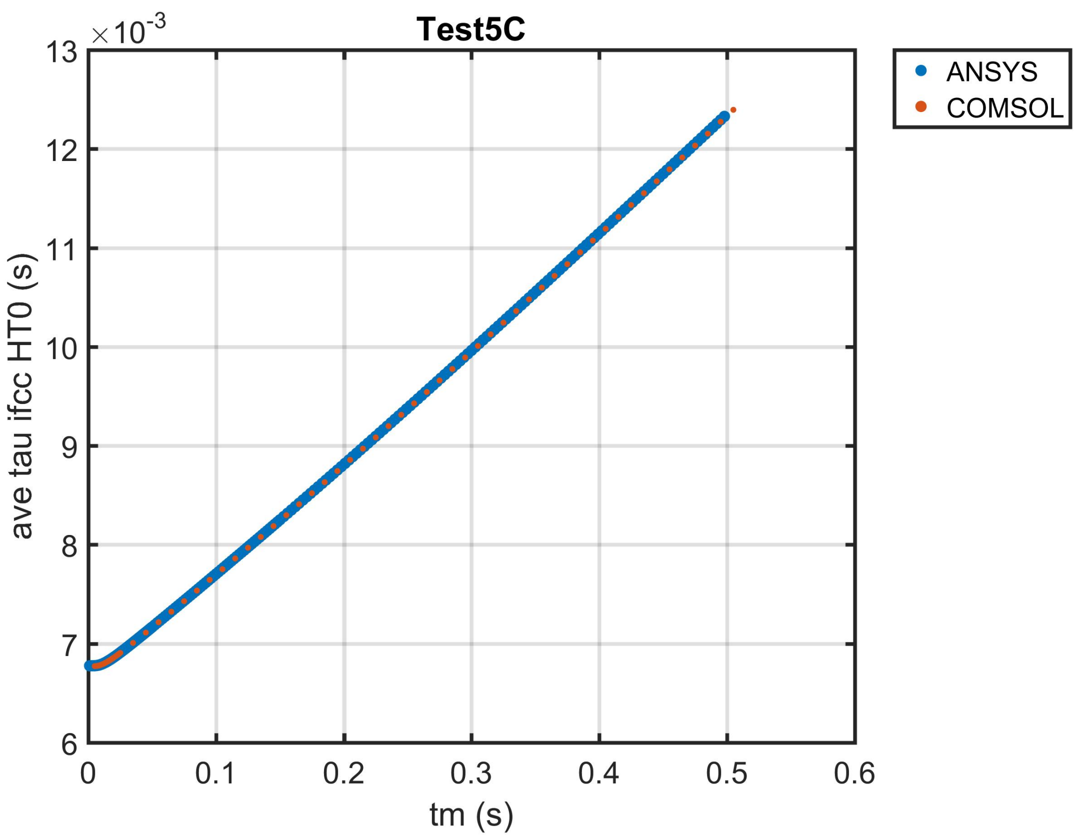
Active physics	EM, CIRCU, THERM
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Always SC
Cable insulation material	None
Cable voids filling material	GLASS FIBER
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	13.8 kA
Rdump	30 mΩ
L_c	N/A
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I(t) [A]
	T_{aveHT0} [K]
	E-dump(t) [J]
	Tau-IFCC$_{aveHT0}$ [s]
	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W/m] (per quad)
	Q-IFCC$_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]

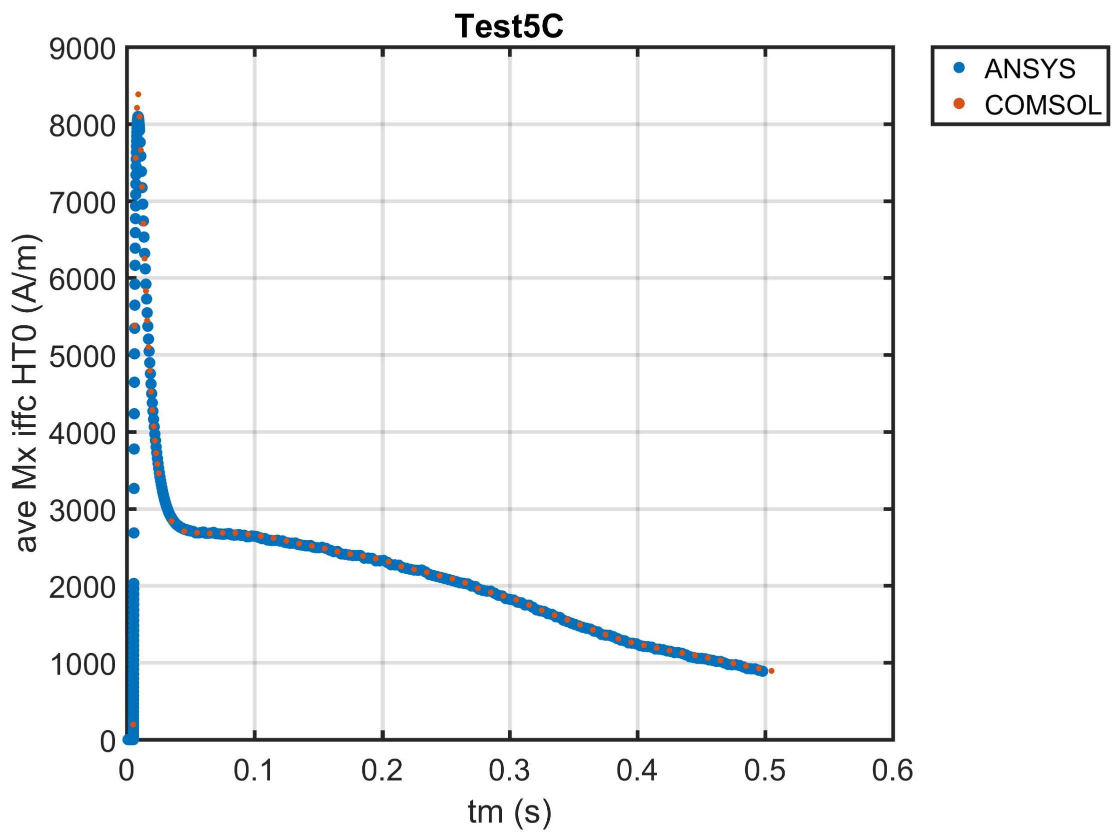
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	1.469 MJ
Stored Energy at 500ms	0.254 MJ
ΔE	1.215 MJ
Edump	1.207 MJ (99.36% of ΔE)
Eifcc	8.07 kJ (0.66% of ΔE)
Edump-CERN	1.205 MJ
Eifcc-CERN	8.05 kJ

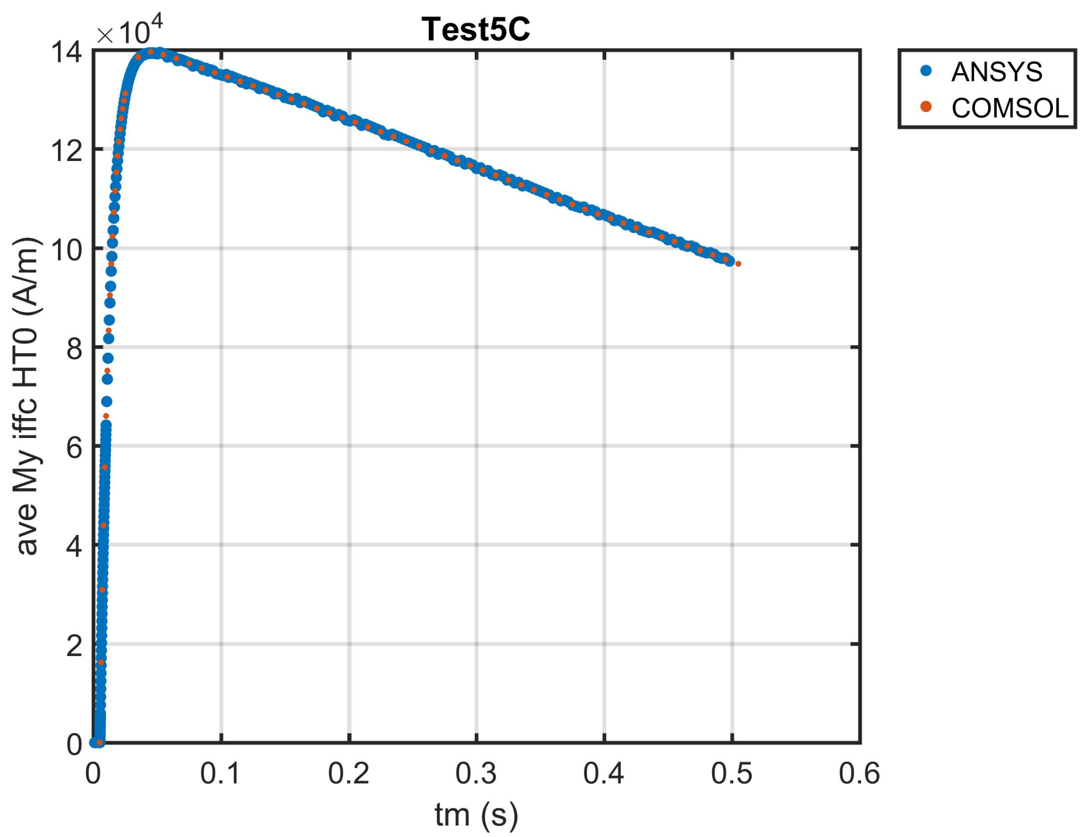

Test5C
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
I (A)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

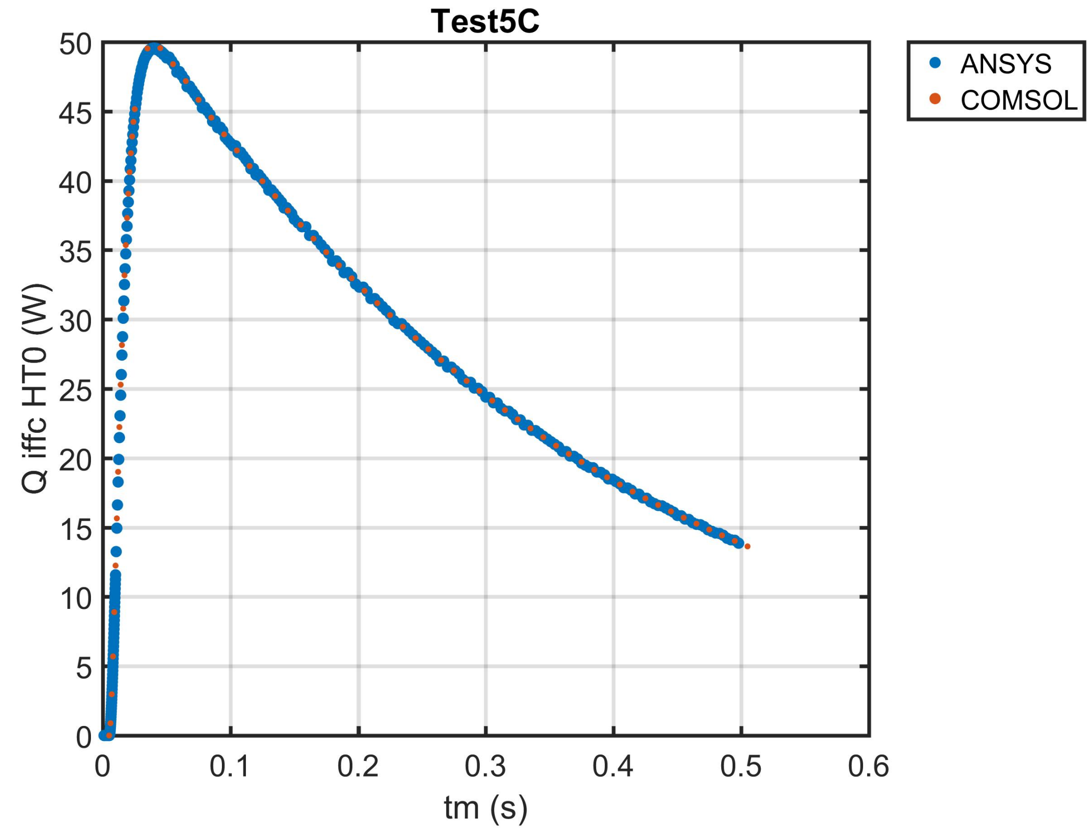

Test5C
22
20
18
16
14
12
10
8
6
4
temp (K)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

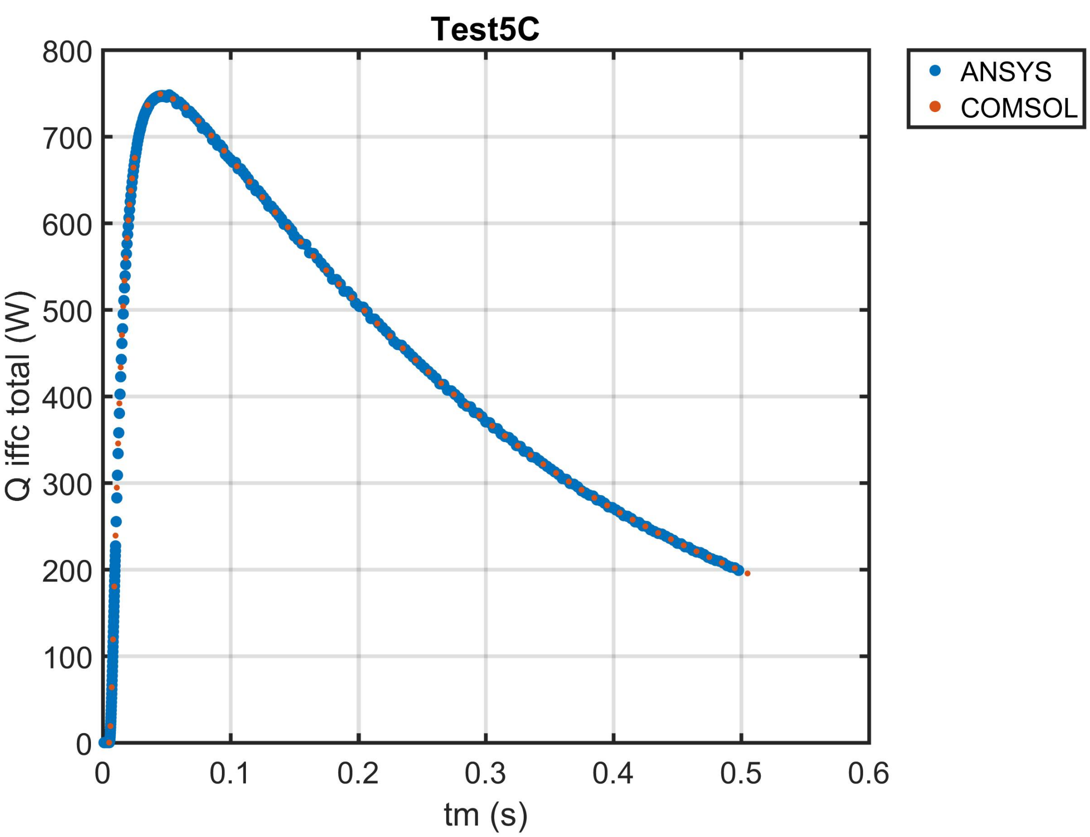

Test5C
$\times 10^5$
14
12
10
8
6
4
2
0
Energy (J)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
E dump
E dump CERN
E IFCC
E IFCC CERN
dE 5ms to 500ms


Test5C
$\times 10^{-3}$
13
12
11
10
9
8
7
6
ave tau ifcc HT0 (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL


Test5C
ave Mx iffc HT0 (A/m)
tm (s)
ANSYS
COMSOL
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5C
$\times 10^4$
ave My iffc HT0 (A/m)
tm (s)
ANSYS
COMSOL
0
2
4
6
8
10
12
14
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5C
Q iffc HT0 (W)
tm (s)
ANSYS
COMSOL
0
5
10
15
20
25
30
35
40
45
50
0
0.1
0.2
0.3
0.4
0.5
0.6

