HB Magnet Quench Calculation

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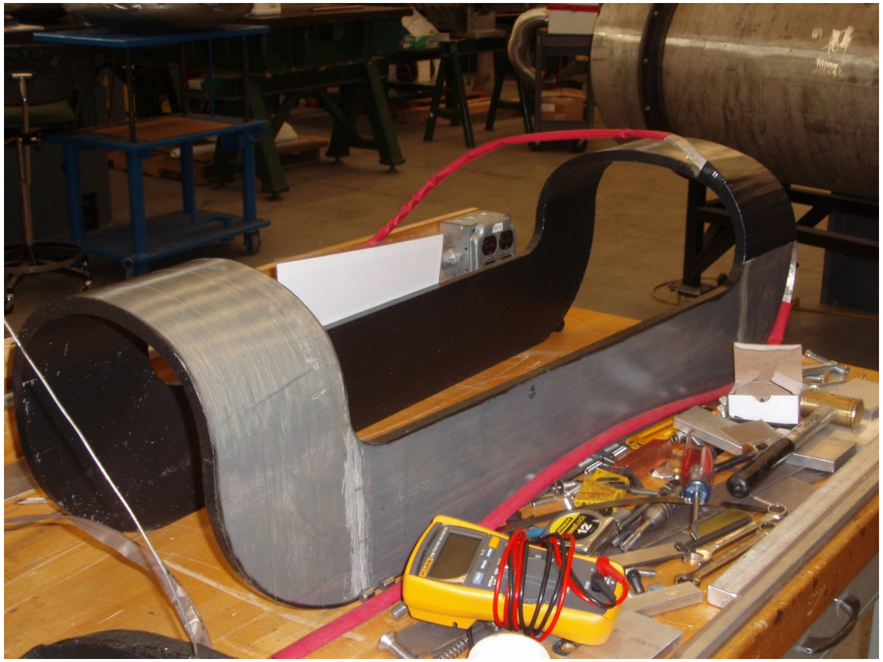
Magnet Details-Coil construction

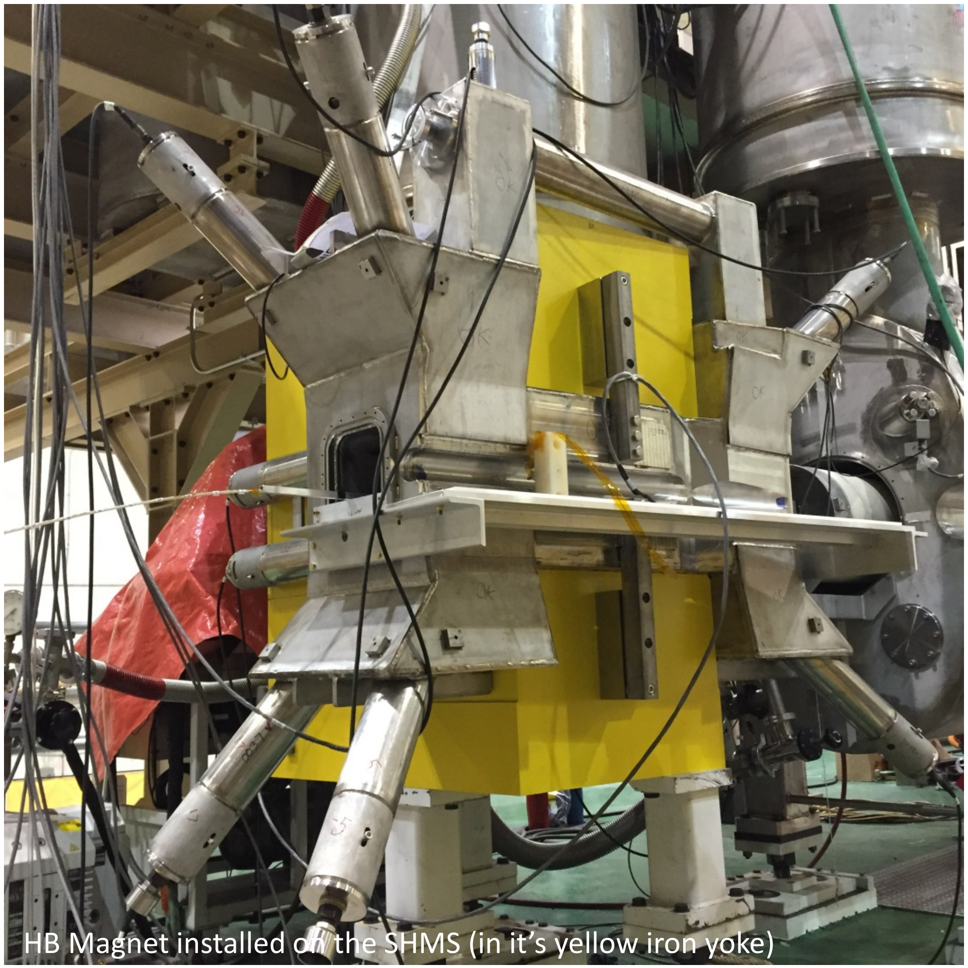
- **234.4 m of SSC cable was used for one coil.**
- **90 turns per coil.**
- **DA409U/S2 pre-preg was used; insulating thickness was 0.28 mm between turns.**
- **Each coil weighs 63 lb (28.6 kg) ; 53.8 lb (24.4 kg) is conductor; insulating materials are 9.2 lb (4.17 kg).**

Figure 1



Magnet Details-Operating Parameters

- **Michigan State U / FRIB**: Cost reimbursement contract, design and build based on reference design, cryogenic control reservoir attached by vendor before shipment to JLab
- **JLab**: Conductor, cryogenic control reservoir (CCR), controls, power supply, assembly, installation and Commissioning



HB Magnet installed on the SHMS (in it's yellow iron yoke)

Parameter	Unit	Design Value
Field	**T**	**2.6**
Effective Length	**m**	**0.752**
Pole Gap (warm)	**m**	**0.35**
11 GeV Current	**A**	**4000**
Number of turns/pole	**t**	**90**
Stored Energy	**MJ**	**0.2**
Field in Coil Max	**T**	**3.12**
Physical Length Overall	**m**	**1.16**
Magnet Weight	**Tons**	**6.8**

Figure 2

Magnet Details-DC Circuit

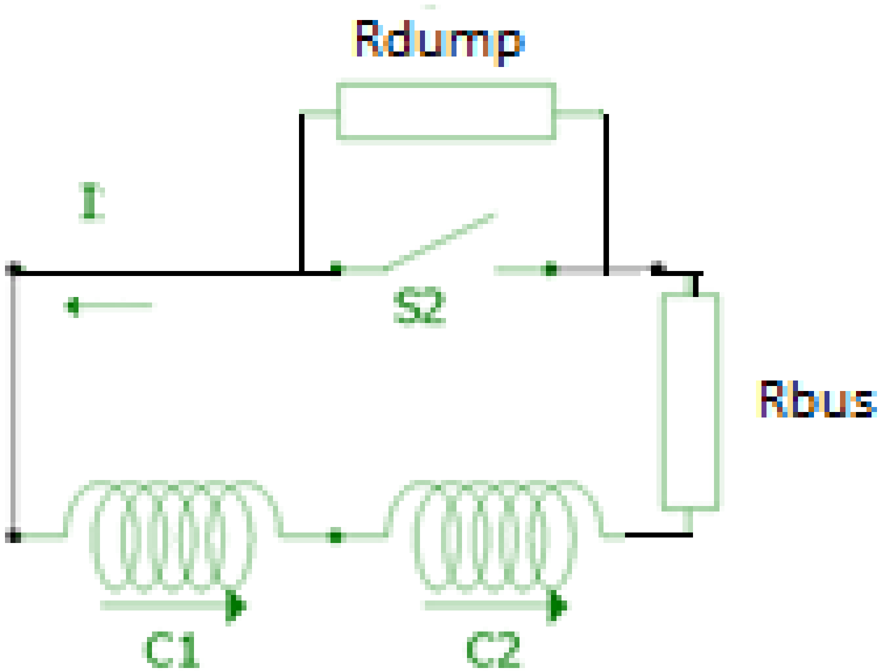
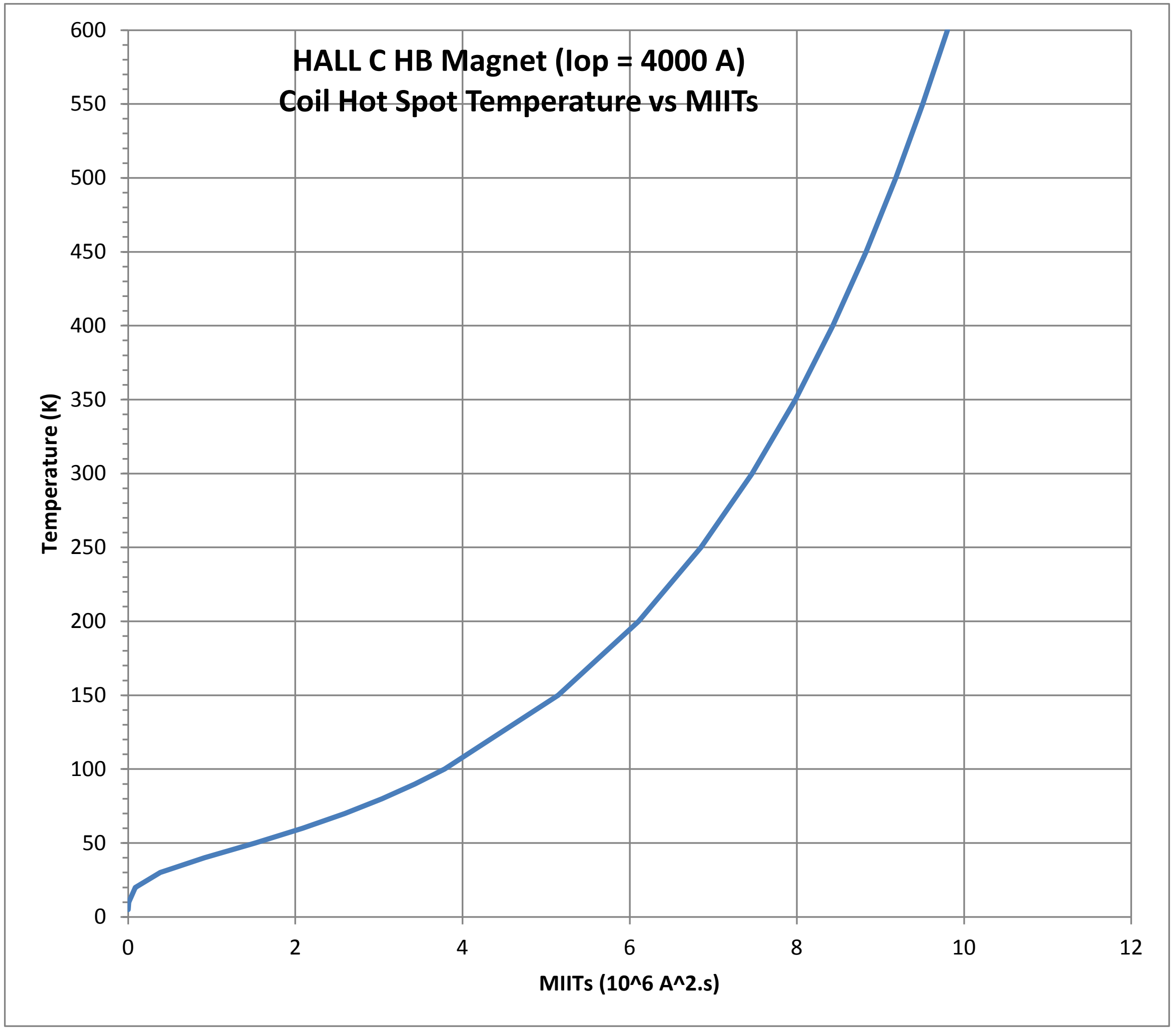


