PANDA solenoid quench calculations

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OUTLINE

Main parameters

Uniform energy dissipation in the solenoid

Powering circuit

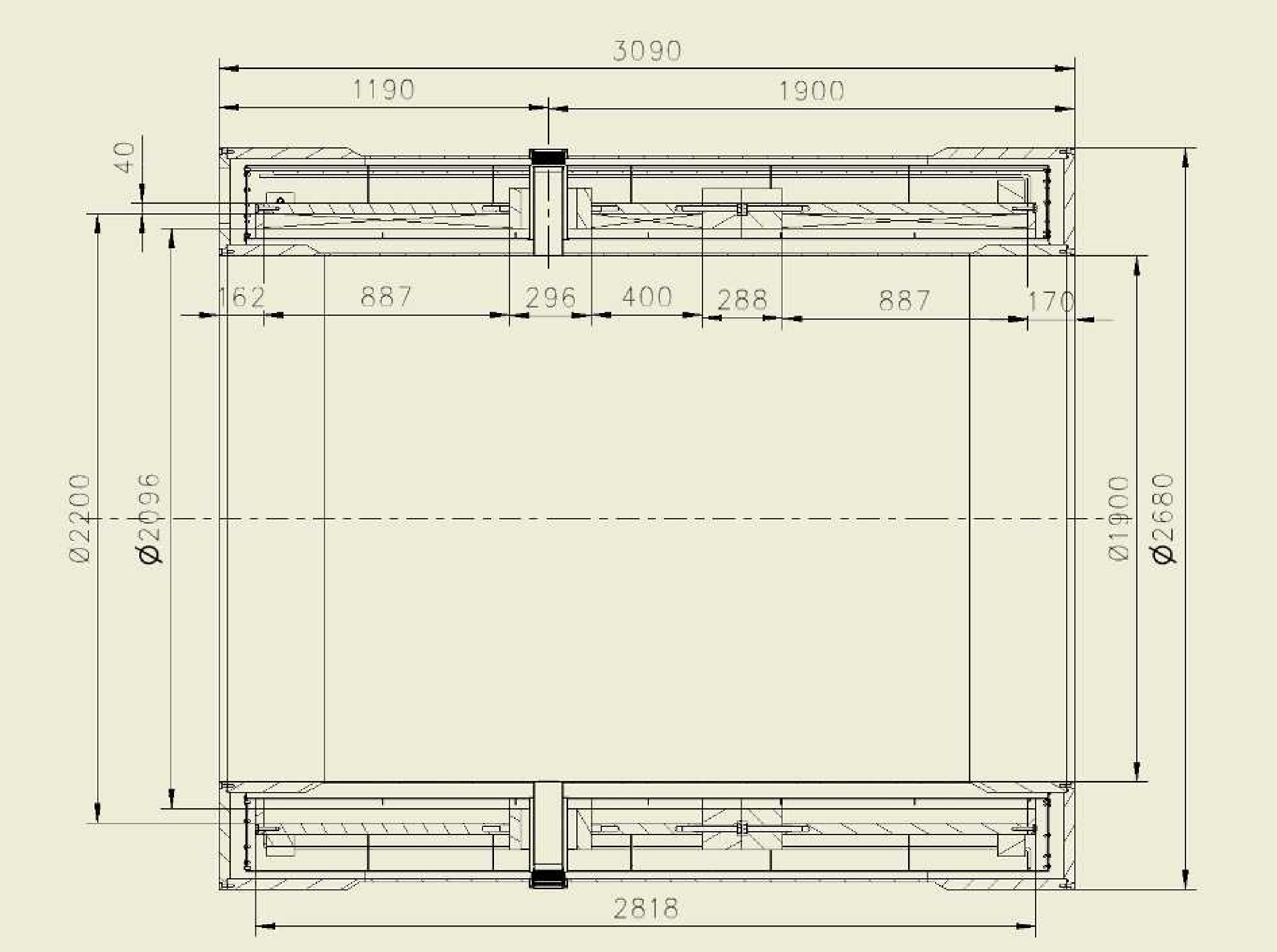
Calculations based normal zone propagation and common equations