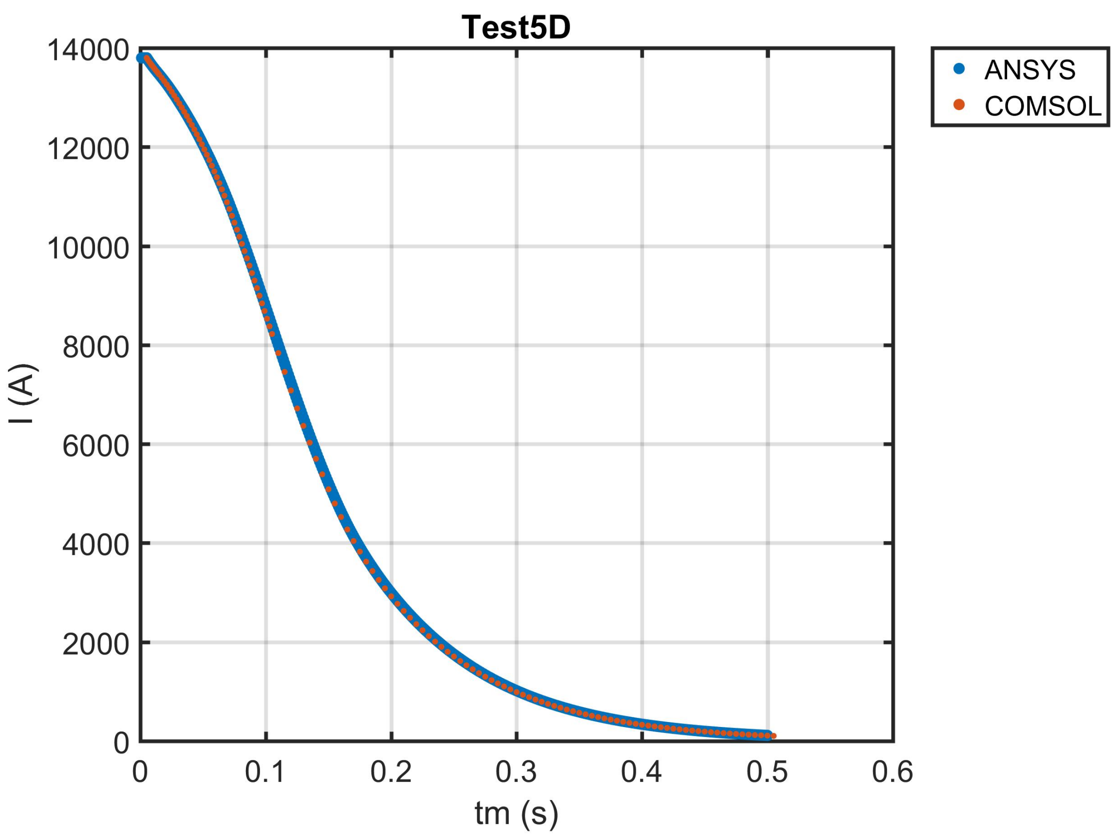

Test5C
Q iffc total (W)
tm (s)
ANSYS
COMSOL
0
100
200
300
400
500
600
700
800
0
0.1
0.2
0.3
0.4
0.5
0.6

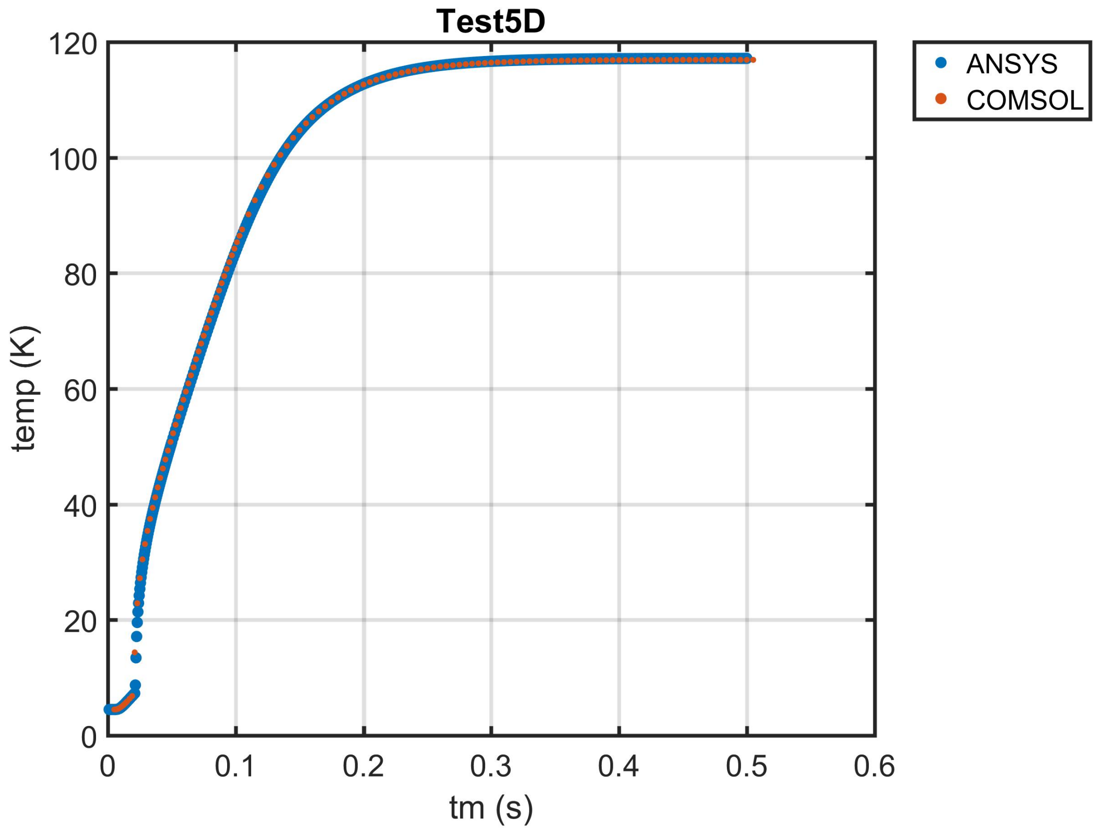
6.4 Test 5.D LR Decay With IFCC Induced Quench Back

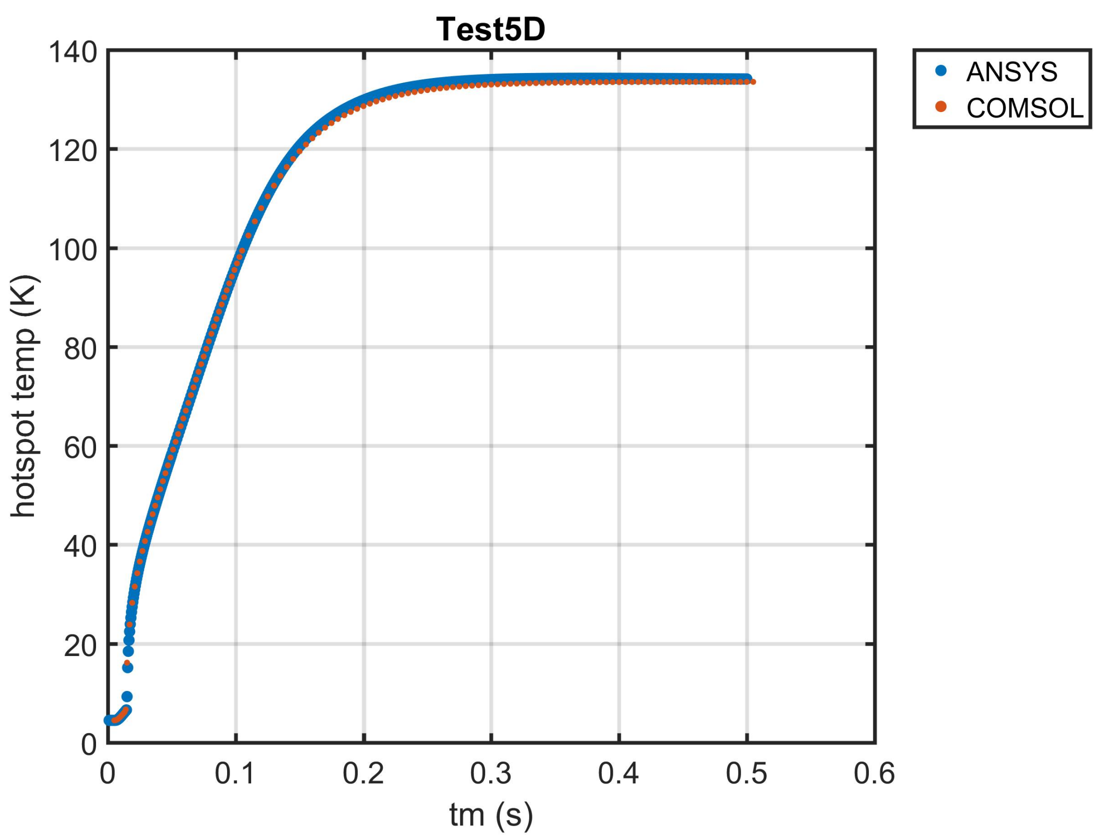
This is the first case where all the effects are combined for a quench back scenario. The high dB/dt due to the dump resistor extraction initiates IFCC losses which heats the coil to the point of quench. Then the coil resistance grows quickly and dominates the decay.

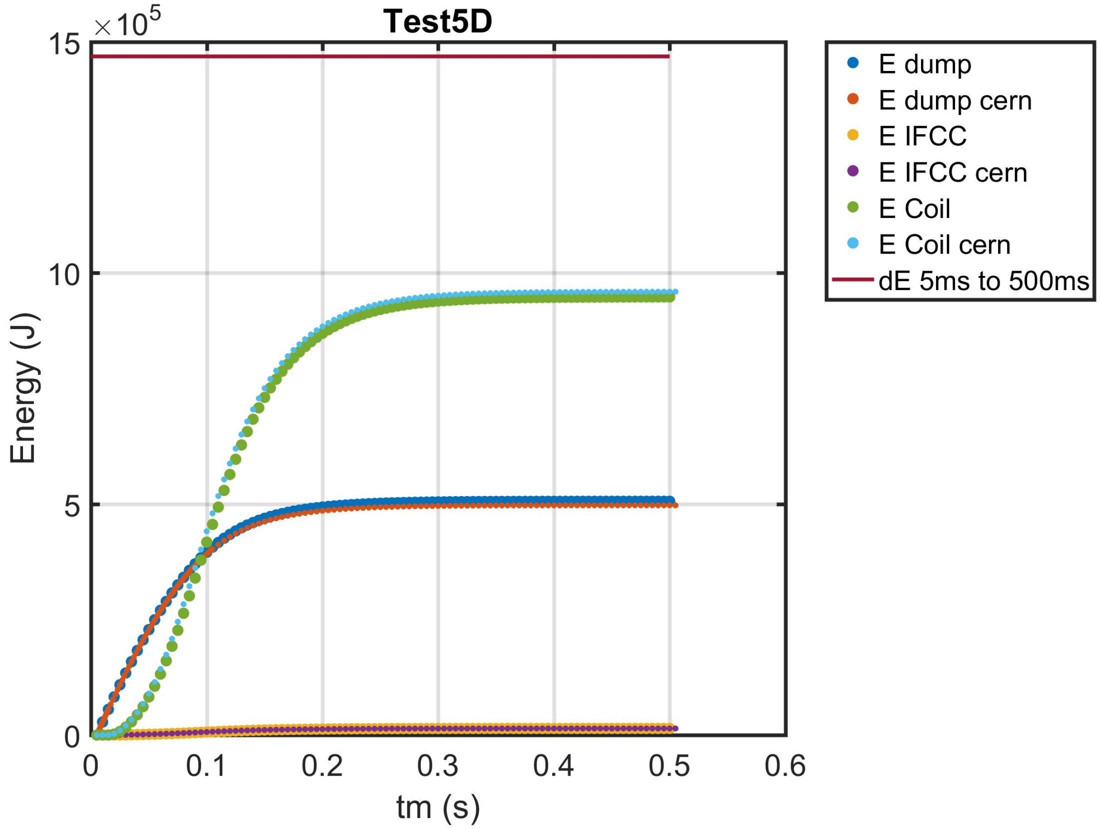
Active physics	EM, CIRCU, THERM
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Allow Quench with no Current Sharing
Cable insulation material	None
Cable voids filling material	GLASS FIBER
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	13.8 kA
Rdump	30 mΩ
L_c	10.11 m
L_i	9.20 m
ρ_{cu} fit	NIST, see Appendix E
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I(t) [A]
	T_{aveHT0} [K]
	T_{hot} [K]
	E-dump(t) [J]
	Tau-$IFCC_{aveHT0}$ [s]
	Mx-$IFCC_{aveHT0}$ [A/m]
	My-$IFCC_{aveHT0}$ [A/m]
	Q-$IFCC_{totHT0}$ [W/m] (per quad)
	Q-$IFCC_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]
	Q-Ohm_{totHT0} [W/m] (per quad)
	Q-$Ohm_{totcoil}$ [W/m] (per quad)
	R-coil(t) [Ω]
	E-Ohm(t) [J]

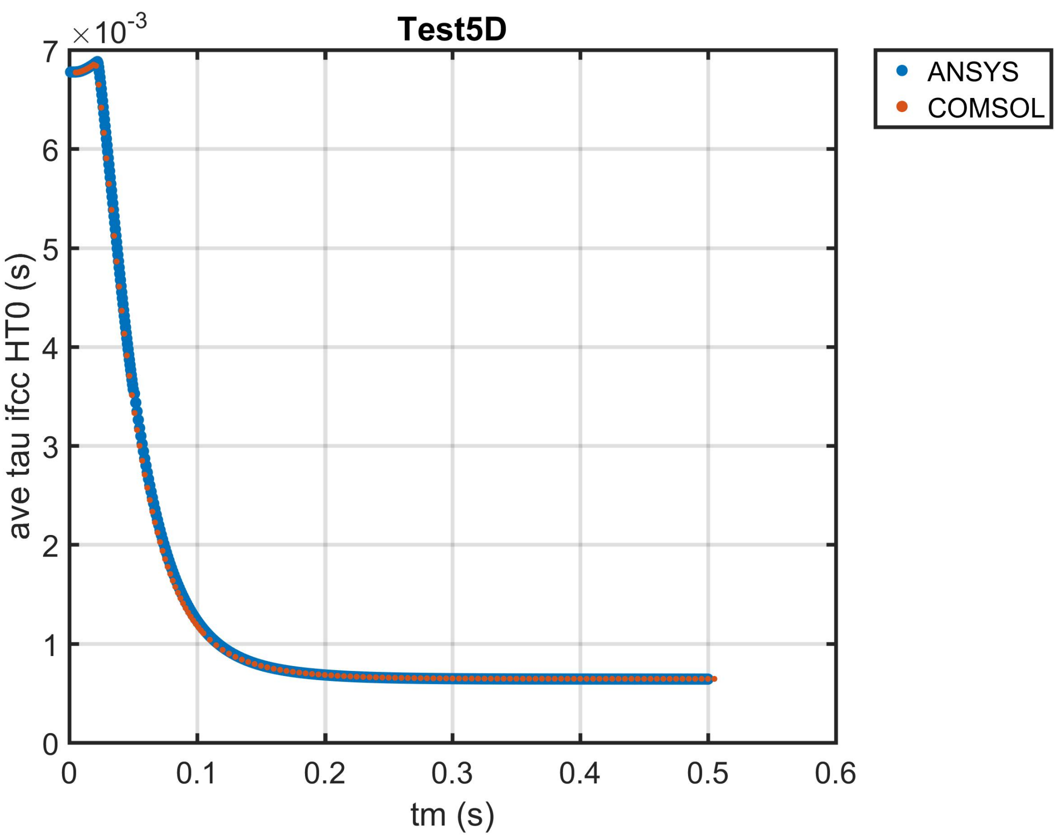
ANSYS: Summary of Energy Loss	
Stored Energy at 5ms	1.469 MJ
Stored Energy at 500ms	0.00 kJ
ΔE	1.469 MJ
Edump	505.96 kJ (34.45% of ΔE)
Eifcc	14.32 kJ (0.98% of ΔE)
Eohm	948.24 kJ (64.56% of ΔE)
Edump-CERN	497.25 kJ
Eifcc-CERN	14.24 kJ
Eohm-CERN	959.55 kJ