Figure 3

- Rdump is the dump resistor
- Rbus is the bus and lead resistance
- This is a representation of what the actual circuit is in reality but within OPERA it is modeled slightly differently and this is explained later.

MIITs Calculations-Assumptions and Temp vs MIITS

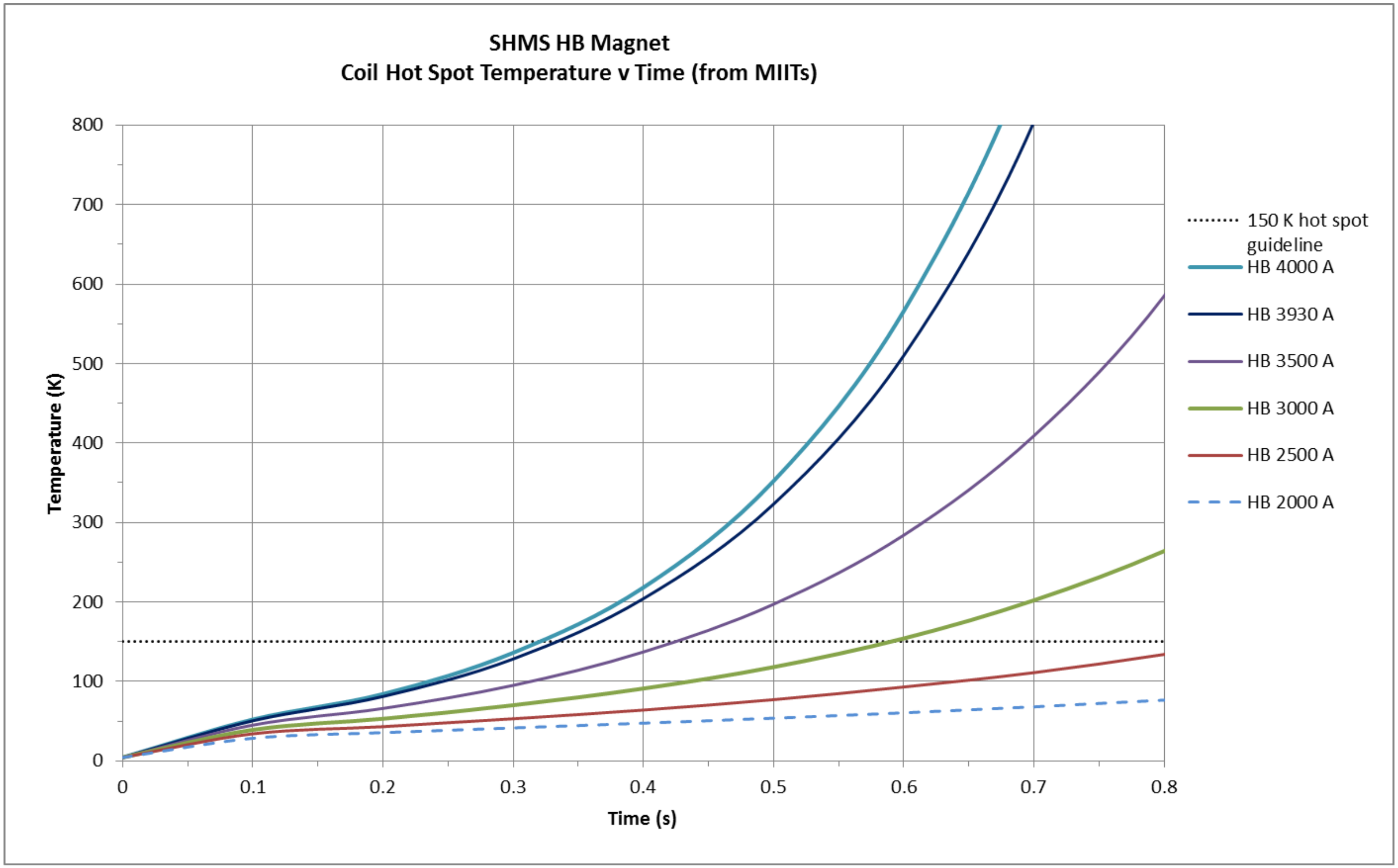


- Operating Current = 4000A
- Peak field in the coil= 3.5 T
- Adiabatic conditions
- Constant Current
- Copper Magneto-resistance is taken into account

Figure 4

MIITS-Calculations-Temp vs Time

Figure 5



Quench Calculations

Assumptions:

- Full operating current = 4000 A
- Iron is not included in the quench model (Comparison of peak field in the coil with and without iron is given in appendix)
- He vessel, thermal shield or OVC not included in the model (it is a coil only model)
- Dump resistor = 15 mΩ (other values of dump resistor are also simulated and some of the results are given in appendix)
- Dump switch fully open by time t = 107 ms (other values of dump switch delay time are also simulated and some of the results are given in appendix)
- Power supply continues to supply full current till the switch opening time
- Quench is initiated in C1 using a heater (heater details are in next slide)
- Quench is initiated from the peak field location
- Coupling losses included in the model
- Run with simple time steps (comparison of simple and adaptive time step given in appendix)

Quench Calculations

Basics of quench calculations:

- VF-Quench module gives the “Peak Temperature” in the coils.
- The coil resistance from quench module is the resistance of the coil at average temperatures.
- Based on the above two the peak temperature plot and resistance plots can not be compared.
- Quench heater size and value might affect the quench results slightly.
- Once the coil quenched completely coupling losses are zero for that coil.
- Once the magnet quenched completely (current is reduced to zero), coupling losses will be zero as well.
- The material properties are given as function of temperature.
- The material properties are different in longitudinal and transverse directions, some of the properties are given in appendix.

Quench Calculations- Coil Model and Circuit

***Figure 6* – Electrical Schematic**

This circuit is different than shown earlier, this circuit is used in VF Quench simulation in order to simulate the time delay. The time delay is the time it takes to detect the quench and switch off the power supply. Switch S1 is closed and S2 is open for the duration of time delay, after time delay S1 is open and S2 is closed, thereby taking the PSU out of the circuit.

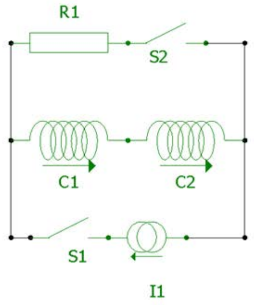
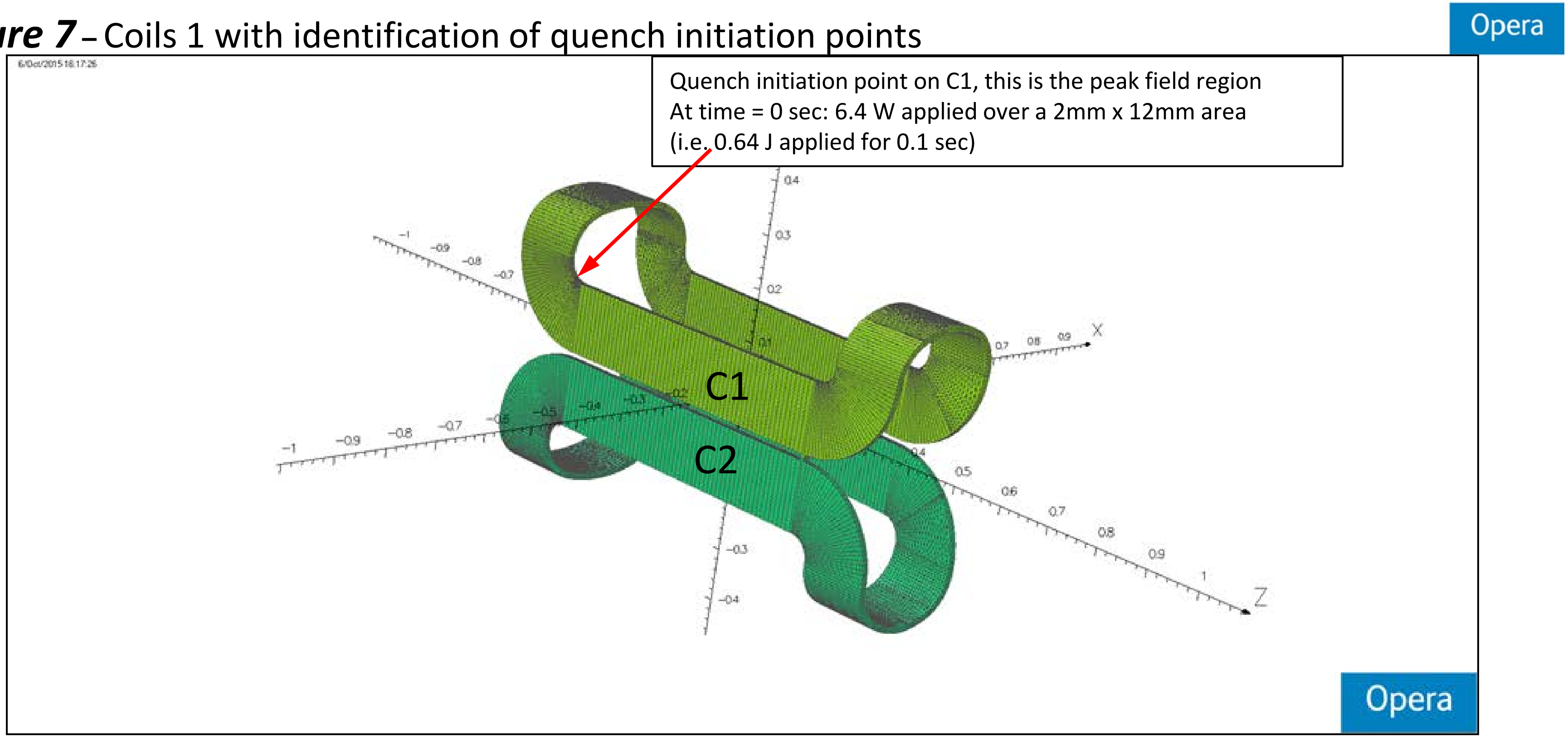