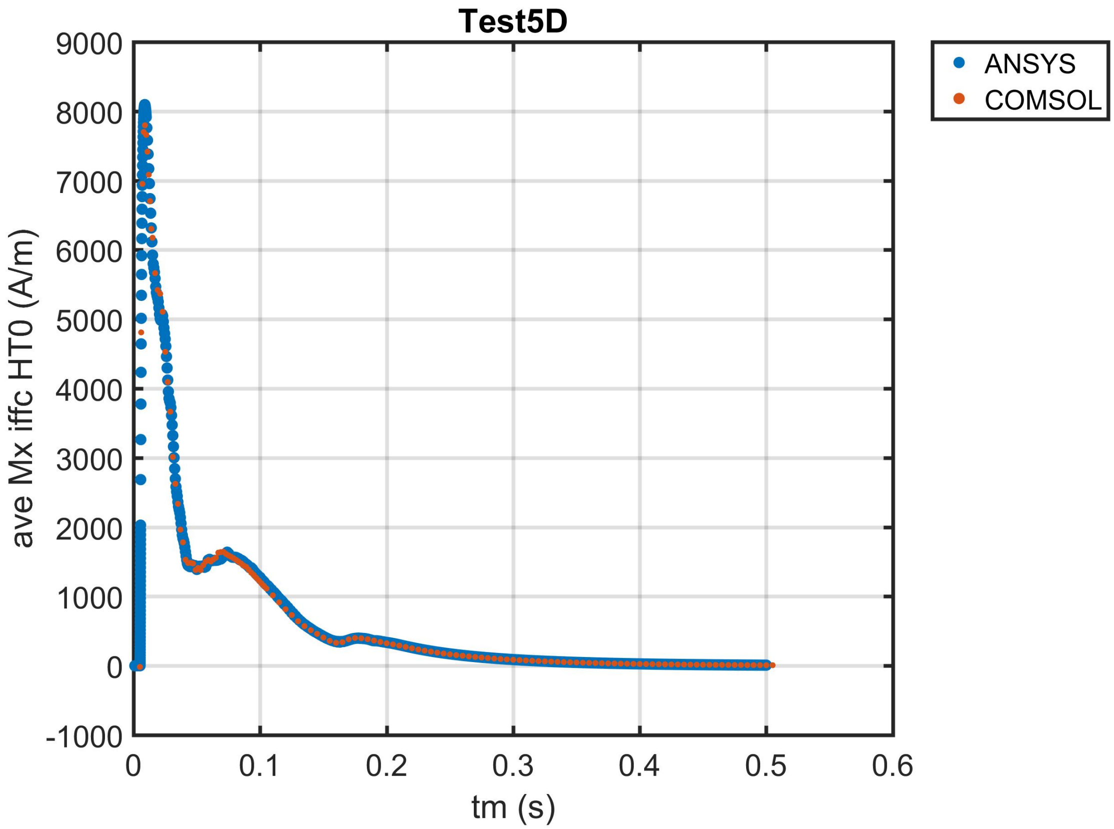


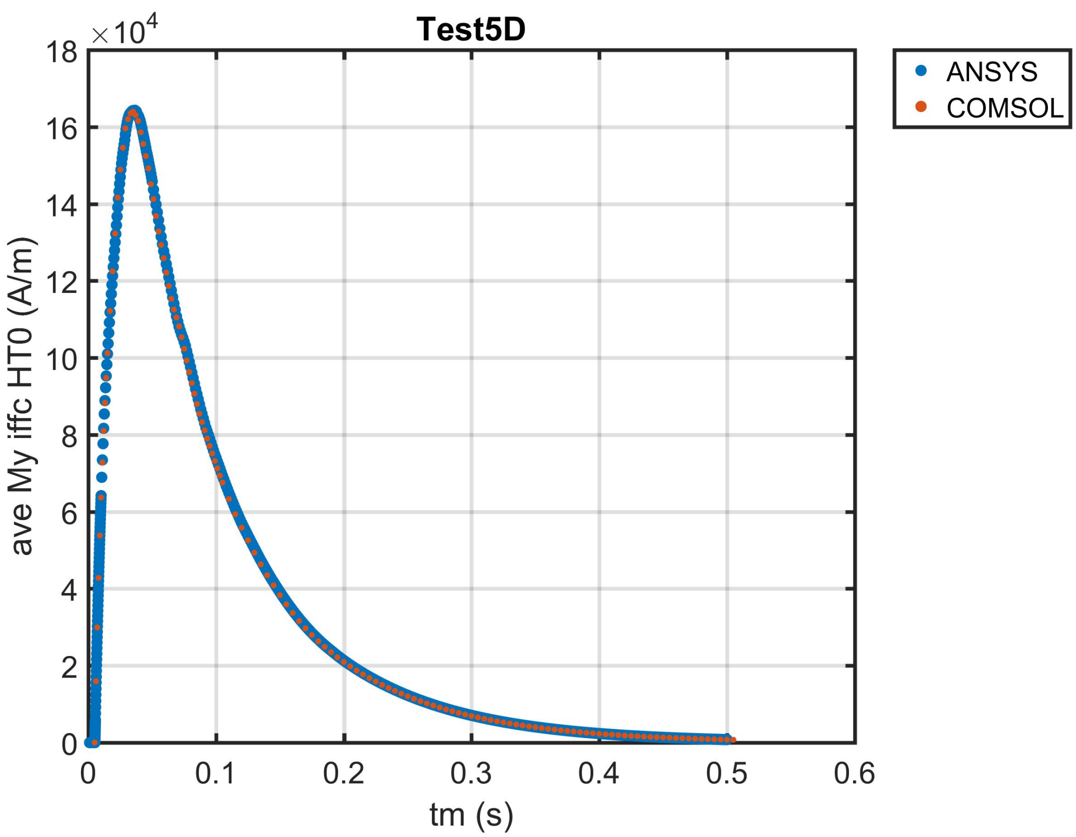

Test5D
temp (K)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.5
0.6

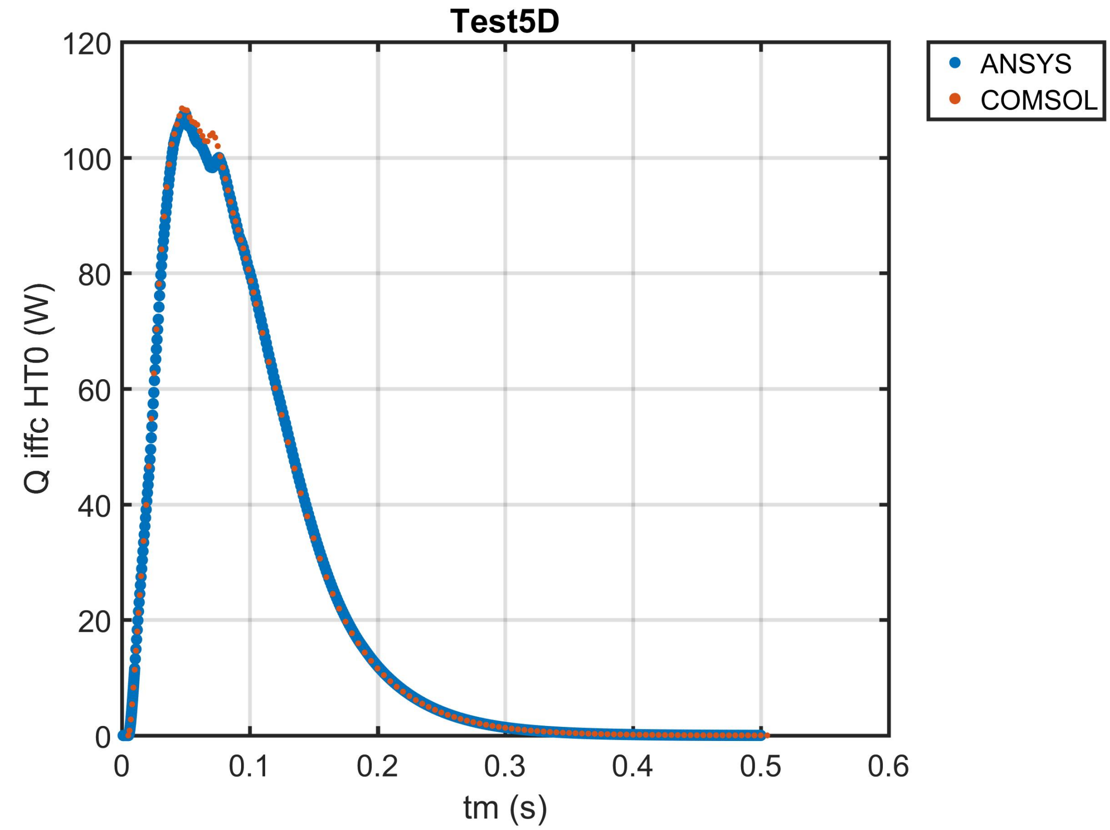

Test5D
hotspot temp (K)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
0.6

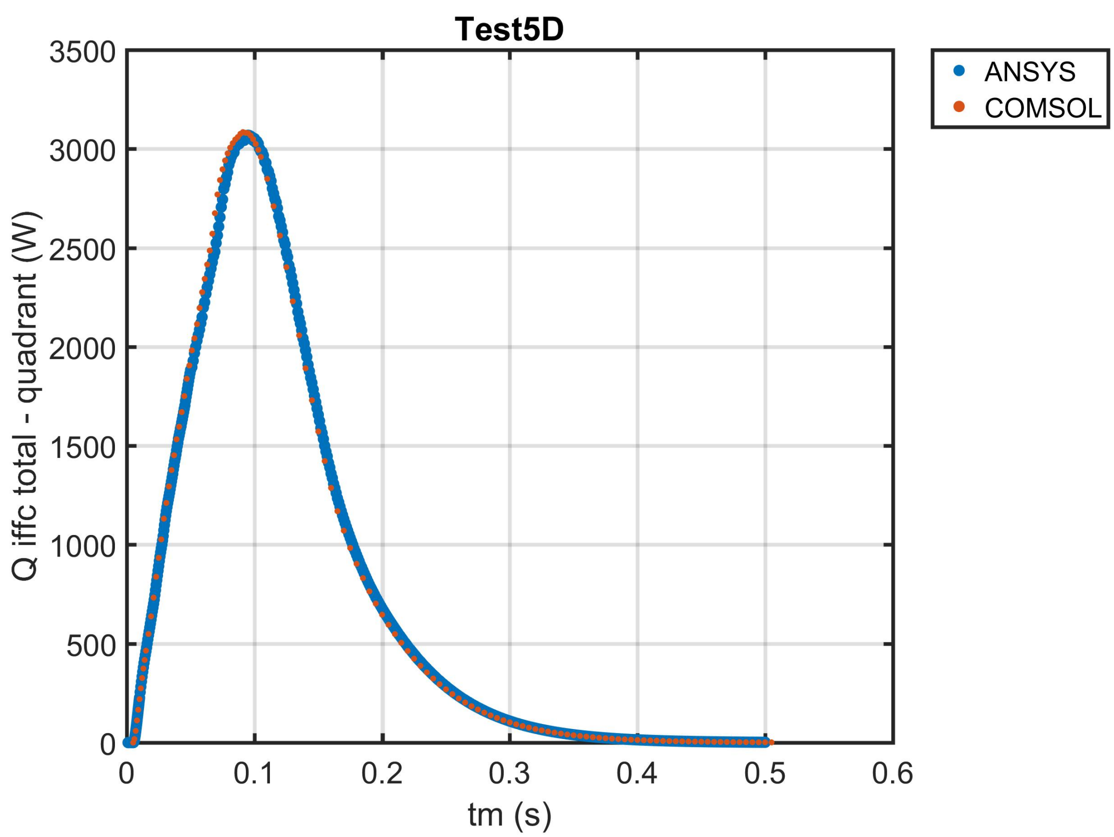

Test5D
×10^5
15
10
5
0
Energy (J)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
E dump
E dump cern
E IFCC
E IFCC cern
E Coil
E Coil cern
dE 5ms to 500ms

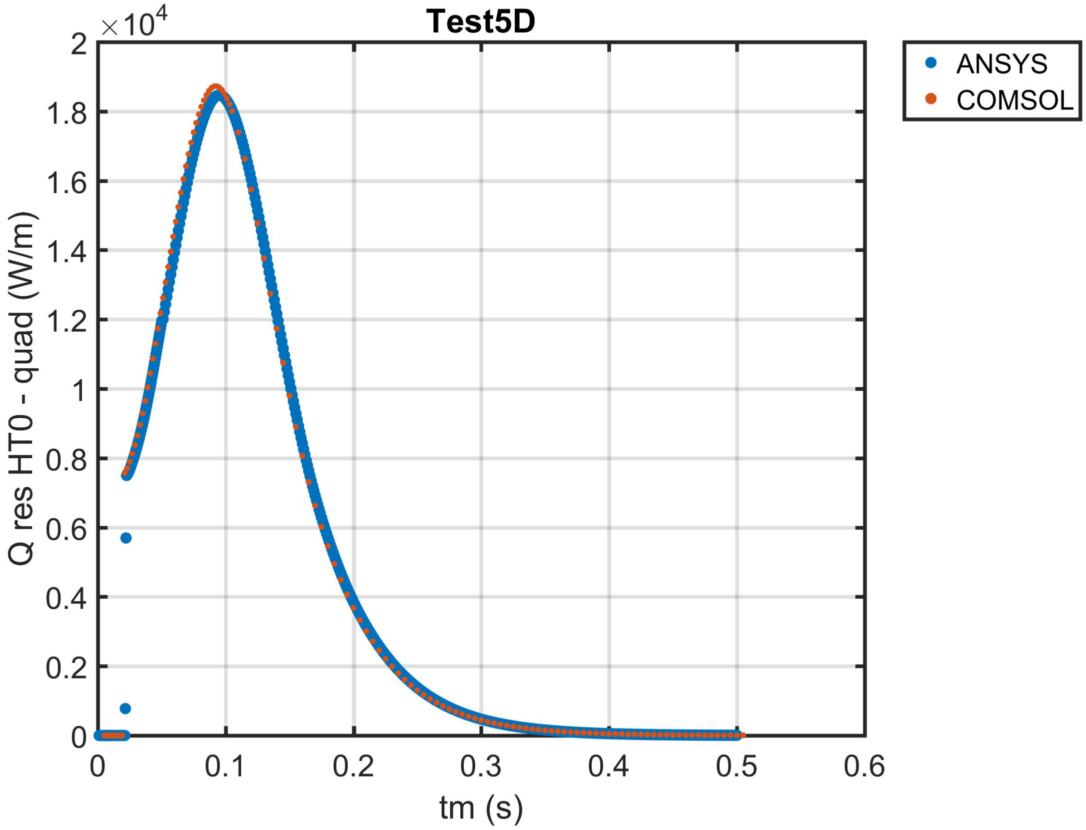

Test5D
×10^-3
7
6
5
4
3
2
1
0
ave tau ifcc HT0 (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

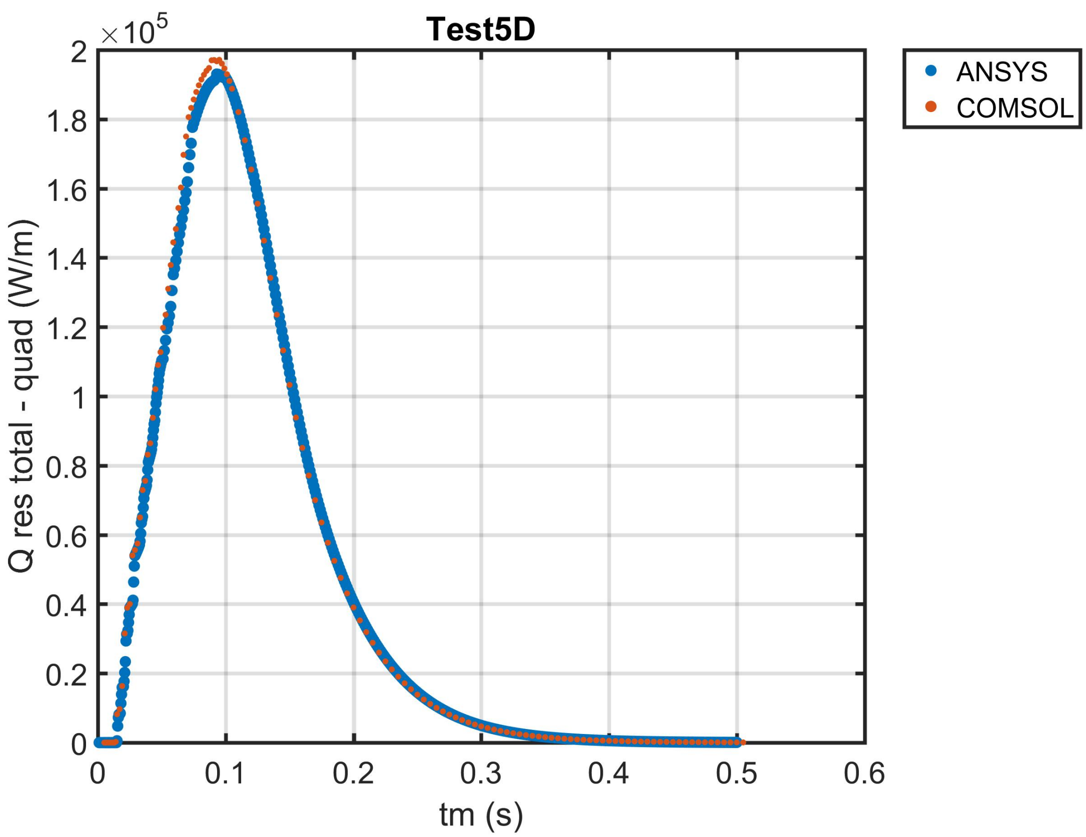

Test5D
ANSYS
COMSOL
ave Mx iffc HT0 (A/m)
tm (s)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
-1000
0
0.1
0.2
0.3
0.4
0.5
0.6