Figure 7 – Coils 1 with identification of quench initiation points



Quench Calculations- **Coupling Losses:**

(as defined by M. N. Wilson and incorporated within the OPERA/QUENCH code)

Ref. 'Coupled transient thermal and electromagnetic finite element analysis for the simulation of quench effects in superconducting magnets', Simkin. J, Taylor. S.C., Xu. E, Michaelides. A.M., Applied Engineering for Magnetic Superconducting and Nanomaterials Workshop, September 6-19, 2007 (included in the pre-brief material)

a) *Coupling loss due to persistent currents **in** the filaments [proportional to $\frac{dB}{dt}$]*

$$P_f = \frac{2}{3\pi} * J_c(B) * d_f * \lambda_{wire} * \frac{dB}{dt}$$

$J_c(B)$ *= critical current density*

d_f *= filament diameter*

λ_{wire} *= fraction of superconductor and copper*

$\frac{dB}{dt}$ *= rate of change of flux density*

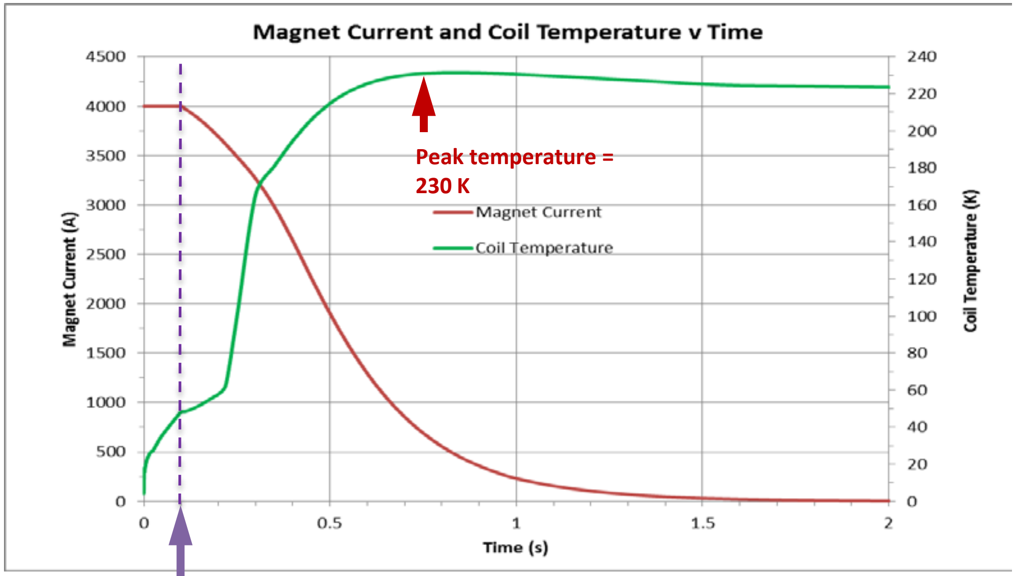
b) *Coupling loss due to currents **between** filaments in the wire [proportional to $(\frac{dB}{dt})^2$]*

$$P_e = \left(\frac{p}{2\pi}\right)^2 * \left(\frac{1}{\rho}\right) * \lambda_{wire} * \left(\frac{dB}{dt}\right)^2$$

p *= twist pitch*

$\left(\frac{1}{\rho}\right)$ *= electrical conductivity*

Quench Calculations- Current Decay and Coil Temperatures



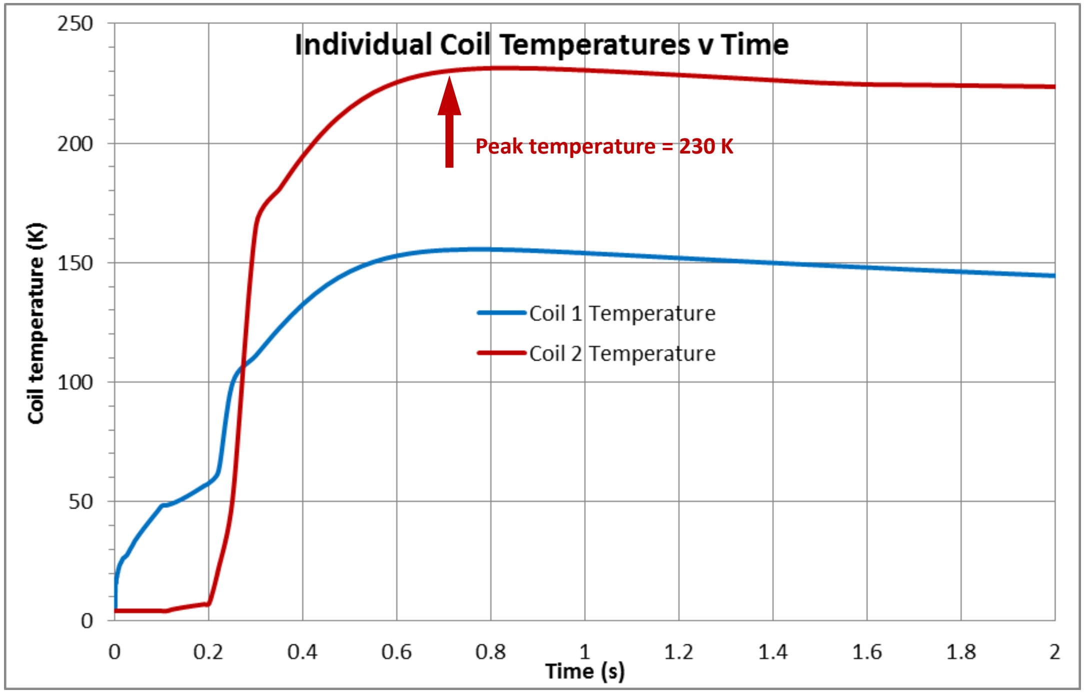
Dump switch opens at
t = 107 ms for this analysis case

Figure 8

The temperature curve shown here is actually a composite curve produced by OPERA by combining the individual temperature curves of Coils 1 and 2 – *refer to Figure 2 below.*

Figure 9

The two coils have different temperature profiles and this is caused by the coupling losses in Coil 2 by the collapsing magnetic field – *refer to the next slide* for *further details*



Quench Calculations-Quench Volume Growth

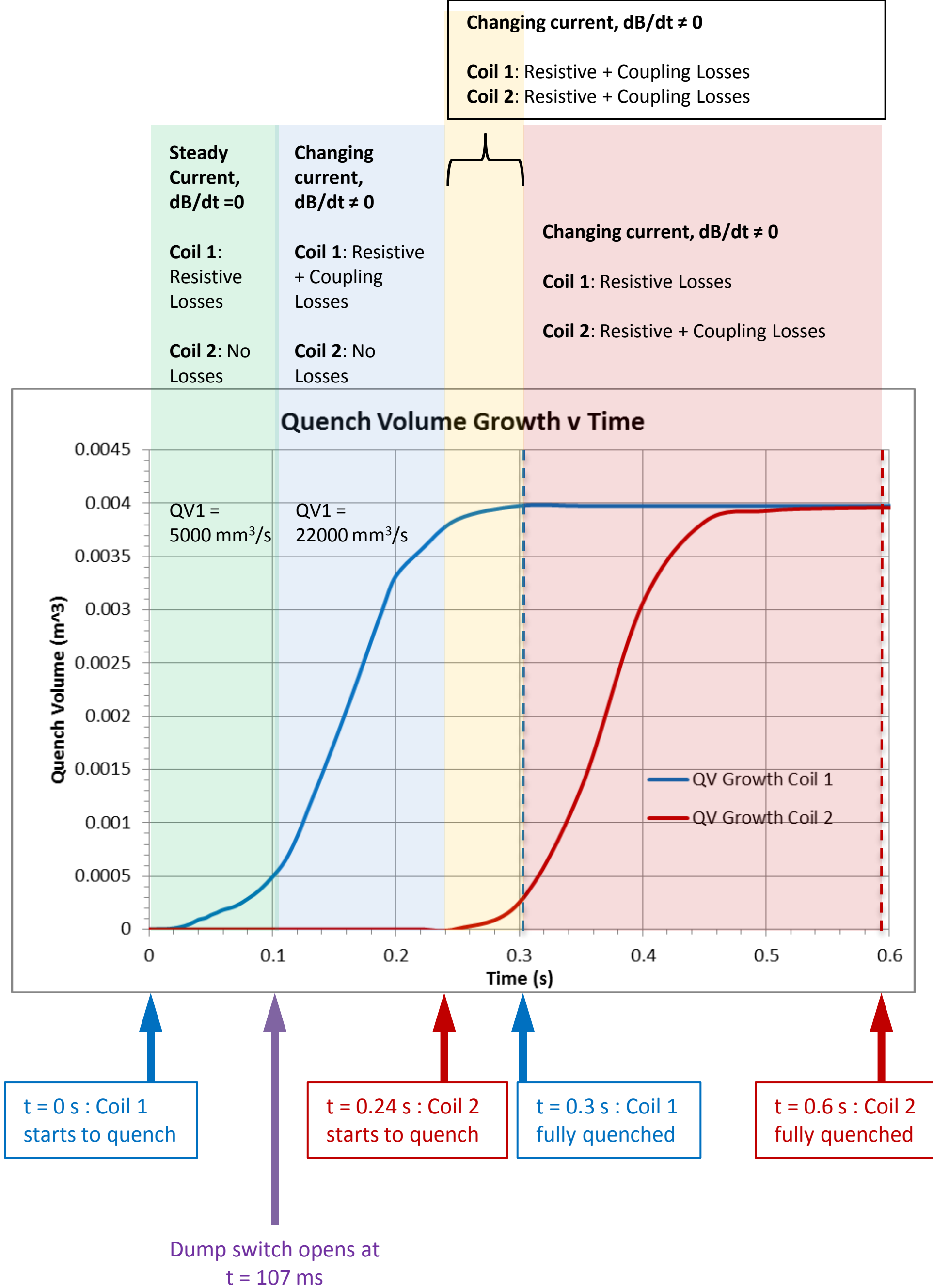
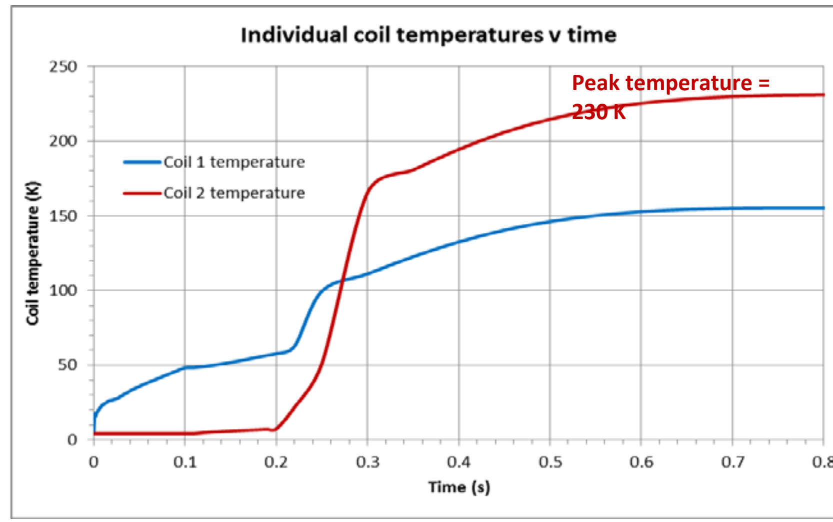


Figure 10

Figure 11 (this is the same as Fig 9)



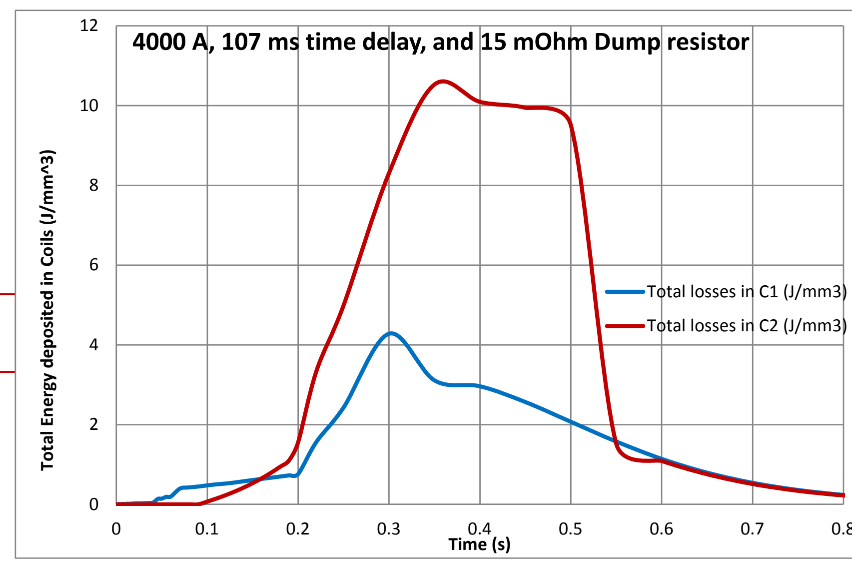
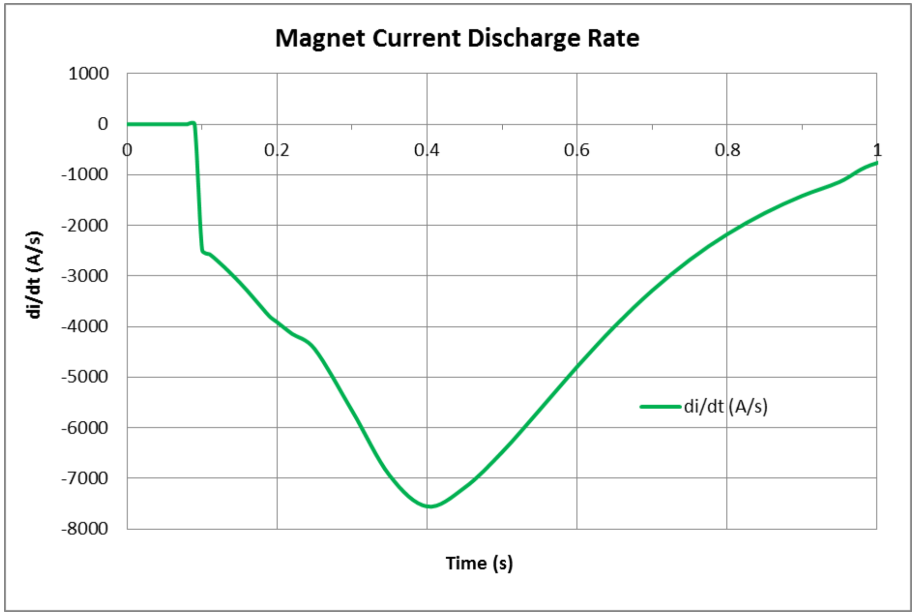


Figure 12

Figure 13



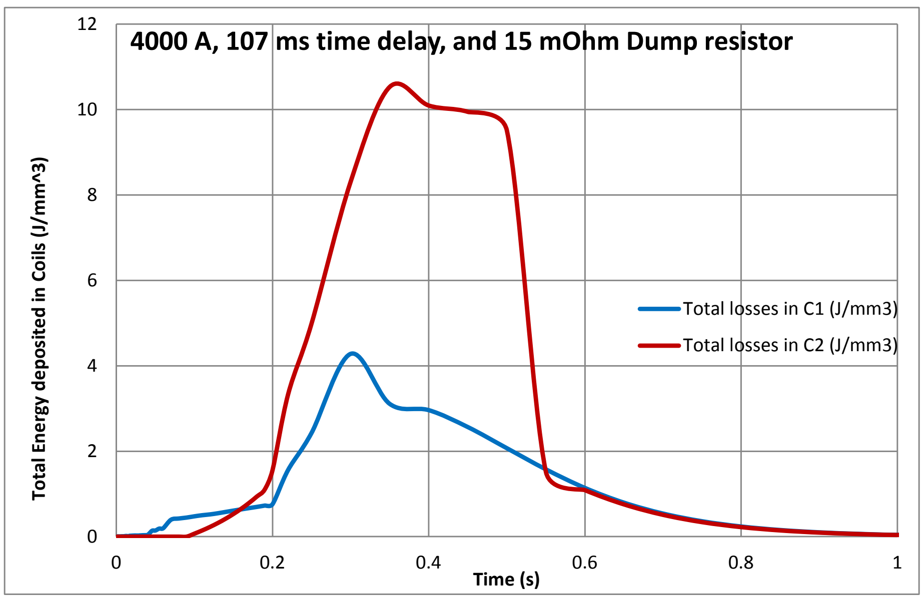


Figure 14 (this is the same as Fig 12)

Quench Calculations- Rate of change of Current and energy deposited

Figures 13 and 14 illustrate the correspondence between the magnet current discharge rate (i.e. di/dt) and the energy deposited within each coil.

Notes:

(i) Coupling losses are proportional to dB/dt and $(dB/dt)^2$ and dB/dt is proportional to di/dt