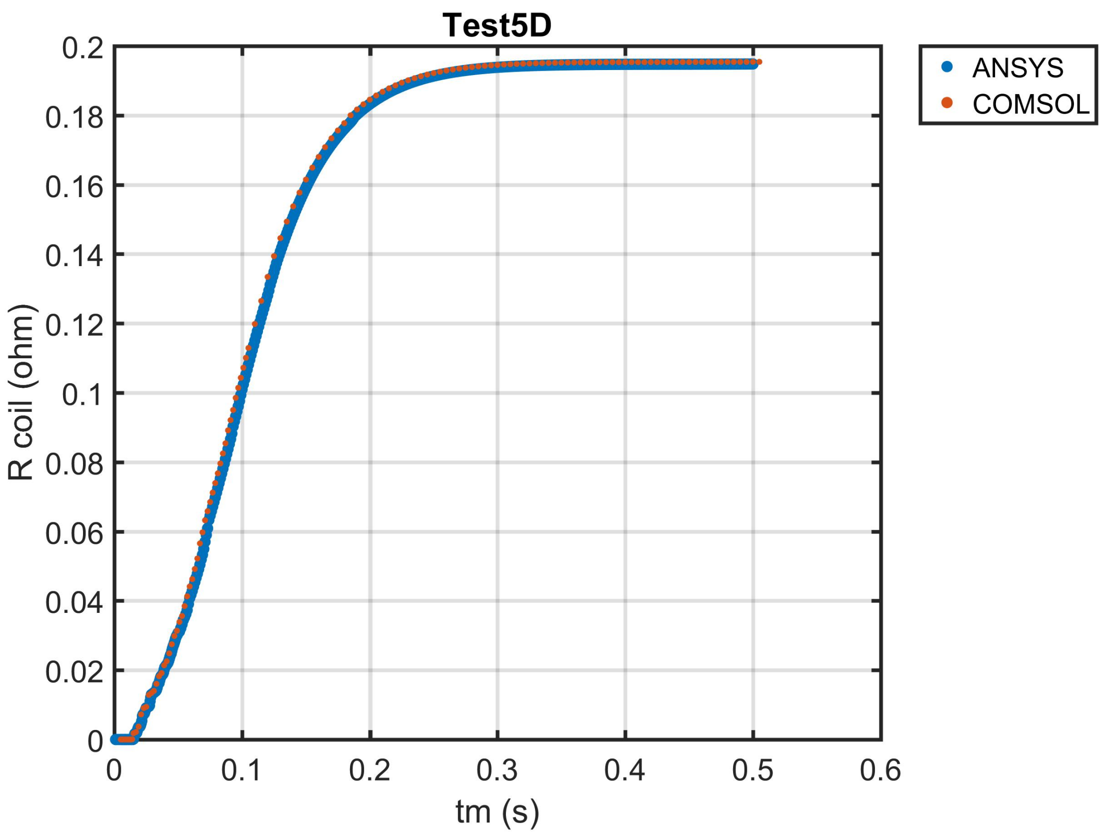

Test5D
×10^4
ANSYS
COMSOL
ave My iffc HT0 (A/m)
tm (s)
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5D
ANSYS
COMSOL
Q iffc HT0 (W)
tm (s)
0
20
40
60
80
100
120
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5D
ANSYS
COMSOL
Q iffc total - quadrant (W)
tm (s)
0
500
1000
1500
2000
2500
3000
3500
0
0.1
0.2
0.3
0.4
0.5
0.6

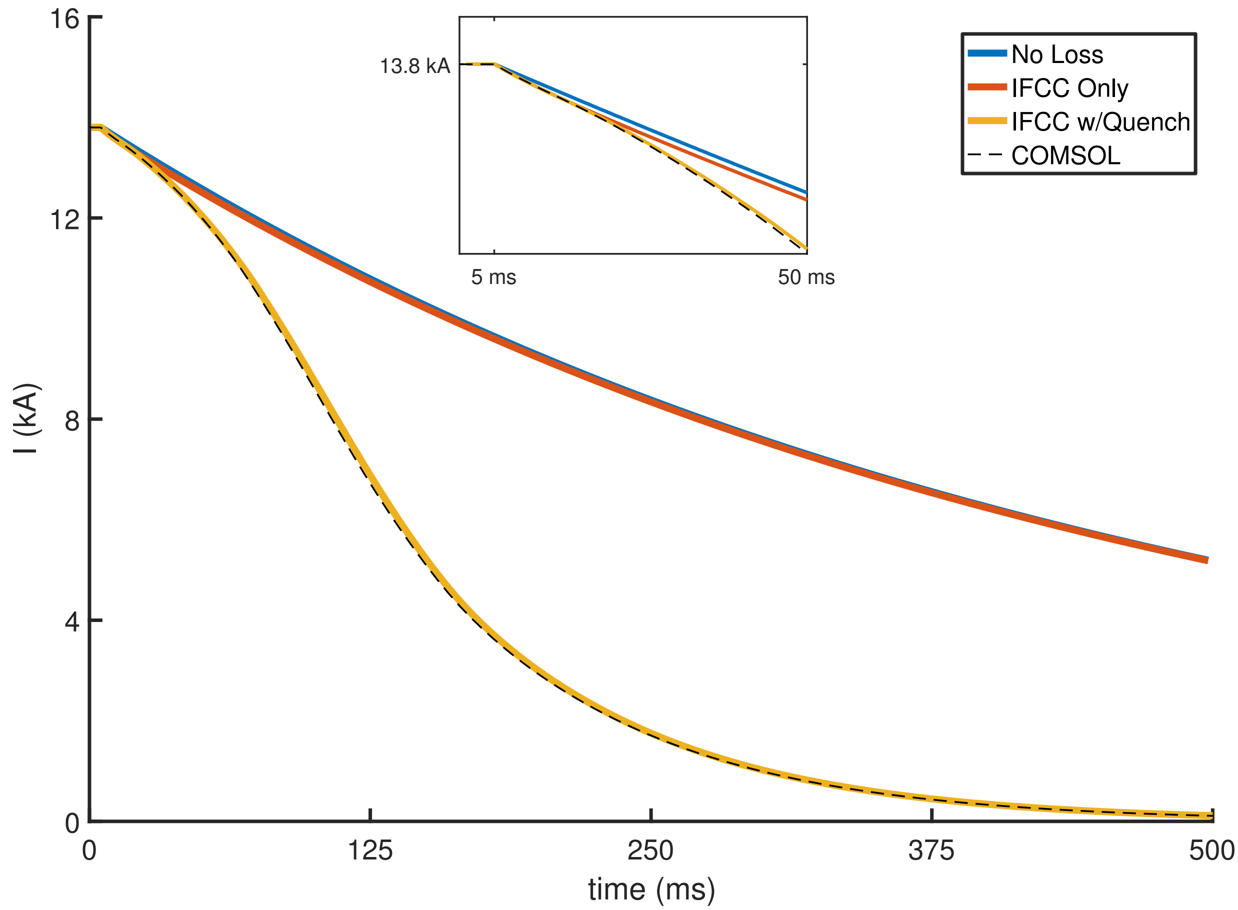

Test5D
×10^4
Q res HT0 - quad (W/m)
tm (s)
ANSYS
COMSOL
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.1
0.2
0.3
0.4
0.5
0.6


Test5D
×10^5
Q res total - quad (W/m)
tm (s)
ANSYS
COMSOL
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
0.1
0.2
0.3
0.4
0.5
0.6

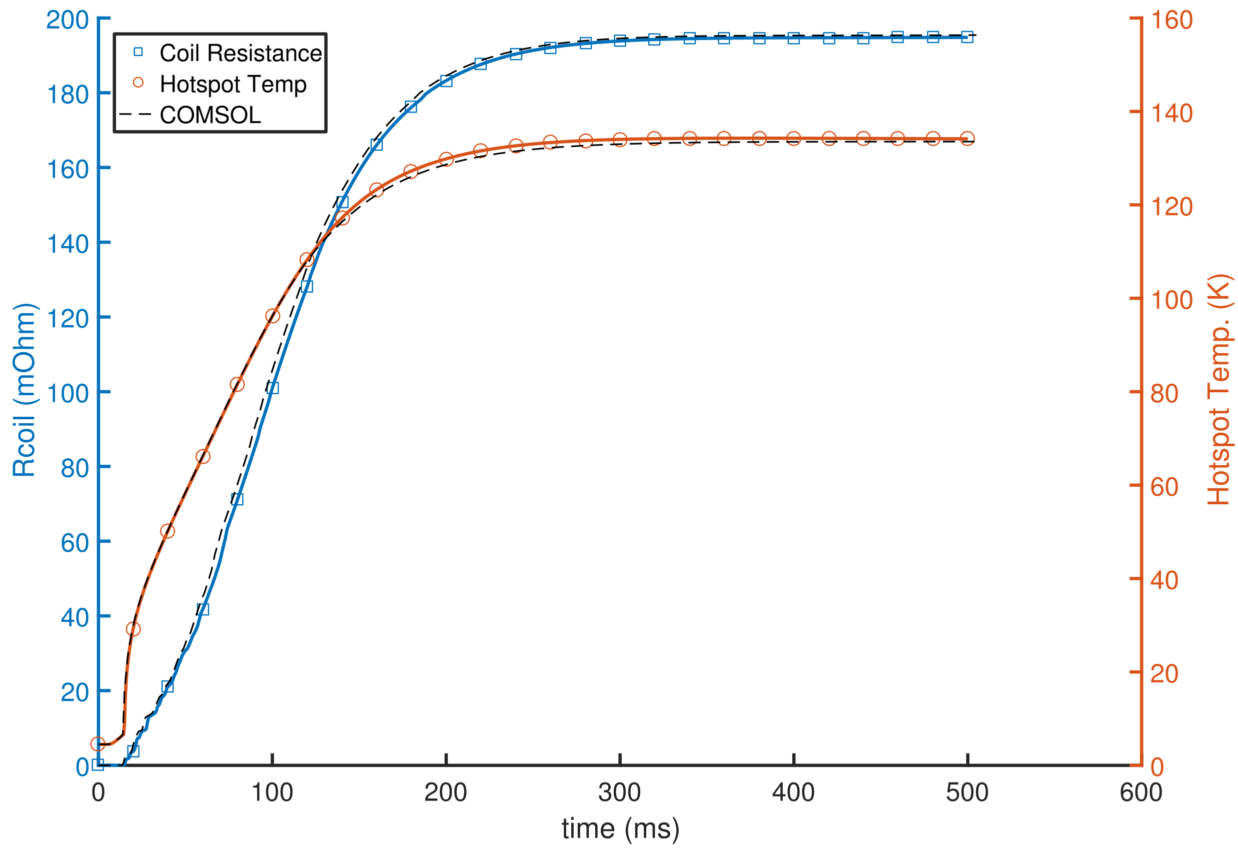

Test5D
R coil (ohm)
tm (s)
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
0.1
0.2
0.3
0.4
0.5
0.6
ANSYS
COMSOL

6.5 Comparison of LR Quench Back

The following figures and tables compare the results between tests 5B, 5C, and 5D. This slowly builds up from "No Loss", to including "IFCC Only", to including "IFCC w/Quench". A slight difference in the initial current decay between the "No Loss" and the other two cases is seen up to about 20 ms. While the coil is not quenched, this difference is due to the impact of the coupling currents on the magnet's differential inductance. At 20 ms, the impact of quench resistance growth is clearly seen as the "IFCC w/Quench" begins to quickly decay away from the "IFCC Only".

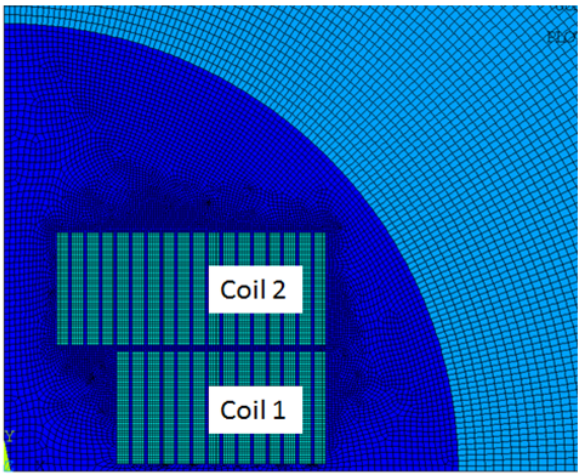


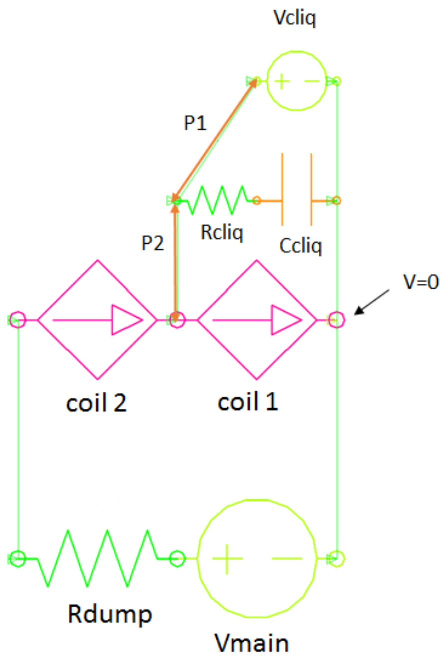
Comparison of Energy Loss for Test 5D				
Energy at 5ms	1.469 MJ			
Energy at 500ms	0.00 MJ			
ΔE	1.469 MJ			
	ANSYS		COMSOL	
	kJ	%	kJ	%
Edump	505.96	34.45	497.25	33.80
Eifcc	14.32	0.98	14.24	0.97
Eohm	948.24	64.56	959.55	65.23


Coil Resistance
Hotspot Temp
COMSOL
Rcoil (mOhm)
Hotspot Temp. (K)
time (ms)
0
20
40
60
80
100
120
140
160
180
200
0
100
200
300
400
500
600

7 Double Layer CLIQ Tests

Tests starting with the label "6" introduce CLIQ [8]. A similar approach is taken here where first no losses are assumed in order to debug potential issues with the circuit set up. The CLIQ is connected across the inner coil as shown in the schematic below. The CLIQ circuit parameters and charge voltage are given in the table for each simulation.





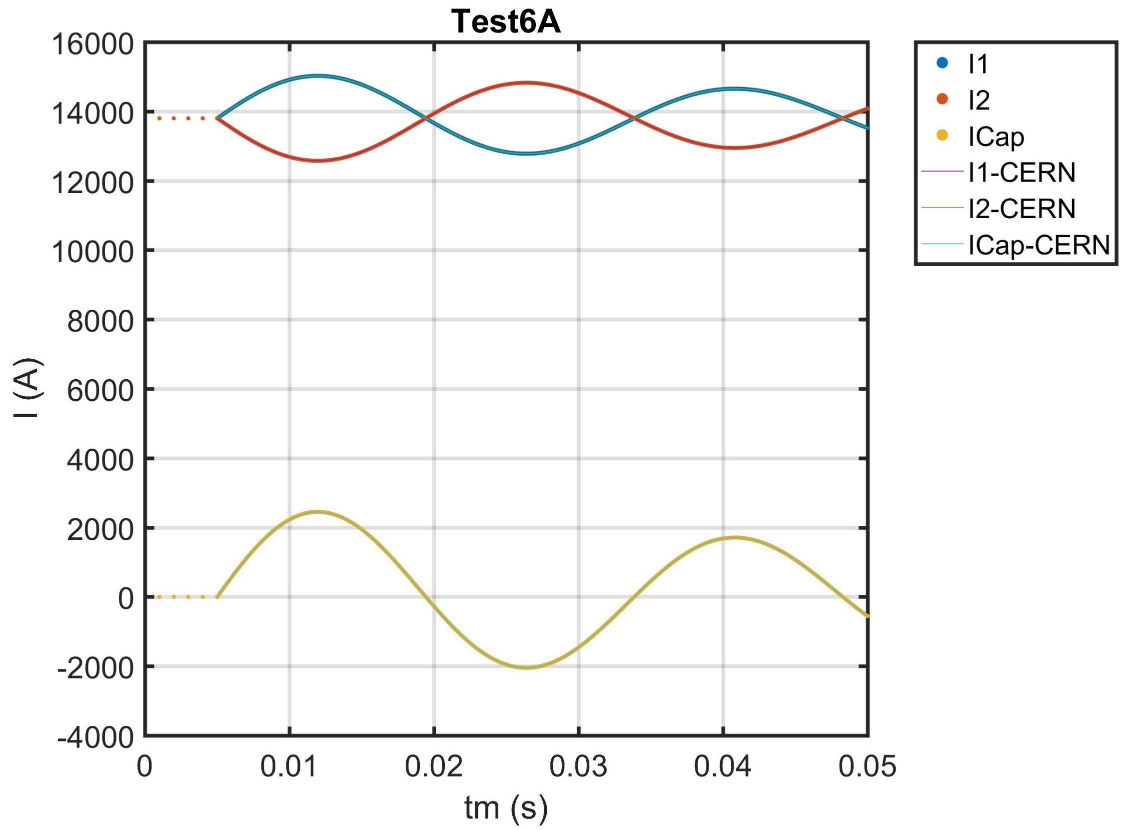
The simulations proceed with the following steps:

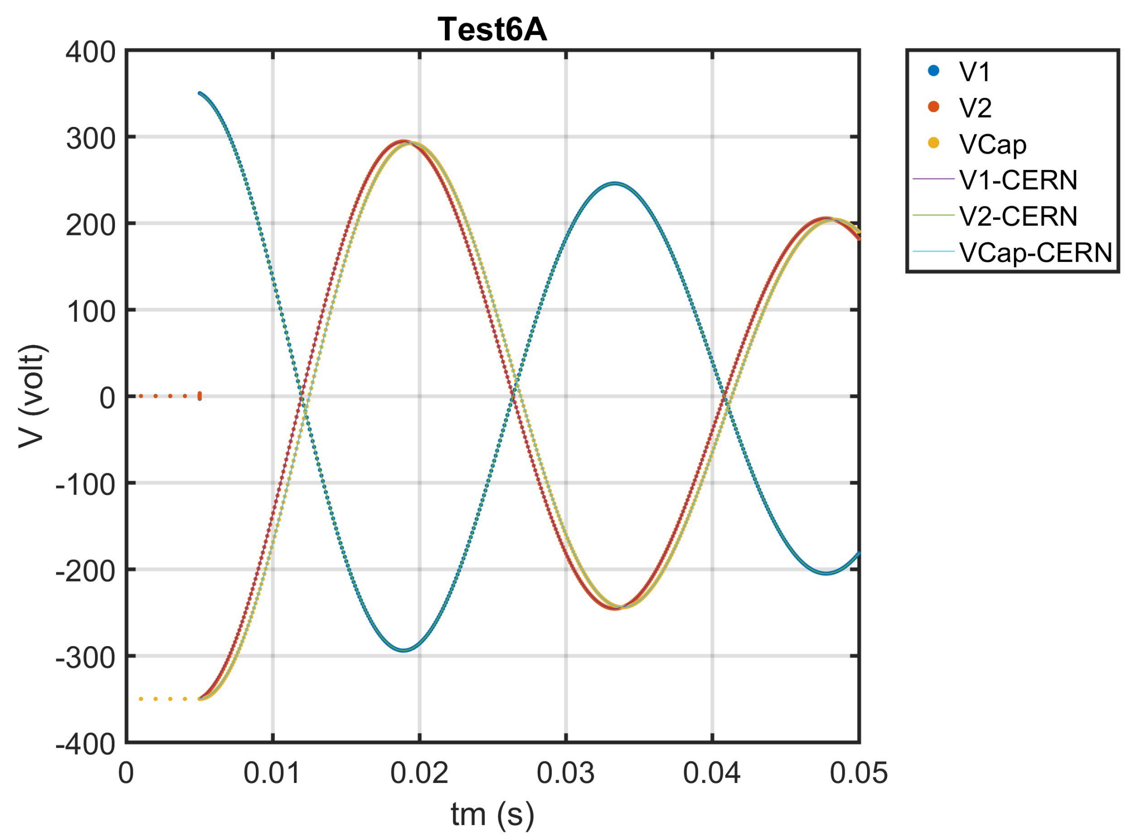
1. 0-5 ms
   (a) P2 is broken
   (b) P1 exists
   (c) a "static" solution is solved to charge the cliq and set up magnet current
2. 5-5.01 ms
   (a) turn on solution transients
   (b) Vmain is ramped to zero
3. 5.01-5.02 ms
   (a) P2 is added
   (b) P1 is broken
   (c) Vcliq is ramped to zero (with extra dump if numerical problem)
4. 5.02 ms +
   (a) solve decay

7.1 Test 6.A CLIQ With No Losses

This first simulation is intended to test the circuit coupling and the CLIQ set up with the coil only contributing inductive voltage. Interfilament coupling currents and quench are turned off so there are no losses. Since there are no heating terms, thermal coupling is not needed and the coil will stay superconducting and at the initial temperature of 4.5 K. The length Li is the effective magnet length used for inductive voltage.

Active physics	EM, CIRCU
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	NO
Quench state	Always SC
Time range for comparison	t=(0,50) [ms], Δt=suff. for conv.
I0	13.8 kA
Rdump	0.0 mΩ
L_c	N/A
L_i	9.20 m
R_{CLIQ}	15 mΩ
C_{CLIQ}	35 mF
V_{CLIQ}	350 V
Output	I1 [A]
	I2 [A]
	I_{CLIQ} [A]
	V1 [V]
	V2 [V]
	V_{Cap} [V]

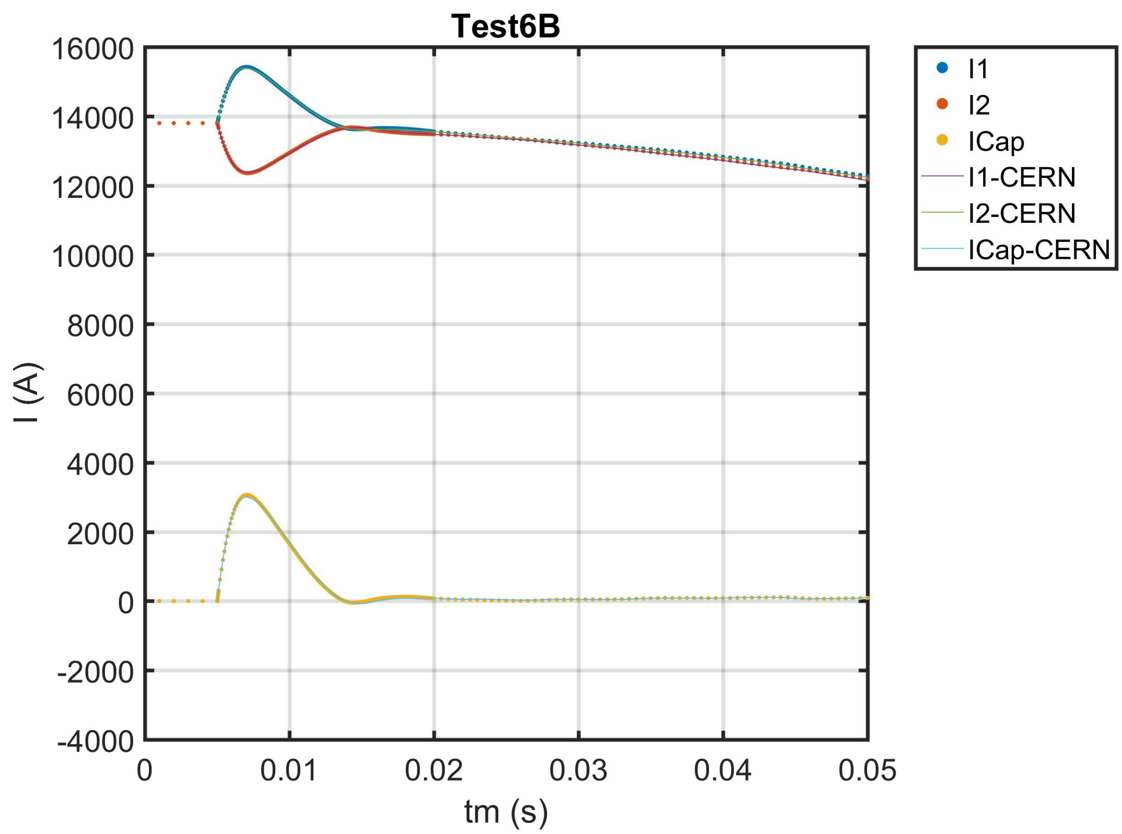

Test6A
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
I (A)
0
0.01
0.02
0.03
0.04
0.05
tm (s)
I1
I2
ICap
I1-CERN
I2-CERN
ICap-CERN

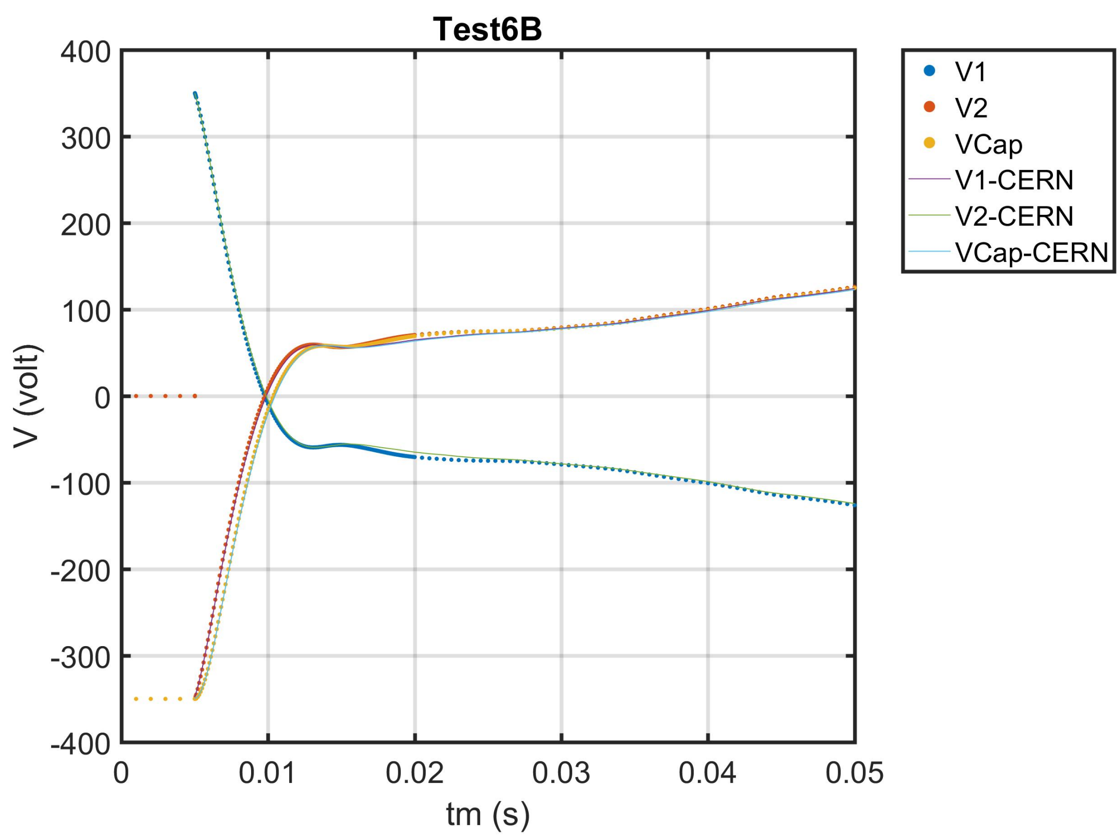

Test6A
400
300
200
100
0
-100
-200
-300
-400
V (volt)
0
0.01
0.02
0.03
0.04
0.05
tm (s)
V1
V2
VCap
V1-CERN
V2-CERN
VCap-CERN