Quench Calculations- Comparison of MIITs and VF temperatures

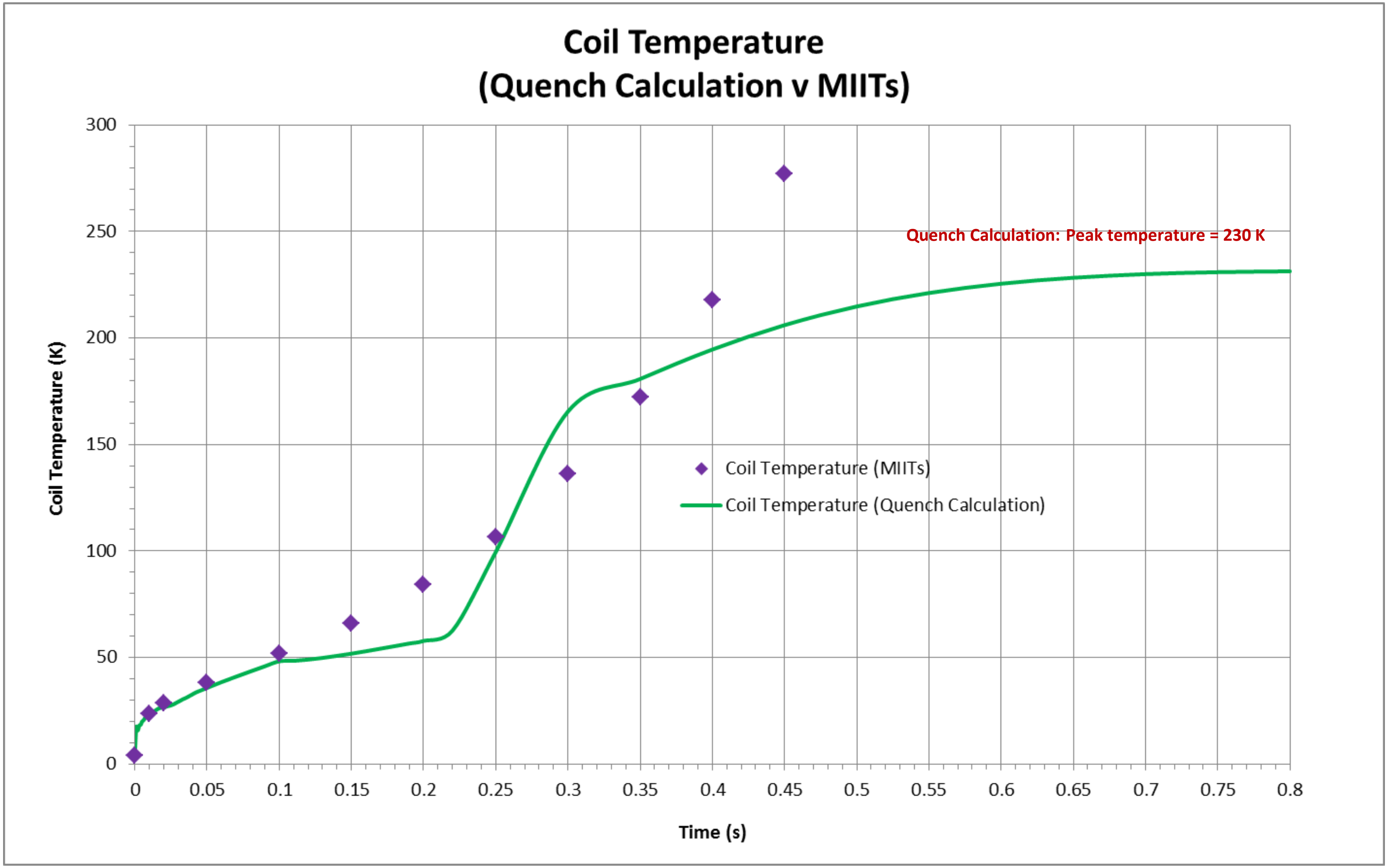


Figure 15

Quench Calculations - Comparison case (760 ms delay)

This is to illustrate that coupling losses do not play a role in temperature rise for this case, because current is still constant till t=760ms and heating is only via resistive normal zone propagation

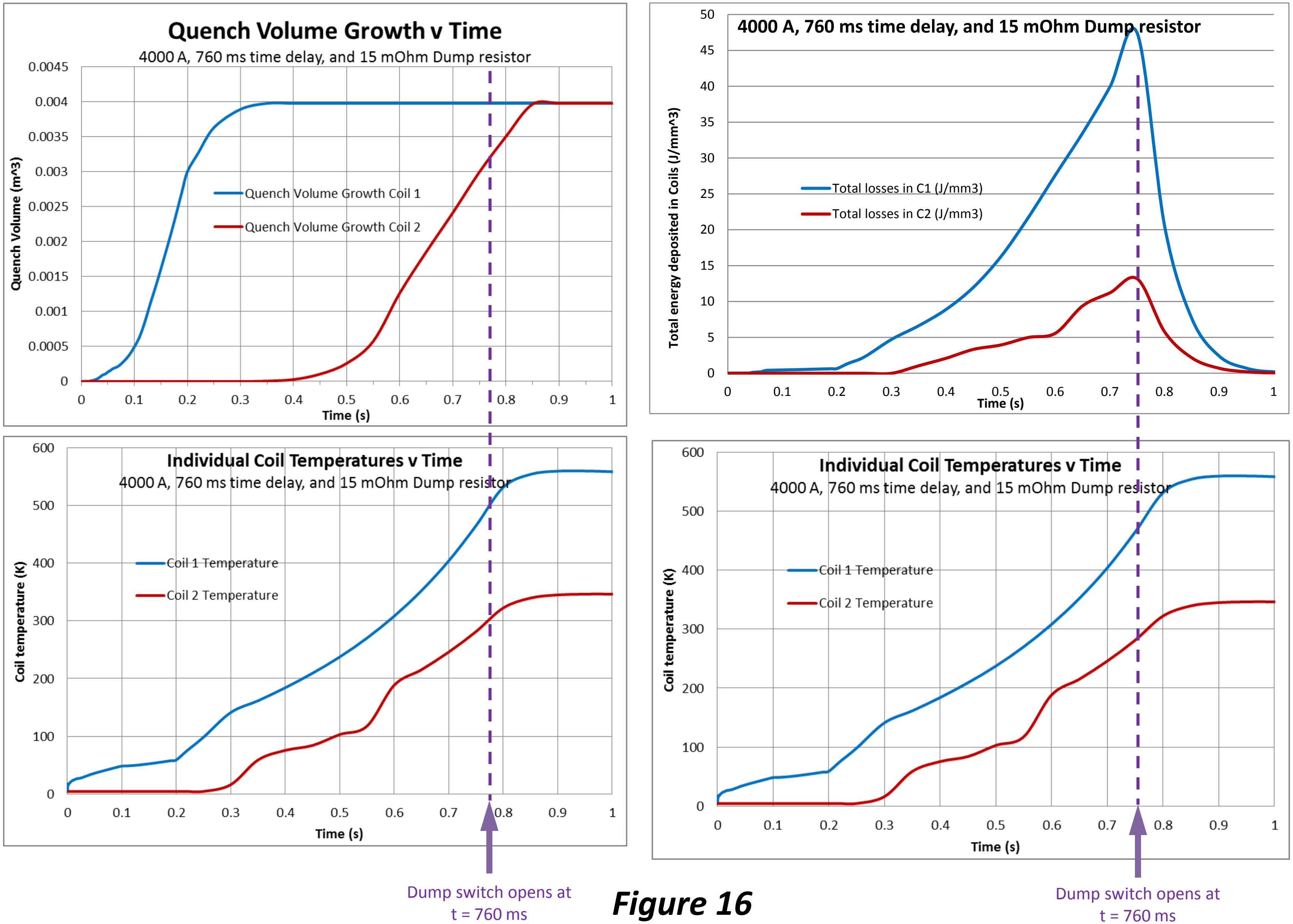


Figure 16

Quench Calculations- Effect of Coupling Losses on Coil Temperatures

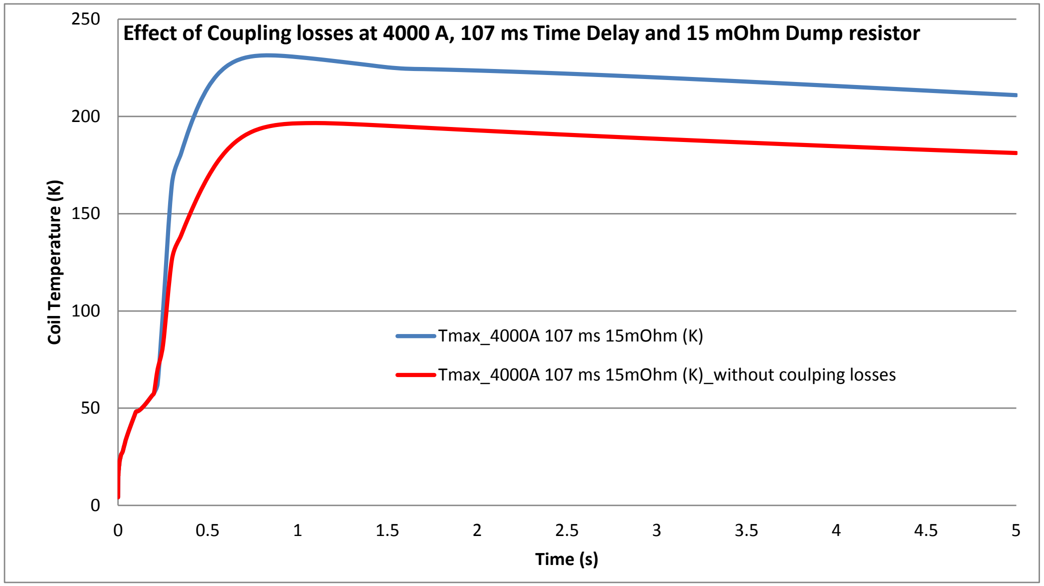
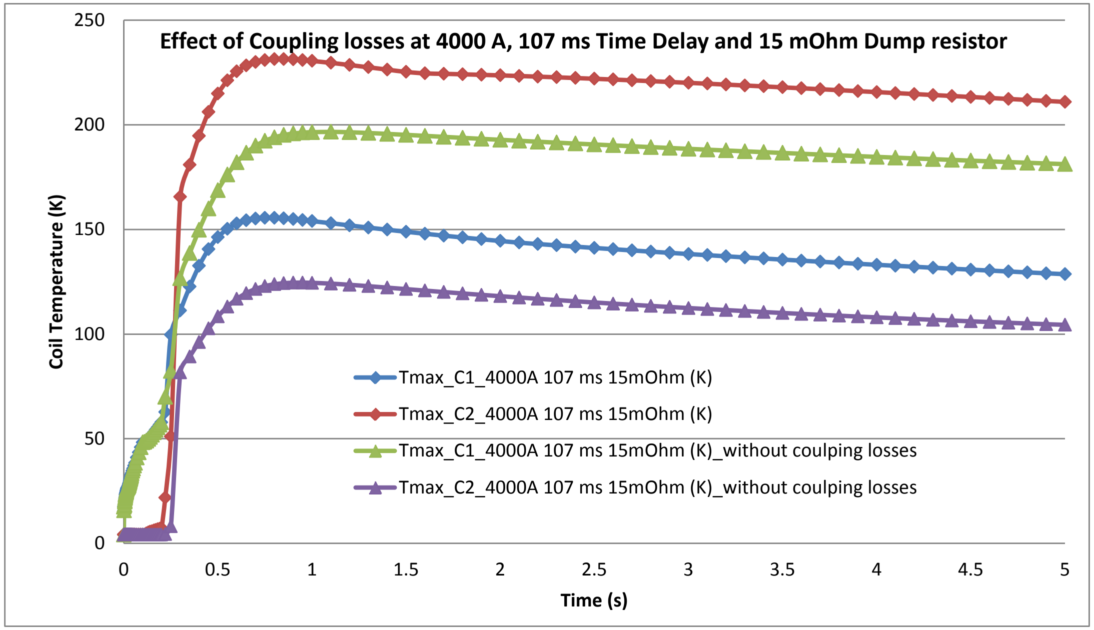


Figure 17

Figure 18



Quench Calculations- Potential Solution to reduce peak coil temperature during a quench

1. Increase the dump resistor value from the proposed 15mOhm to 20mOhm or 30mOhm
   - However, the increased current discharge rate and subsequent eddy currents and forces on the thermal shield will need to reexamined.
2. Reduce the dump switch opening time further, e.g. to 70ms

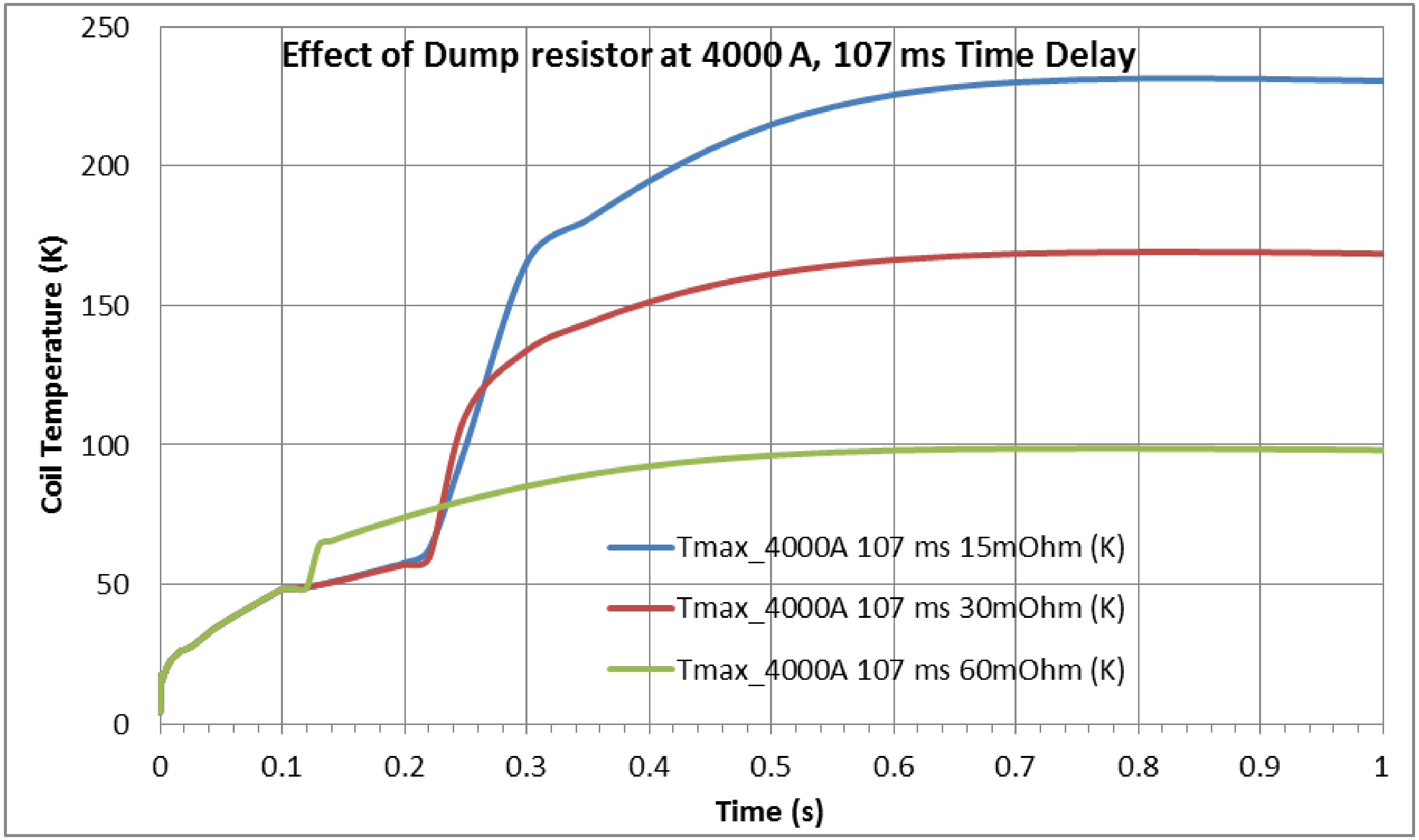


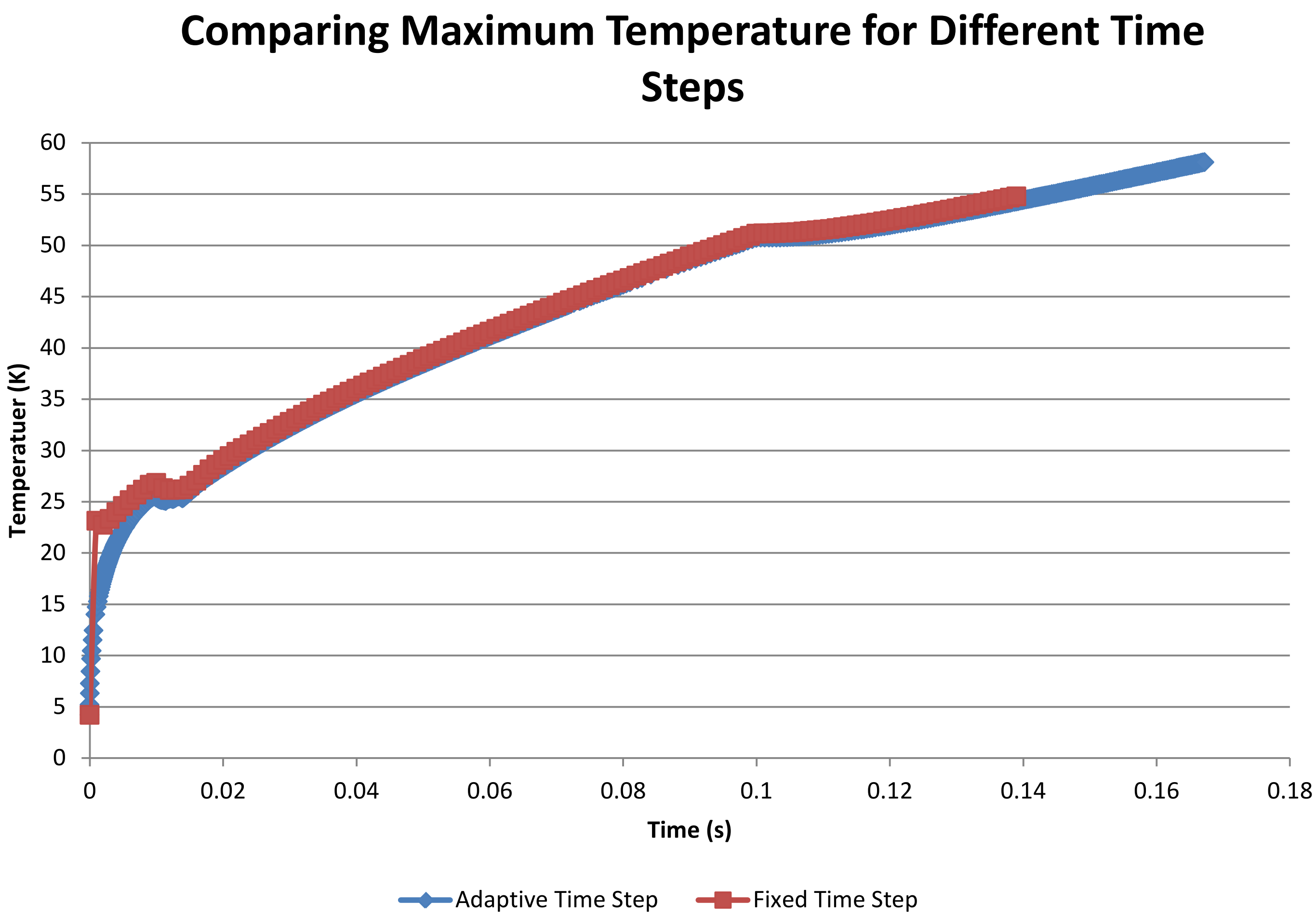
Figure 19

Summary

- Quench calculations done for the HB magnet using VF-Quench module.
- The peak coil temperature depends on the inclusion of coupling losses.
- The peak temperature reduces with increasing dump resistor value in the circuit.
- The initial temperature profile matches well with the MIITs calculations.
- The switch opening time (delay time) affects the peak temperature in the coil significantly.