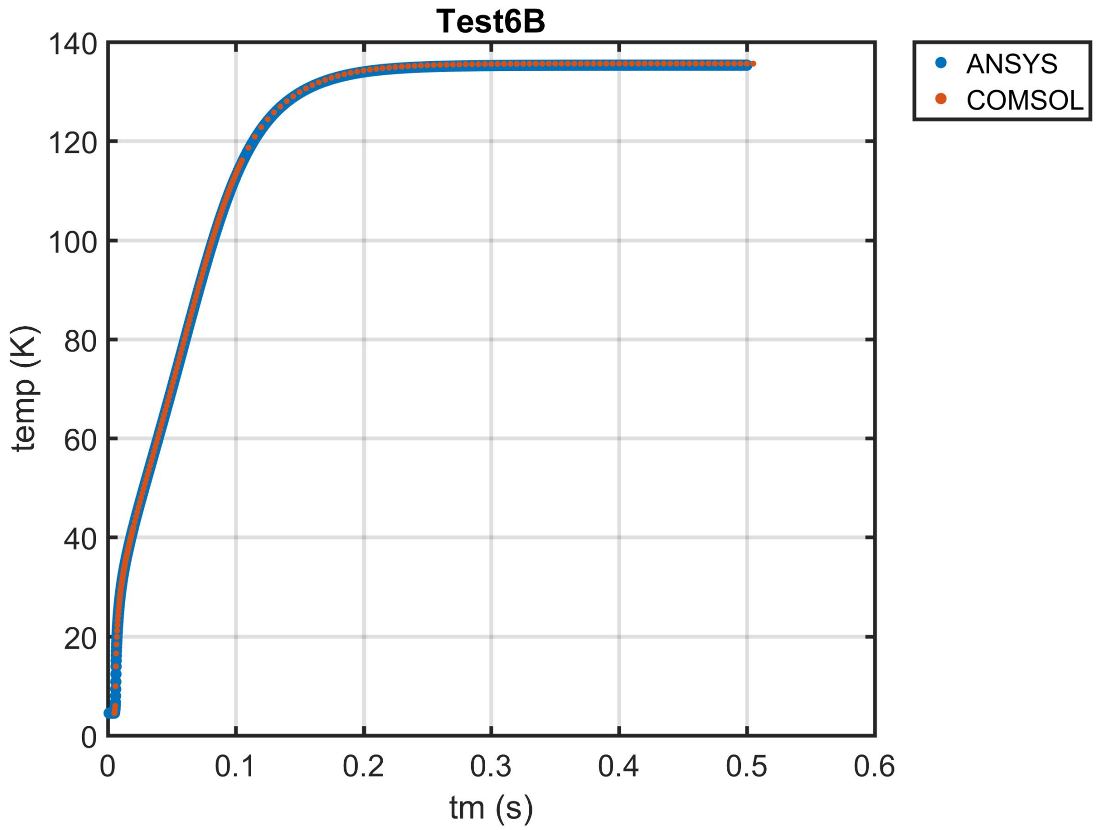
7.2 Test 6.B CLIQ Induced Quench Back

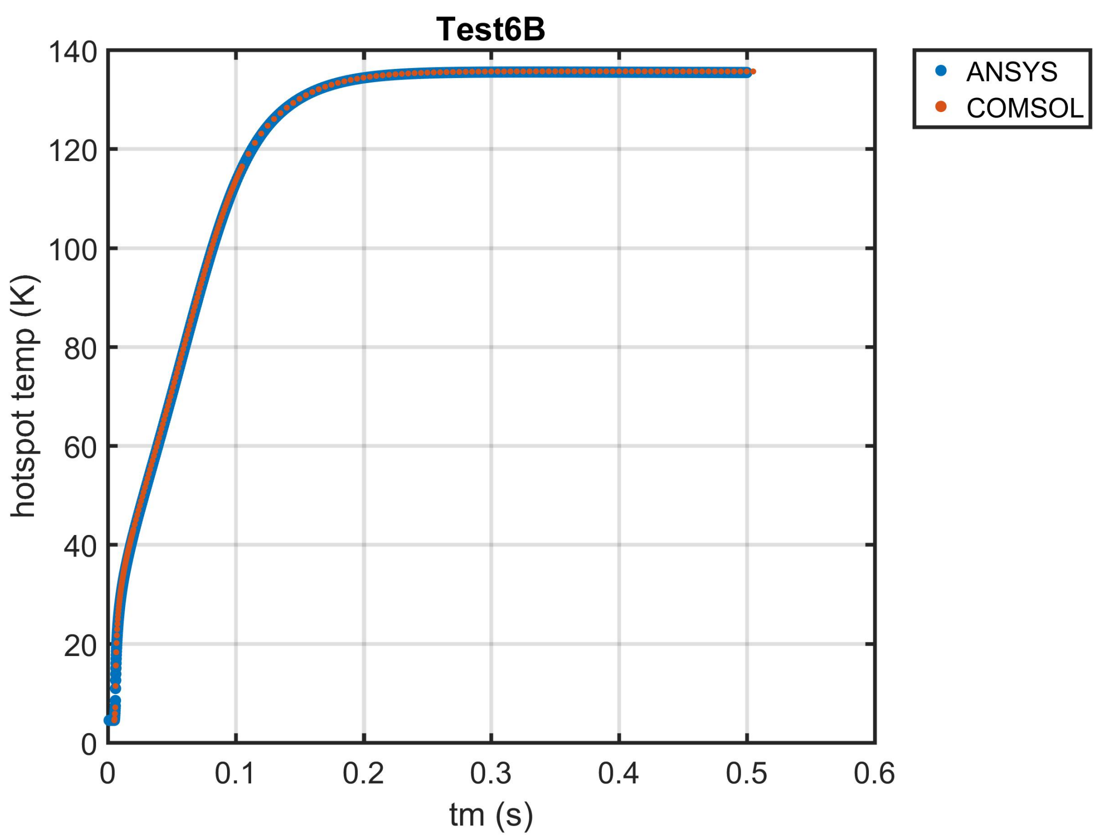
Test 6A is rerun with all effects included. The CLIQ induced current and field osciallation quenches the coil. The coil resistance growth then brings down the magnet current.

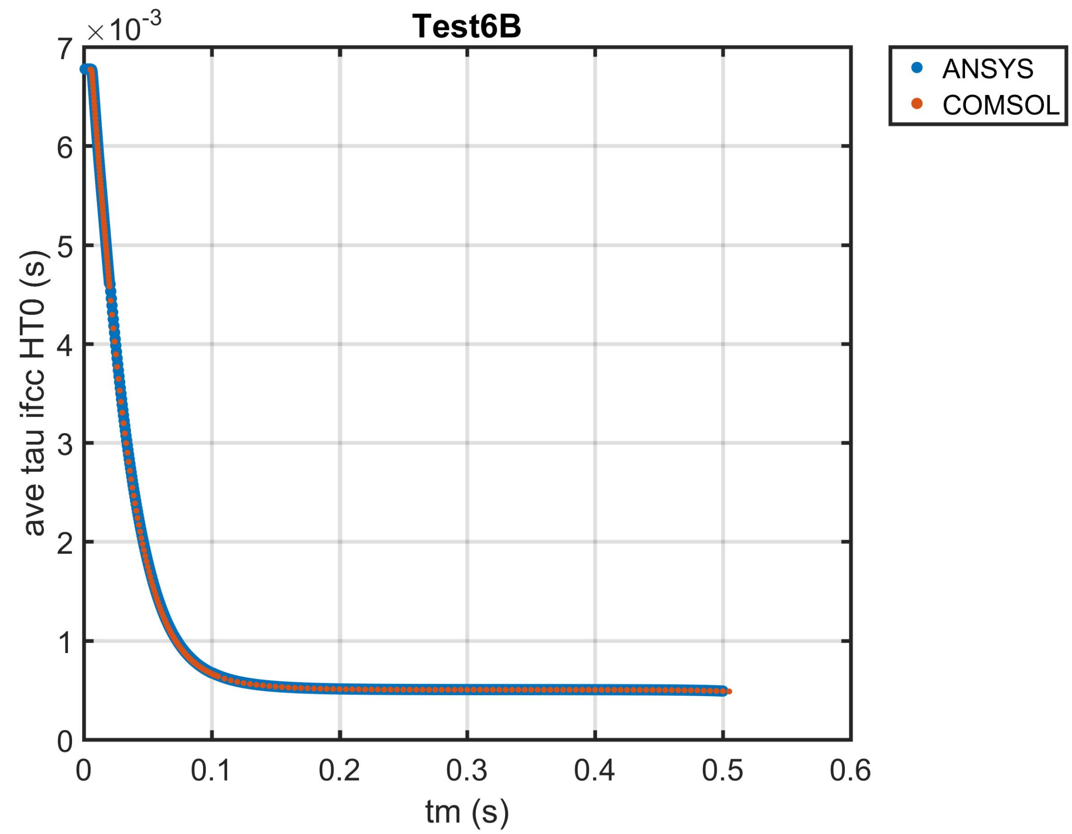
Active physics	EM, CIRCU, THERM
Coil initial temp	4.5 [K]
Iron yoke	YES
IFCC	YES
Quench state	Allow Quench with no Current Sharing
Cable insulation material	None
Cable voids filling material	GLASS FIBER
Time range for comparison	t=(0,500) [ms], Δt=suff. for conv.
I0	13.8 kA
Rdump	0.0 mΩ
L_c	10.11 m
L_i	9.20 m
R_{CLIQ}	15 mΩ
C_{CLIQ}	35 mF
V_{CLIQ}	350 V
ρ_{cu} fit	NIST, see Appendix E
C_v-Cu fit	CUDI, see Appendix E
C_v-Nb_3Sn fit	NIST, see Appendix E
C_v-G10 fit	NIST, see Appendix E
k-Cu fit	NIST, see Appendix E
τ-IFCC	Internally calculated
Output	I1, I2, I_{CLIQ} [A]
	V1, V2, V_{Cap} [V]
	T_{aveHT0} [K]
	T_{hot} [K]
	Tau-IFCC$_{aveHT0}$ [s]
	Mx-IFCC$_{aveHT0}$ [A/m]
	My-IFCC$_{aveHT0}$ [A/m]
	Q-IFCC$_{totHT0}$ [W/m] (per quad)
	Q-IFCC$_{totcoil}$ [W/m] (per quad)
	E-IFCC(t) [J]
	Q-Ohm$_{totHT0}$ [W/m] (per quad)
	Q-Ohm$_{totcoil}$ [W/m] (per quad)
	R-coil(t) [Ω]
	E-Ohm(t) [J]

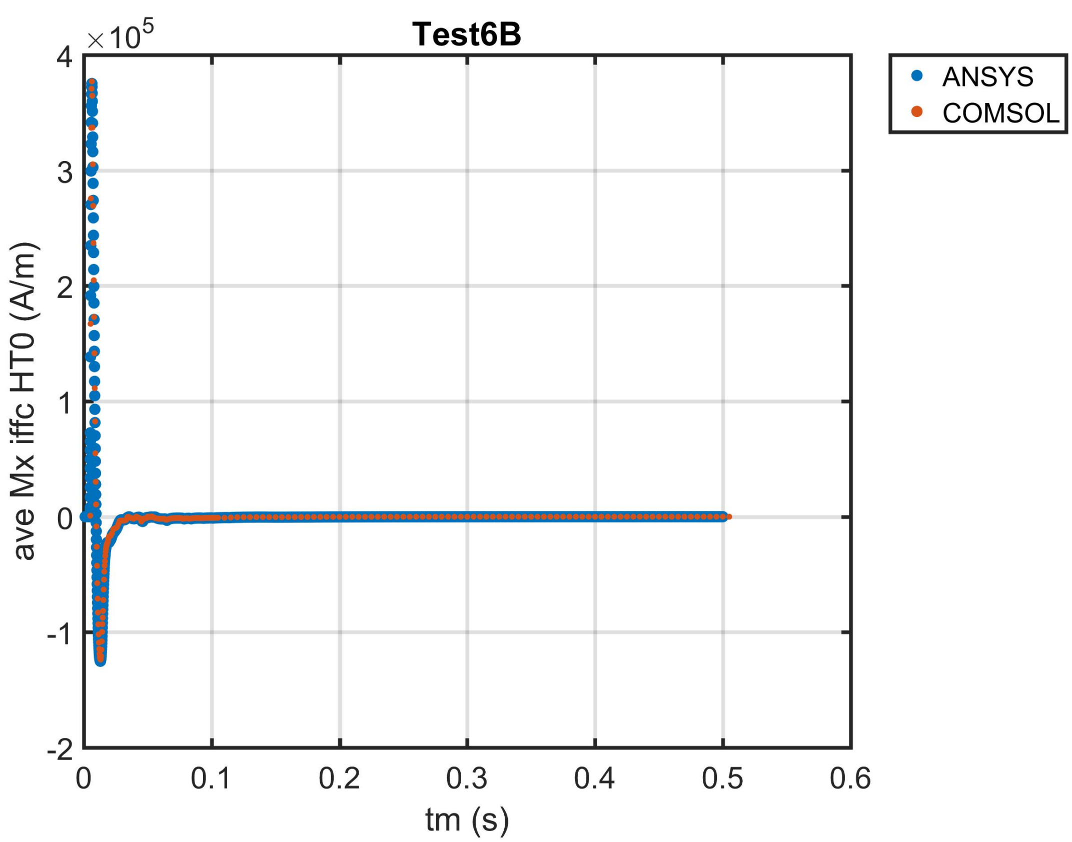

Test6B
16000
14000
12000
10000
8000
6000
4000
2000
0
-2000
-4000
I (A)
0
0.01
0.02
0.03
0.04
0.05
tm (s)
I1
I2
ICap
I1-CERN
I2-CERN
ICap-CERN

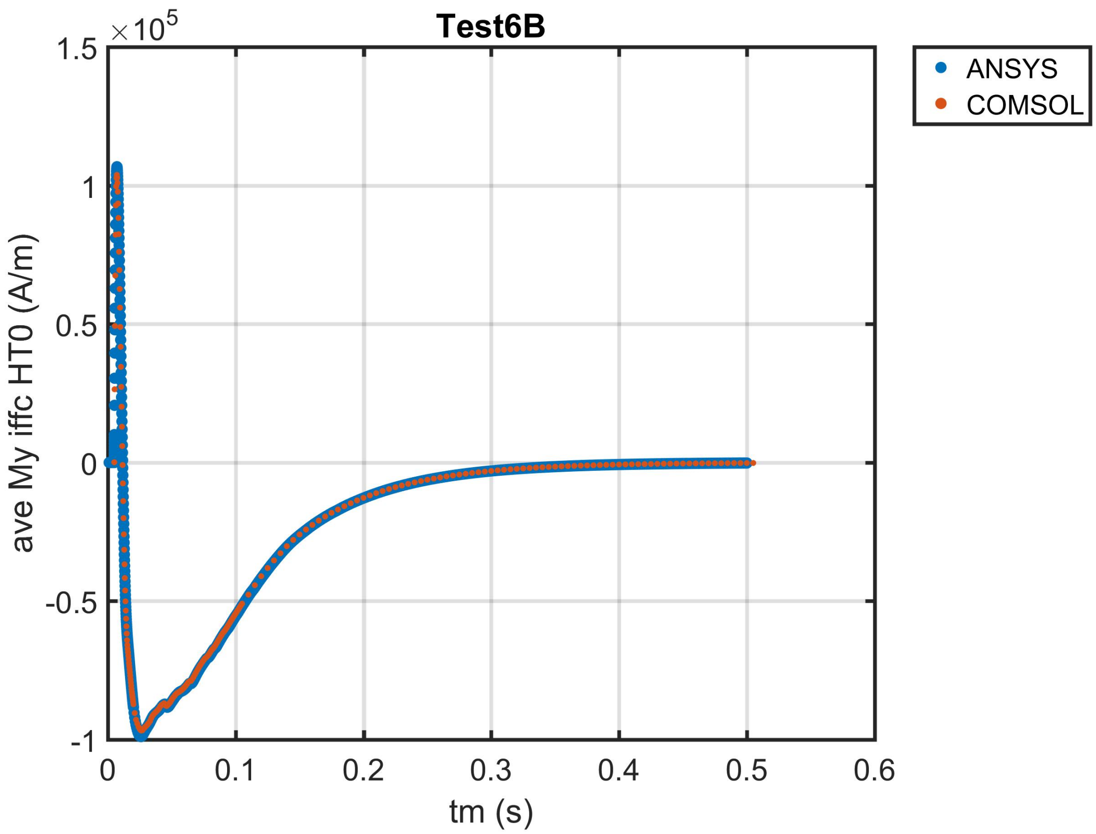

Test6B
400
300
200
100
0
-100
-200
-300
-400
V (volt)
0
0.01
0.02
0.03
0.04
0.05
tm (s)
V1
V2
VCap
V1-CERN
V2-CERN
VCap-CERN