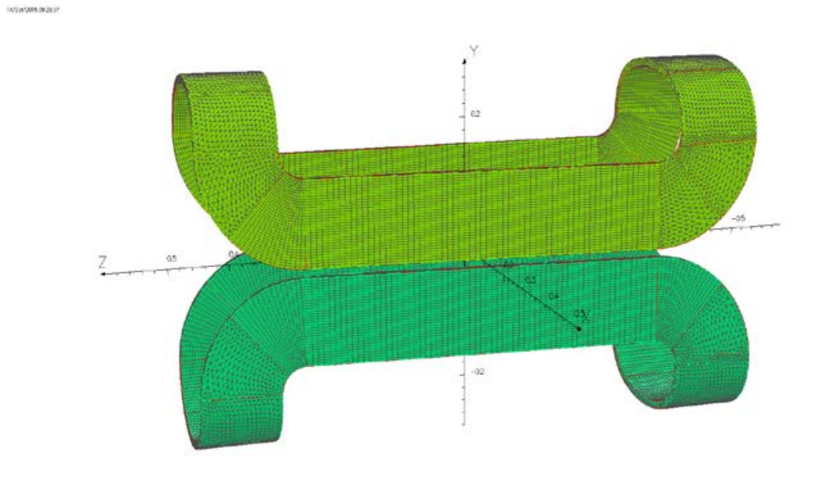
Appendix

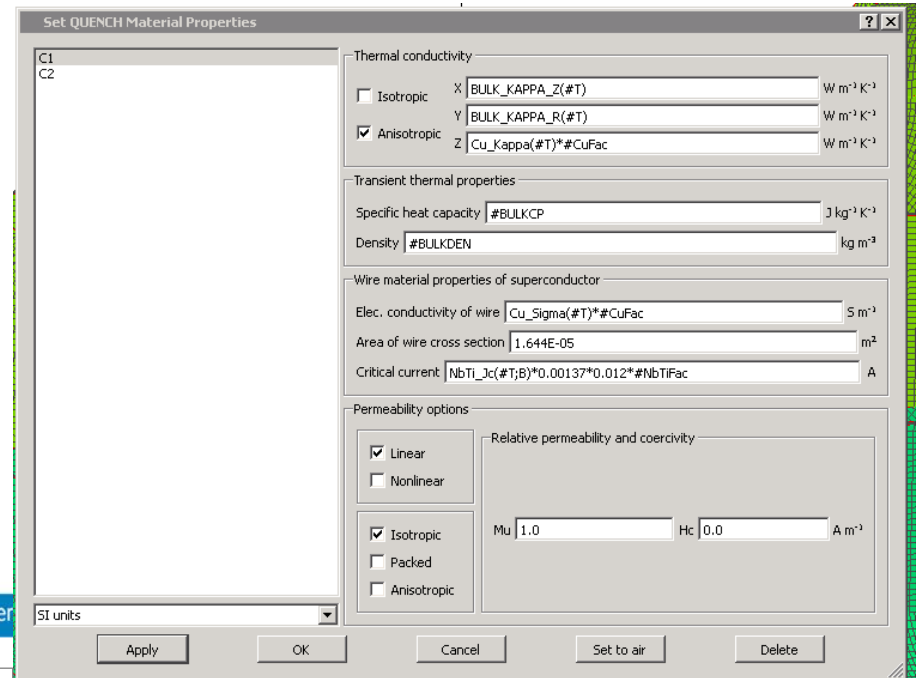
Simple vs Adaptive Time Steps

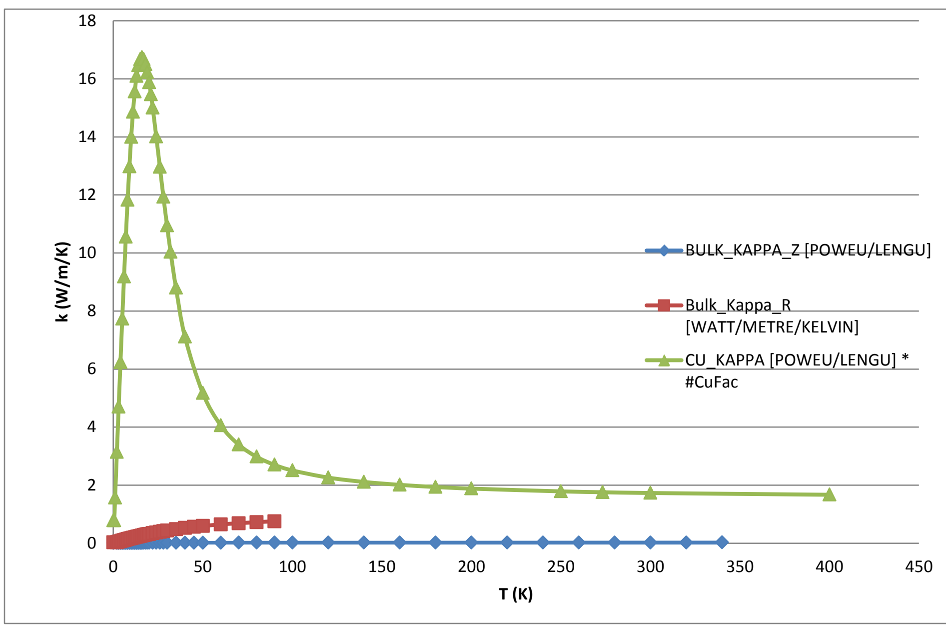


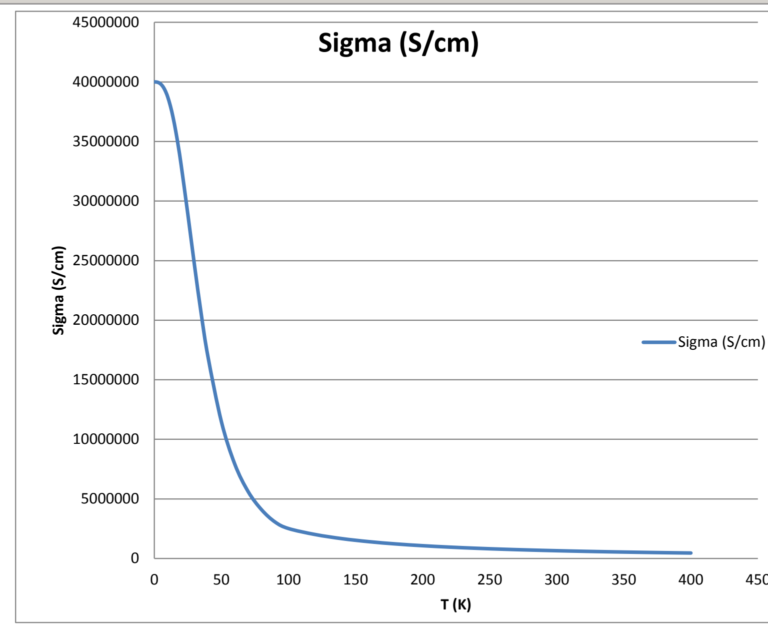
This is from one of the initial analysis at 3930 A, without time delay.
This shows, that the simple time step is adequate for these quench calculations

Material Properties







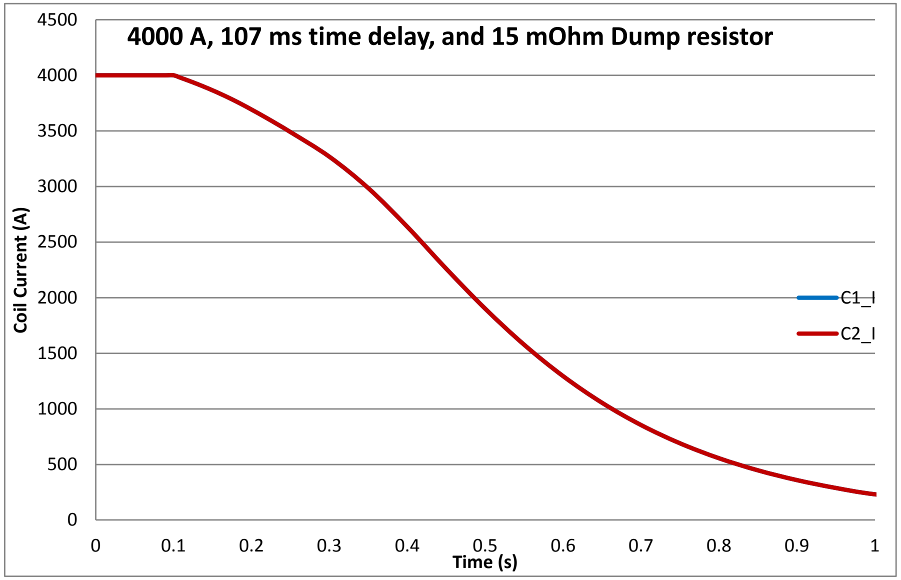


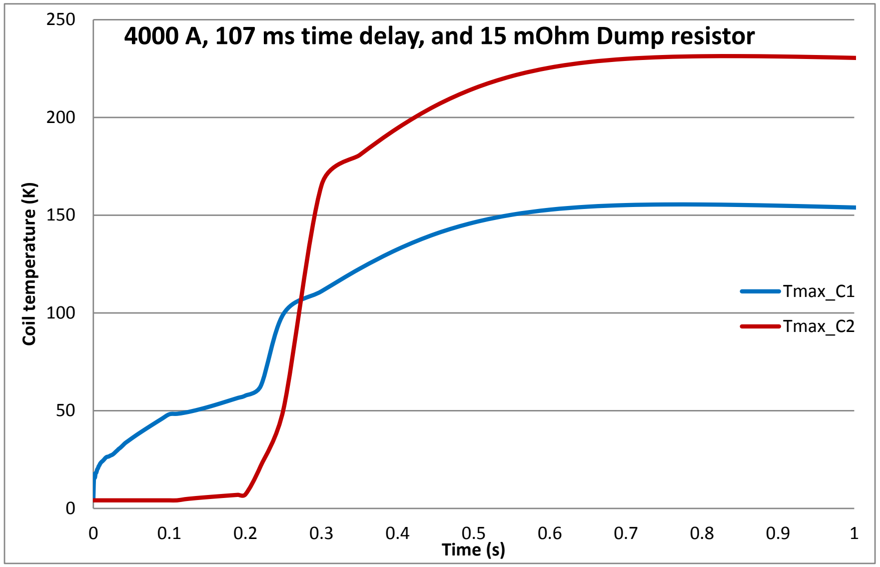
Material Properties-Continued

Thermal conductivity values in the transverse and longitudinal directions shown in the table here are default values from Vector Fields and allows for Cu, SC and insulation.
The resultant transverse to longitudinal ratio is about 0.1 and this corresponds well to that quoted by MSU for pre-preg insulation material (as used in this magnet).