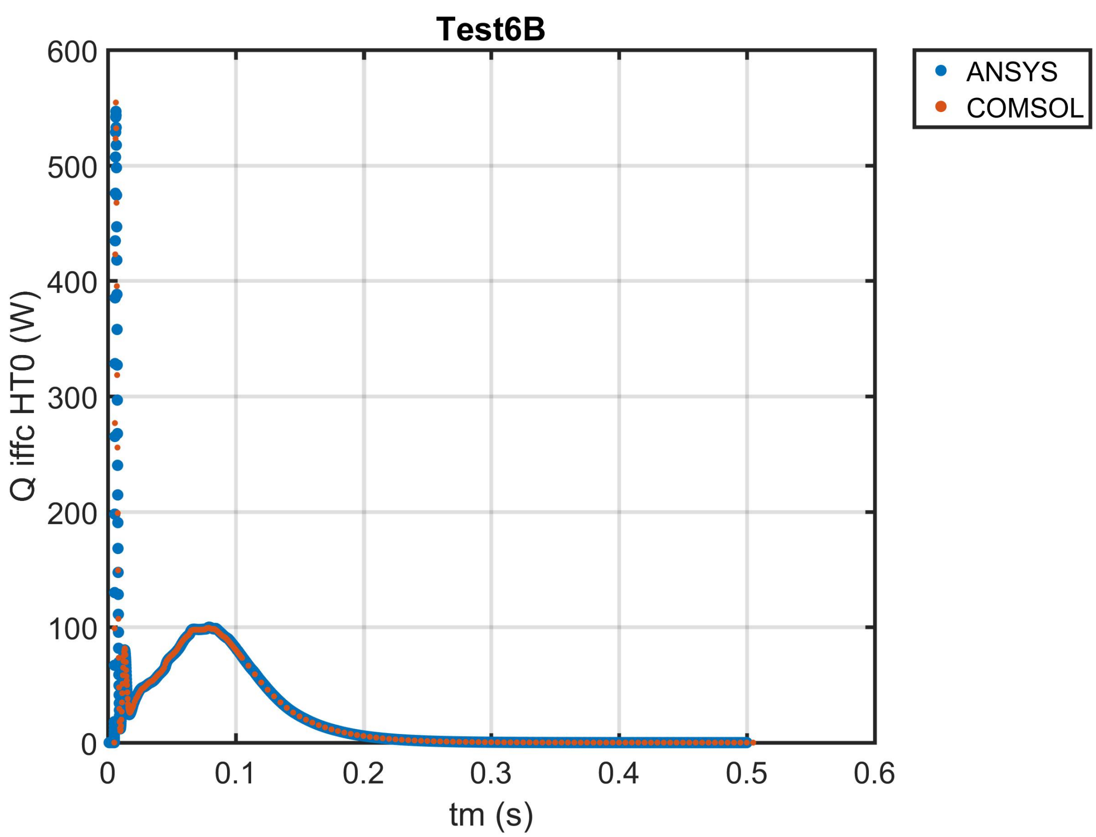

Test6B
temp (K)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
0.6

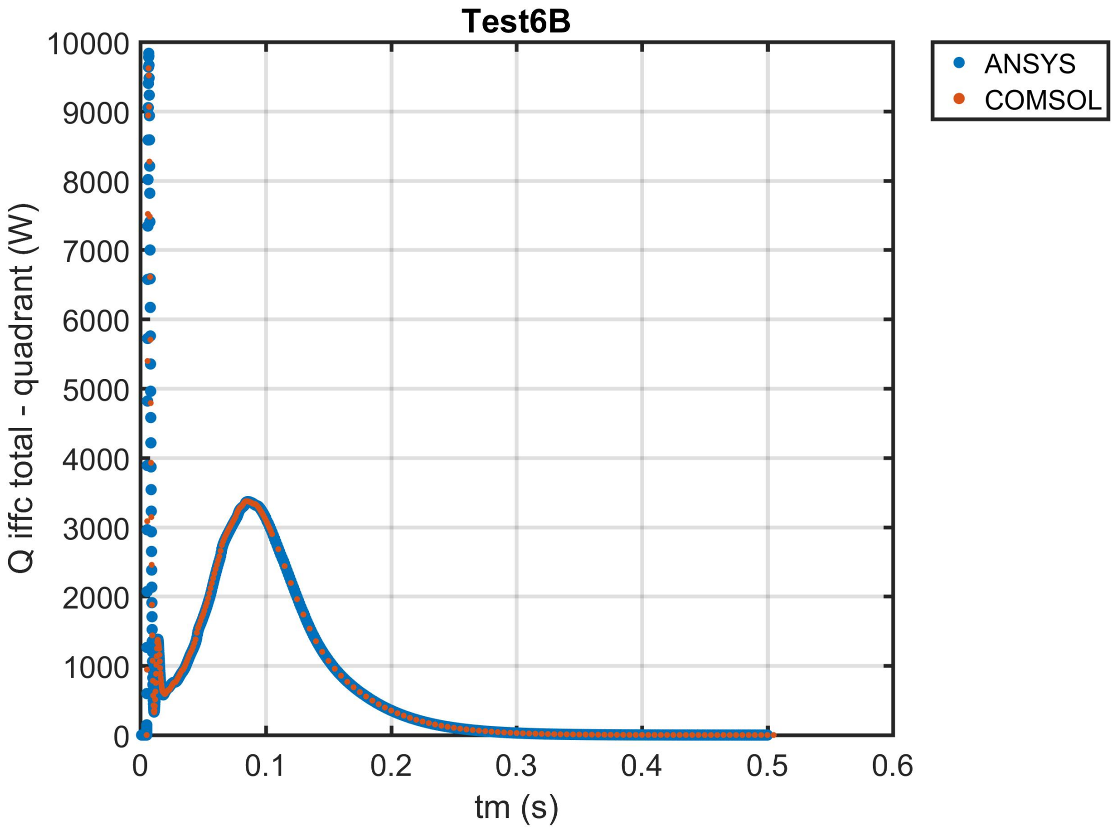

Test6B
hotspot temp (K)
tm (s)
ANSYS
COMSOL
0
20
40
60
80
100
120
140
0
0.1
0.2
0.3
0.4
0.5
0.6

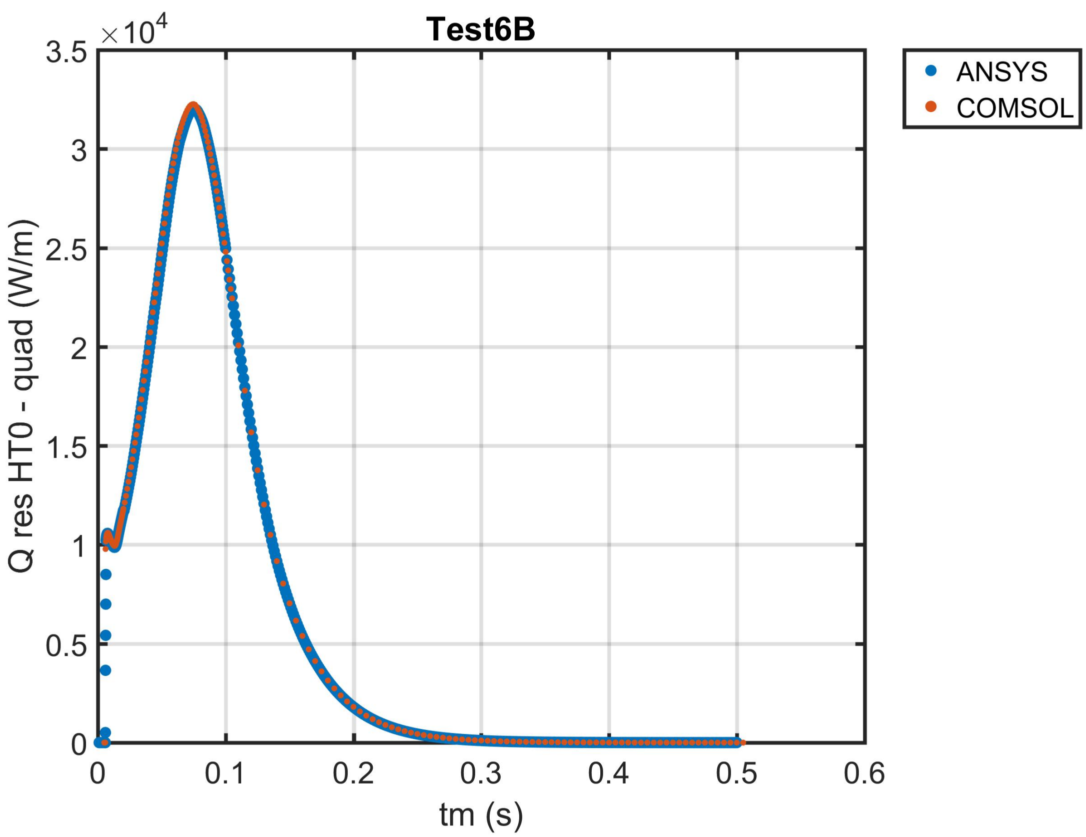

Test6B
×10^-3
7
6
5
4
3
2
1
0
ave tau ifcc HT0 (s)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

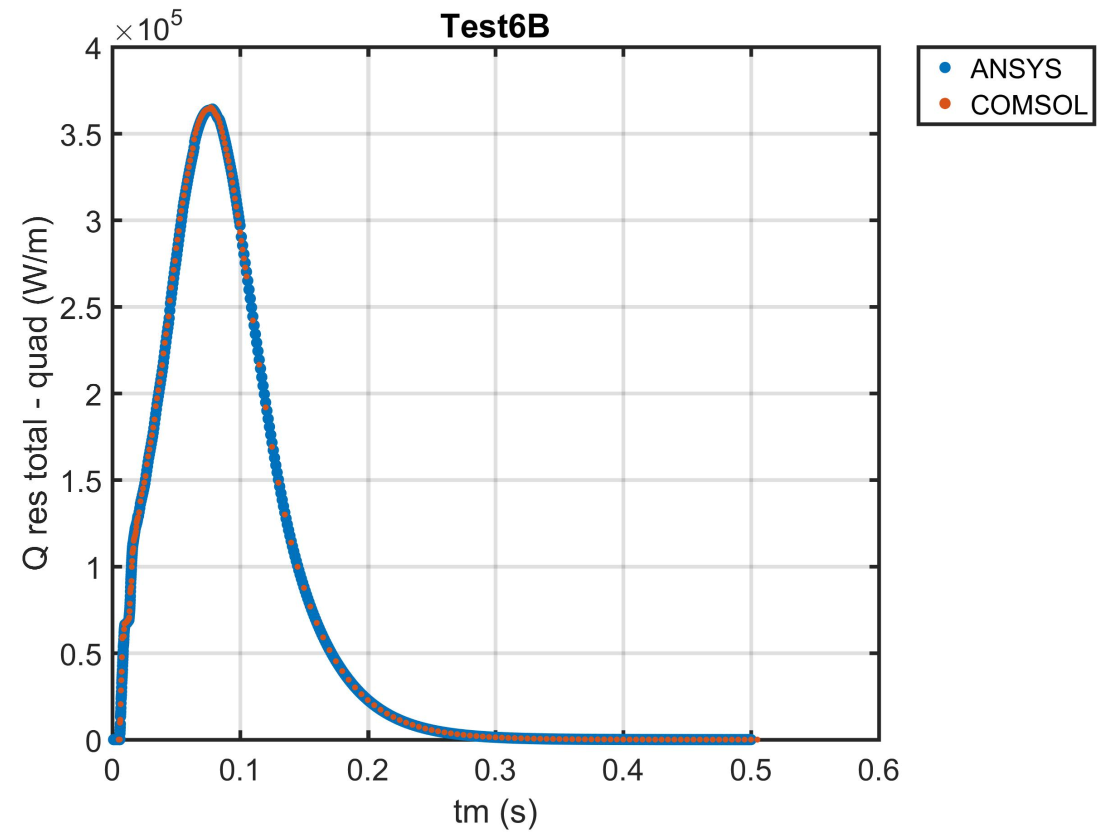

Test6B
×10^5
4
3
2
1
0
-1
-2
ave Mx iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

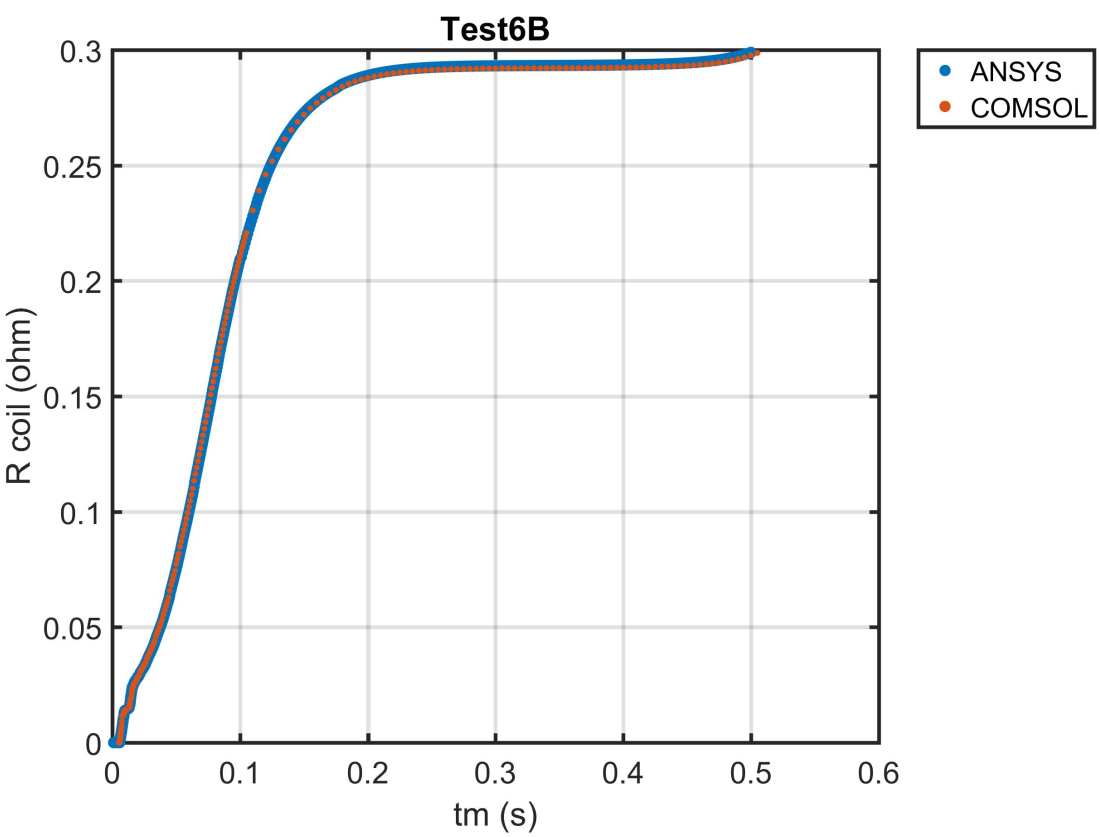

Test6B
$\times 10^5$
1.5
1
0.5
0
-0.5
-1
ave My iffc HT0 (A/m)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL

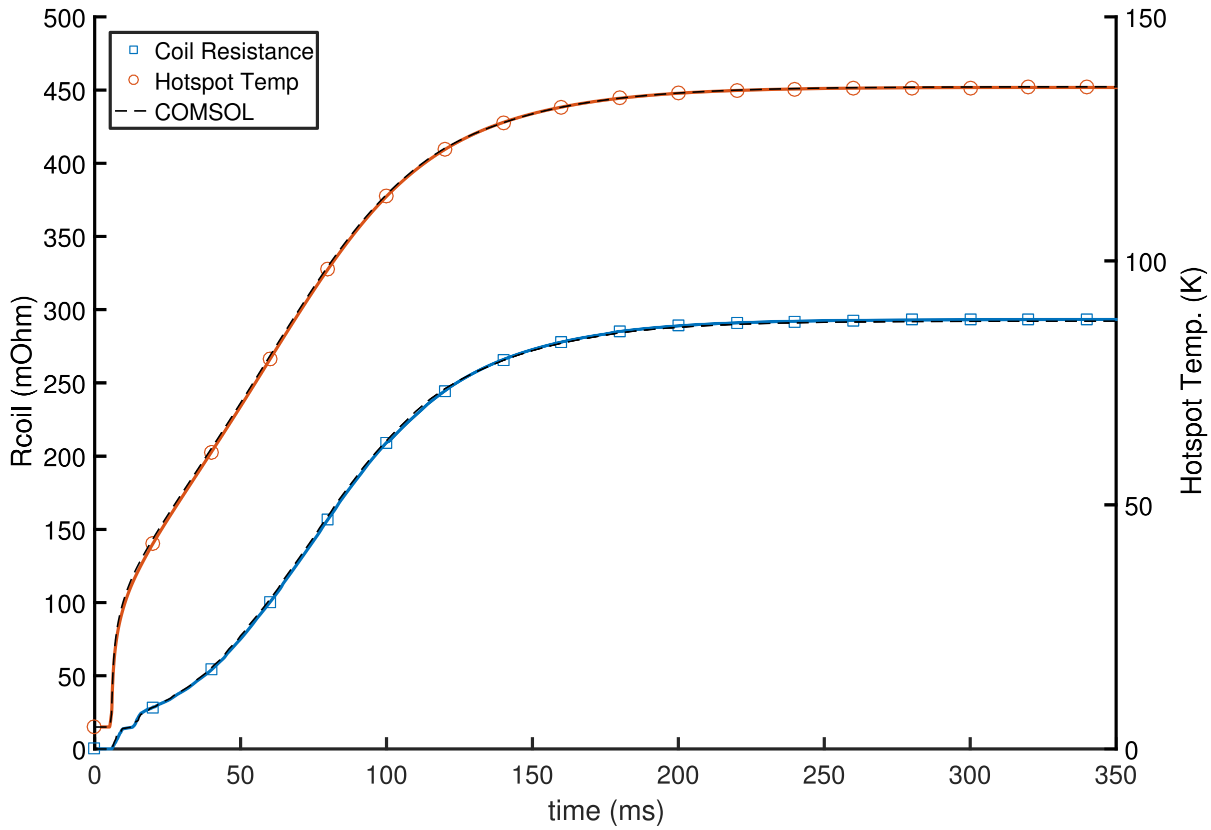

Test6B
600
500
400
300
200
100
0
Q iffc HT0 (W)
0
0.1
0.2
0.3
0.4
0.5
0.6
tm (s)
ANSYS
COMSOL


Test6B
ANSYS
COMSOL
Q iffc total - quadrant (W)
tm (s)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
0
0.1
0.2
0.3
0.4
0.5
0.6


Test6B
ANSYS
COMSOL
×10^4
Q res HT0 - quad (W/m)
tm (s)
0
0.5
1
1.5
2
2.5
3
3.5
0
0.1
0.2
0.3
0.4
0.5
0.6


Test6B
×10^5
Q res total - quad (W/m)
tm (s)
ANSYS
COMSOL
0
0.5
1
1.5
2
2.5
3
3.5
4
0.1
0.2
0.3
0.4
0.5
0.6


Test6B
R coil (ohm)
tm (s)
ANSYS
COMSOL
0
0.05
0.1
0.15
0.2
0.25
0.3
0.4
0.5
0.6


Coil Resistance
Hotspot Temp
COMSOL
Rcoil (mOhm)
Hotspot Temp. (K)
time (ms)
0
50
100
150
200
250
300
350
400
450
500
0
50
100
150
0
50
100
150
200
250
300
350

References

[1] L. Brouwer, D. Arbelaez, B. Auchmann, L. Bortot, and E. Stubberud, "User Defined Elements in ANSYS for 2D Multiphysics Modeling of Superconducting Magnets," 2019, submitted for publication.