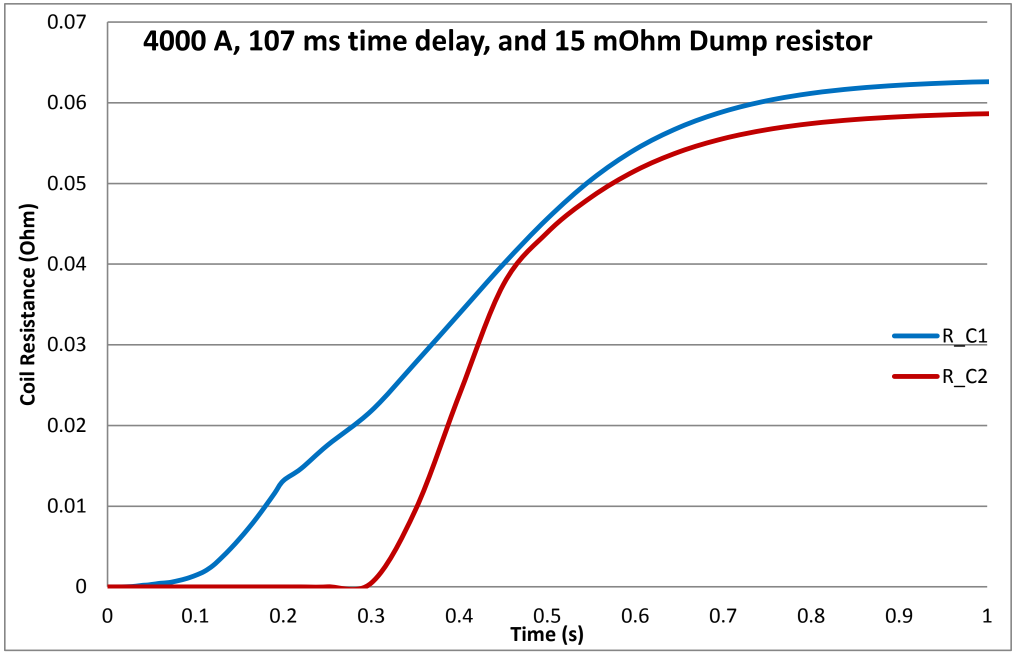
T (K)	ky_Bulk_Kappa_Transverse [WATT/METRE/KELVIN]	CU_KAPPA [POWEU/LENGU]	kz_Bulk_Kappa_Longitudinal [WATT/METRE/KELVIN]	sqrt (ky/kz)
0	0.0352064	1.8262438	0.785284834	0.21173722
2	0.0352064	7.297943106	3.138115536	0.1059196
3	0.0542216	10.92154859	4.696265894	0.10745084
4	0.0728512	14.49664982	6.233559423	0.10810613
5	0.0911	17.98759657	7.734666525	0.10852715
6	0.1089728	21.35095911	9.180912417	0.10894721
7	0.1264744	24.53795721	10.5513216	0.1094833
8	0.1436096	27.49766246	11.82399486	0.11020711
9	0.1603832	30.18075043	12.97772268	0.1111681
10	0.1768	32.5434156	13.99366871	0.11240234
11	0.1928648	34.55095932	14.85691251	0.11393632
12	0.2085824	36.18056045	15.55764099	0.11578891
13	0.2239576	37.42285271	16.09182667	0.11797235
14	0.2389952	38.28213609	16.46131852	0.12049313
15	0.2537	38.77528813	16.6733739	0.12335265
16	0.2680768	38.92964681	16.73974813	0.12654796
17	0.2821304	38.78026302	16.6755131	0.13007246
18	0.2958656	38.36694748	16.49778742	0.13391659
19	0.3092872	37.73147859	16.22453579	0.13806857
20	0.3224	36.91522904	15.87354849	0.14251498
22	0.3477184	34.89350546	15.00420735	0.15223247
24	0.3718592	32.56949628	14.0048834	0.16294818
26	0.3948608	30.1422079	12.9611494	0.17454212
28	0.4167616	27.74546805	11.93055126	0.18690185
30	0.4376	25.46080188	10.94814481	0.19992559
35	0.4853	20.46670735	8.800684161	0.2348264
40	0.5272	16.54408998	7.113958691	0.27222752
50	0.596	12.02597835	5.171170691	0.33949133
60	0.6488	9.445416208	4.061528969	0.39967837
70	0.6904	7.902458232	3.39805704	0.4507493
80	0.7256	6.929744819	2.979790272	0.49346436
90	0.7592	6.284353103	2.702271834	0.53004603

4000A 107 ms Time Delay and 15 mOhm Dump Resistor Results

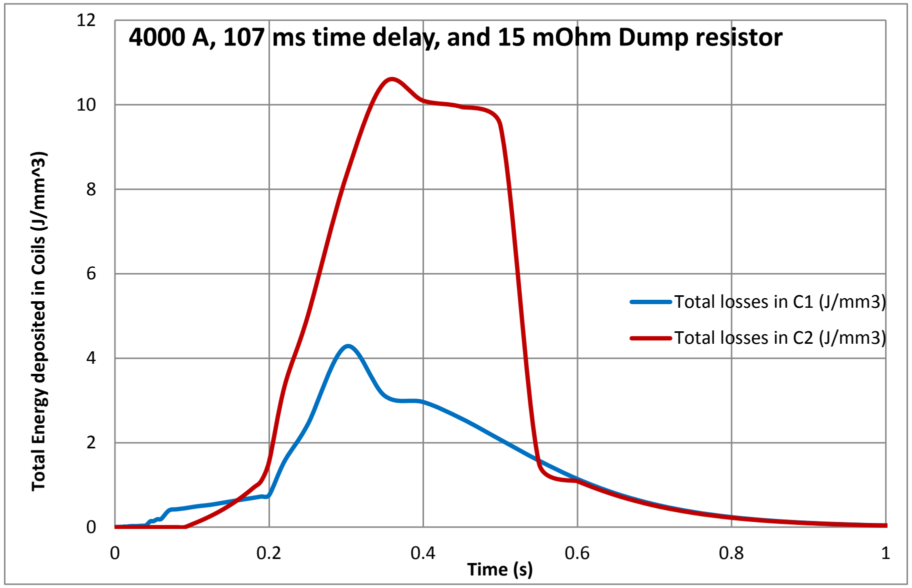


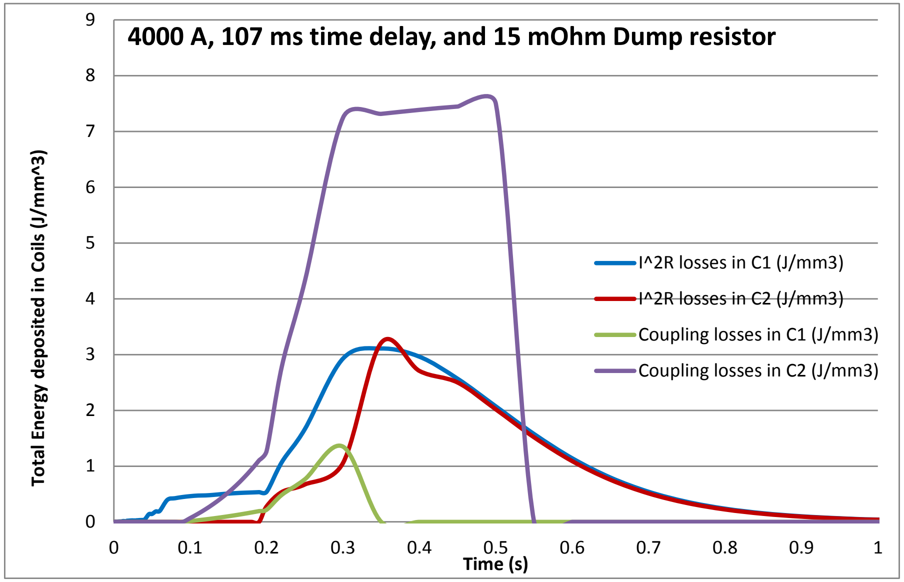


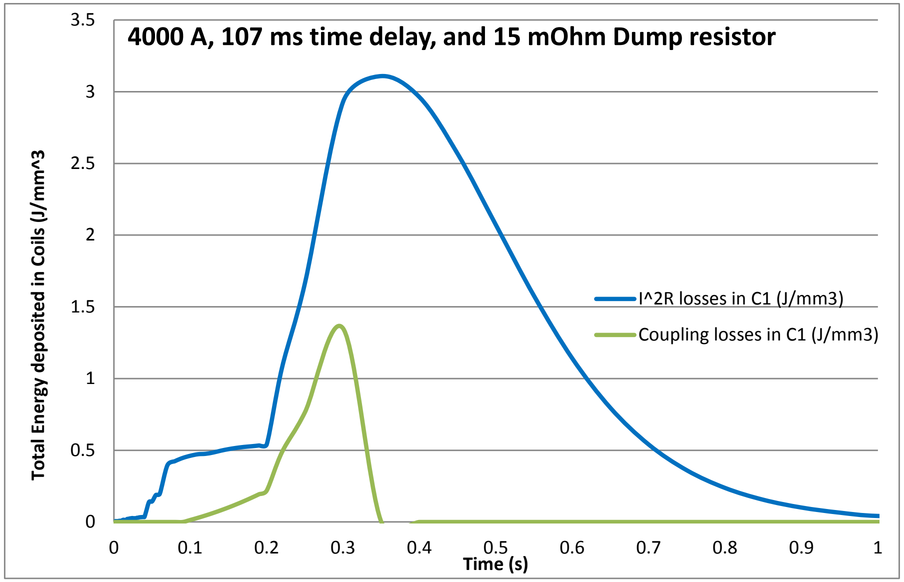
This is the average coil resistance and is reproduced here just for illustrative purposes. This average coil resistance does not correspond to the peak temperature point in the coil, as there will be temperature gradient across the coil.

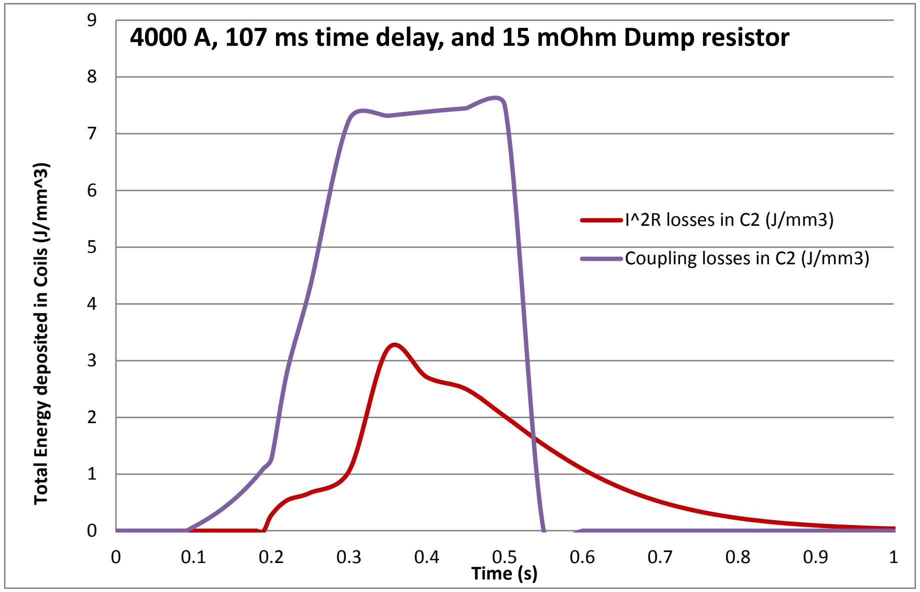


Separation of Resistive and coupling losses









Effect of Coupling Losses on Current Decay