[2] L. Bortot, B. Auchmann, I. Cortez-Garcia, A. M. Fernandez-Navarro, M. Maciejewski, M. Mentink, M. Prioli, E. Ravaioli, S. Schops, and A. Verweij, "Steam: A hierarchical co-simulation framework for superconducting accelerator magnet circuits," *IEEE Trans. Appl. Supercond.*, vol. 28, no. 3, p. 4900706, 2018.

[3] L. Bortot, B. Auchmann, I. Cortez-Garcia, A. M. Fernandez-Navarro, M. Maciejewski, M. Prioli, S. Schops, and A. Verweij, "A 2-d finite-element model for electro-thermal transients in accelerator magnets," *IEEE Trans. Appl. Supercond.*, vol. 54, no. 3, p. 7000404, 2018.

[4] "SCPACK: a User Element Package for Superconducting Magnet Modeling in ANSYS." [Online]. Available: https://usmdp.lbl.gov/scpack-code/

[5] L. Brouwer, "Documentation for USER101: a 2D User-Defined Thermal Element in ANSYS," *LBNL Eng. Note: SU-1010-4837, R1.0*, 2019. [Online]. Available: https://usmdp.lbl.gov/scpack-code/

[6] ——, "Documentation for USER102: a 2D User-Defined Electromagnetic Element in ANSYS," *LBNL Eng. Note: SU-1010-4838, R1.0*, 2019. [Online]. Available: https://usmdp.lbl.gov/scpack-code/

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[8] E. Ravaioli, "CLIQ. a new quench protection technology for superconducting magnets," Ph.D. dissertation, University of Twente, Netherlands, 6 2015.

[9] G. Morgan, "Theoretical Behavior of Twisted Multicore Superconducting Wire in a Time-Varying Uniform Magnetic Field," *Journal of Applied Physics*, vol. 41, p. 3673, 1970.

[10] M. Wilson, *Superconducting Magnets.* Oxford University Press, 1983.

[11] G. Manfreda, "Review of ROXIE's Material Properties Database for Quench Simulation," *CERN Internal Note: EDMS NR*, vol. 1178007, 2018.

A Strand and Cable Parameters

The cable parameters which stay constant across all tests are included in the table below. If additional assumptions are made they will be given in the description of the particular test.

Filament		
Diameter	50	μm
Strand		
Diameter	0.75	mm
Non-Cu Fraction	0.4	
Cu RRR	200	from 295 K
Effective resistivity	1.0	
Filament twist pitch	14	mm
Cable		
Width	15	mm
Height	1.5	mm
Number of strands	40	
Cable Insulation		
Radial thickness	100	μm
Azimuthal thickness	100	μm

B Nb_3Sn Jc Fit

When needed for determining current sharing and quench, the follow fit for the J_c of Nb_3Sn is used.

T_{c0}	16.0	K
B_{c0}	28.11	T
J_{c0}	6190	A/mm^2
p	1.52	
α	0.96	

$$J_c = J_{c0}(1 - t^p)^{\alpha-1}(1 - t^2)^{\alpha} h^{-.5}(1 - h)^2$$

where

$$t = \frac{T}{T_{c0}}$$

$$B_c = B_{c0}(1 - t^p)$$

$$h = \frac{B}{B_c}$$

C Interfilament Coupling Currents

Interfilament coupling currents (IFCC) are an important loss mechanism for superconducting magnets. Their relatively short time constant (tens of milliseconds or less) and localized heat deposition within the strand make them an effective mechanism for magnet quench back. As shown in Fig. 1, these induced currents flow along the superconducting filaments which are twisted along the length of the strand and then across the strand matrix.

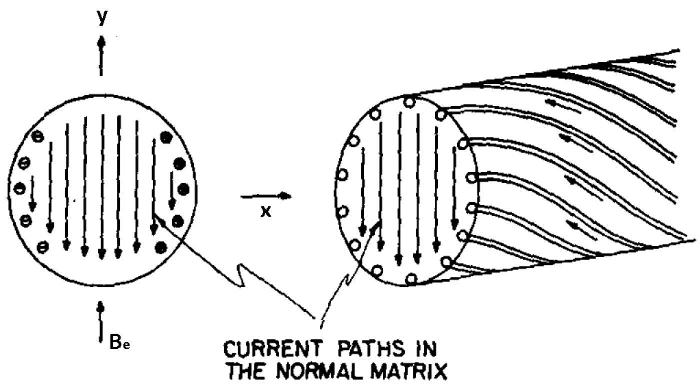

Figure 1: The path of interfilament coupling currents induced by a changing vertical field is shown (Fig. from [9]). The current flows along the twisted filaments and then across the strand matrix. This results in strand magnetization as well as resistive losses in the matrix material.

For a uniform field change within the strand, the induced axial current is typically approximated using a cosine theta (dipole producing) current density [9, 10]

$$g_z(\theta) = \dot{B}_i \left(\frac{L}{2\pi}\right)^2 \frac{cos(\theta)}{\rho_{et}}, \tag{1}$$

where $\dot{B}_i$ is the vertical field change within the strand, L is the filament twist pitch, and ρ_{et} is the effective resistivity of the strand matrix. To include contact resistance between matrix and filaments, the effective resistivity is defined as $\rho_{et} = f_{eff}\rho_{cu}$ where ρ_{cu} is the stabilizer resistivity and f_{eff} is a single scaling parameter. If B_e is an applied, uniform external vertical field, the field within the strand is depressed by the induced IFCC currents as

$$B_i = B_e - \frac{1}{2}\mu_0 g_z(\theta = 0) \tag{2}$$

$$B_i = B_e - \tau \dot{B}_i, \tag{3}$$

where the natural time constant for the induced current is clearly

$$\tau = \frac{\mu_0}{2\rho_{et}} \left(\frac{L}{2\pi}\right)^2. \tag{4}$$

The strand magnetization is then given by

$$M_e = -\frac{4}{\mu_0 \pi} \int_0^{\pi/2} g_z(\theta) cos(\theta) d\theta \tag{5}$$

$$M_e = -\frac{2\tau}{\mu_0} \dot{B}_i. \tag{6}$$

For those reviewing this approach in Wilson's textbook [10], it is helpful to note there is a missing μ_0 in Equation 8.51 (to match Equation 6). See the derivation of the finite element matrices in [6] to see this equivalent magnetization approach added to the vector potential formulation, leading to the addition of a curl-curl term in the damping matrix of the FEM. These induced currents deposit energy as heat within the strand matrix with a power per unit volume of

$$P_e = \vec{M}_e \cdot \frac{\partial \vec{B}}{\partial t}, \tag{7}$$

which in many cases leads to IFCC losses being an effective quench back mechanism.

D Iron BH Curve

H(A/m)	B(T)
7.941831506	0.00712
15.88366301	0.0167
23.82549452	0.02925
31.76732602	0.04522
47.53162283	0.08891
63.36753936	0.15434
79.21937139	0.24066
158.8127569	0.76507
317.649387	1.29683
475.1809466	1.45217
633.6276471	1.52043
792.1061786	1.55841
1192.094374	1.60954
1589.758907	1.63892
1987.081257	1.66055
2386.281635	1.67826
2782.290957	1.69427
3179.493941	1.70828
3577.039107	1.72175
3971.377302	1.73414
4765.210312	1.75706
5559.099026	1.77805
6354.069994	1.79764
7149.486595	1.81567
7944.083548	1.8333
10590	1.85
13160	1.9
21170	2
33760	2.1
66000	2.2
120960	2.28
169600	2.3443
212170	2.3996
283130	2.4905
339890	2.5627
425040	2.6706
566950	2.8498
850760	3.2074
1702300	4.2782
2128000	4.8134
2837700	5.7052
3405100	6.4186
4256700	7.4887

E Material Property Fits

Many of these fits originate from the ROXIE Material Database [11].

```
function rhocunist_Tref(TT,RRR,BB,TREF)


        DOUBLE PRECISION TT,RRR,BB,b,rhocunist_Tref,TREF,tref_RRR,t
        DOUBLE PRECISION c0,c0_scale,P1,P2,P3,P4,P5,P6,P7
        DOUBLE PRECISION a0,a1,a2,a3,a4
        DOUBLE PRECISION rho_0,rho_i,rho_i0,rho_n
        DOUBLE PRECISION x,log_x,f_exp,corr

        c0 = 1.553e-8
        tref_RRR = 273

        P1 = 1.171e-17
        P2 = 4.49
        P3 = 3.841e10
        P4 = 1.14
        P5 = 50
        P6 = 6.428
        P7 = 0.4531

        a0 = -2.662
        a1 = 0.3168
        a2 = 0.6229
        a3 = -0.1839
        a4 = 0.01827


        b=abs(BB)
        T = TT

        c0_scale = TREF/tref_RRR
        rho_0 = c0_scale*c0/RRR
        rho_i = P1*(T**P2)/(1+P1*P3*(T**(P2-P4))*exp(-((P5/T)**P6)))
        rho_i0 = P7*rho_i*rho_0/(rho_i+rho_0)
        rho_n = rho_0+rho_i+rho_i0

        if (b.gt.0.01d0) then
                x = c0 * B / rho_n
                log_x = log10(x)
                f_exp = a0+a1*log_x+a2*(log_x**2)+a3*(log_x**3) + a4*(log_x**4)
                corr = 10.0d0**f_exp
        else
                corr=0.0d0
        endif

        rhocunist_tref=rho_n*(1+corr);

end function rhocunist_Tref


function cvcucudi(TT)

        DOUBLE PRECISION, INTENT(IN) :: TT
        DOUBLE PRECISION             :: cvcucudi

  IF(TT<9.441D0)THEN
                cvcucudi=-0.0308*TT**4.0D0+7.229*TT**3.0D0-2.1286*TT**2.0D0+101.89*TT+2.5631
        ELSE
        IF(TT<31.134D0)THEN
                cvcucudi=-0.3045*TT**4.0D0+29.871*TT**3.0D0-455.61*TT**2.0D0+3469.5*TT-8250.3
        ELSE
        IF(TT<123.34D0)THEN
                cvcucudi=0.0419*TT**4.0D0-14.024*TT**3.0D0+1508.9*TT**2.0D0-31595*TT+178432
        ELSE
        IF(TT<306.12D0)THEN
                cvcucudi=-8.48E-4*TT**4.0D0+0.8419*TT**3.0D0-325.52*TT**2.0D0+60590*TT-1.2851E6
        ELSE
        IF(TT<498.15D0)THEN
                cvcucudi=-4.80E-5*TT**4.0D0+0.09173*TT**3.0D0-64.12*TT**2.0D0+20363*TT+1.028E6
        ELSE
                cvcucudi=12E-5*TT**3.0D0-0.21486*TT**2.0D0+1003.84*TT+3.1823E6
        ENDIF
        END IF
        END IF
        END IF
        END IF

end function cvcucudi



function cvnb3snnist(TT,BB)

        DOUBLE PRECISION, INTENT(IN) :: TT
```

```
        DOUBLE PRECISION, INTENT(IN) :: BB
        DOUBLE PRECISION cvnb3snnist


        DOUBLE PRECISION a0,a1,a2,a3,a4,a5,a6,a7
        DOUBLE PRECISION beta,gamma,rho
        DOUBLE PRECISION T1,T2,logT,fexp
        DOUBLE PRECISION Tc,Tc0,Bc20

        Tc0 = 17.8d0
        Bc20 = 27.012d0
        T1 = 20d0
        T2 = 400d0

        a0 = 79.78547d0
        a1 = -247.44839d0
        a2 = 305.01434d0
        a3 = -186.90995d0
        a4 = 57.48133d0
        a5 = -6.3977d0
        a6 = -0.6827738d0
        a7 = 0.1662252d0
        beta = 1.241d0/(1000.0d0)
        gamma = 0.138d0
        rho = 8950d0

        IF (BB .lt. Bc20)THEN
                Tc = Tc0*((1.0d0-BB/Bc20)**0.59d0)
        ELSE
                Tc =  0.0d0
        END IF

        IF (TT .lt. Tc)THEN                    !Superconducting
                cvnb3snnist = rho*((beta+3.0d0*gamma/(Tc0**2d0))*(TT**3d0) + gamma*BB/Bc20*TT)
        ELSE  IF  (  (TT .gt. Tc) .AND. (TT .le. T1) )THEN
                cvnb3snnist = rho*(beta*(TT**3.0d0) + gamma*TT)
        ELSE  IF  (  (TT .gt. T1) .AND. (TT .le. T2) )THEN
        logT = LOG10(TT)
        fexp = (a0+a1*logT+a2*(logT**2d0)+a3*(logT**3d0)+a4*(logT**4d0)+a5*(logT**5d0)+a6*(logT**6d0)+a7*(logT**7d0))
        cvnb3snnist = rho*(10d0**fexp)
        ELSE
                cvnb3snnist = rho*(234.89d0+0.0425d0*TT)
        END IF


end function cvnb3snnist



function cvG10nist(TT)

        double precision :: dc_a, dc_b, dc_c, dc_d, dc_e, dc_f, dc_g, dc_h
        double precision :: density
        double precision, intent(in) :: TT
        DOUBLE PRECISION :: cvG10nist, p

        dc_a = -2.4083
        dc_b =  7.6006
        dc_c = -8.2982
        dc_d =  7.3301
        dc_e = -4.2386
        dc_f =  1.4294
        dc_g = -0.24396
        dc_h =  0.015236

        density = 1900.0 ! No value in NIST database, so equal to Cryocomp and Fermilab


        p = dc_a+dc_b*(LOG10(TT))**1.0D0+dc_c*(LOG10(TT))**2.0D0+dc_d*(LOG10(TT))**3.0D0
        p = p+dc_e*(LOG10(TT))**4.0D0+dc_f*(LOG10(TT))**5.0D0+dc_g*(LOG10(TT))**6.0D0+dc_h*(LOG10(TT))**7.0D0
        cvG10nist = density * 10**p

end function cvG10nist



function kxxnist_tref(TT,RRR,BB,TREF)

  DOUBLE PRECISION TT, RRR, BB,TREF, kxxnist_tref
        kxxnist_tref = kxxnist_B0(TT,RRR)*rhocunist_tref(TT,RRR,0.0D0,TREF)/rhocunist_tref(TT,RRR,BB,tref)

end function kxxnist_tref


function kxxnist_B0(TT,RRR)

        DOUBLE PRECISION TT, RRR, kxxnist_B0
        DOUBLE PRECISION beta, k_0, k_i, k_i0
        DOUBLE PRECISION P1, P2, P3, P4, P5, P6, P7

        beta = 0.634/RRR
        P1 = 1.754E-8
```

```
        P2 = 2.763
        P3 = 1102
        P4 = -0.165
        P5 = 70
        P6 = 1.756
        P7 = 0.838/(beta/0.0003)**0.1661

        k_0 = beta/TT
        k_i = P1*TT**P2/(1+P1*P3*TT**(P2+P4)*exp(-(P5/TT)**P6))
        k_i0 = P7*k_i*k_0/(k_i+k_0)
        kxxnist_B0 = 1/(k_0+k_i+k_i0)

end function kxxnist_B0
```

F Fixed Material Properties

Tests 2A, 2B, and 2C require fixed material properties. These are given below.

Copper		
ρ	1e-8/pi	Ωm
k	300	W/m/K
c_v	500	J/m^3/K

Nb_3Sn		
ρ	0	Ωm
k	300	W/m/K
c_v	250	J/m^3/K

Glass Fiber (G10)		
ρ	0	Ωm
k	0.01	W/m/K
c_v	750	J/m^3/K