Main parameters

Solenoid parameters	Values
Inner radius of the winding, mm	1048
Outer radius of the winding, mm:	1140
Total length of the solenoid, mm	2828
Number of turns in the solenoid (12*78 + 6*35)	1146
Number of layers	6
Length of one turn, m	6.75
Operating current Io, A	4960
Test current, Io*1.05, A	5208
Magnetic field on the coil Bmax, T	2.95
Io/Ic ratio along the load line, %	30
Operating temperature, K	4.5
Temperature of current sharing, K	6.7
Stored energy of the magnet, MJ	21
Cold mass, kg	5283
Cold mass of the SC cable without insulation, kg	2251
Inductance of the magnet at full current, H	1.68
E/M ratio for cold mass, kJ/kg	4.0
E/M ratio for SC cable mass, kJ/kg	9.3

quench parameters

Design of the solenoid



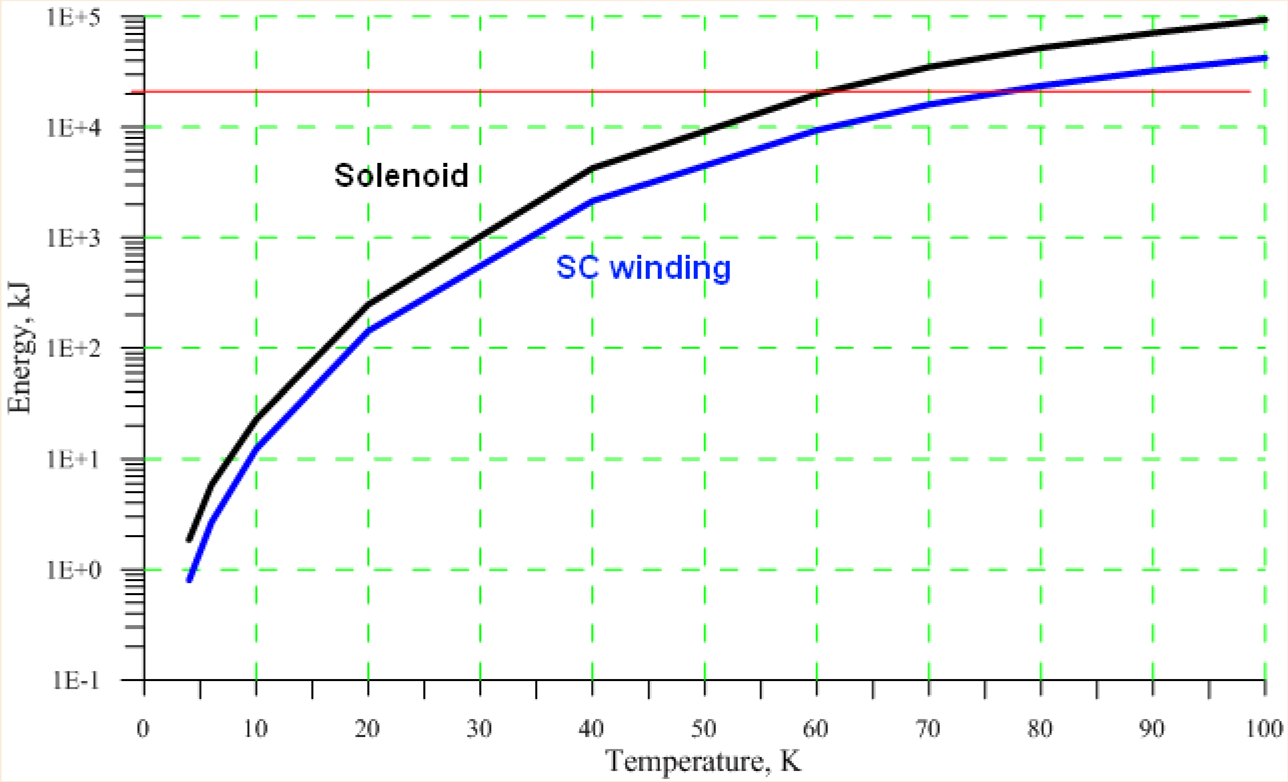
Uniform energy dissipation

Material and parameters	Mass, kg	Volume, m^3
Aluminum structure, 5083	2835	1.052
Epoxy and insulation	116	0.097
High purity strips of Al, ~99.999% the 50% of the area is covered	81	0.030
SC cable		
Al stabilizer	*1541*	*0.570*
Cu stabilizer	*424*	*0.048*
NbTi contuctor	*286*	*0.048*
Sub-total SC cable	2251	0.666
Total solenoid	**5283**	**1.845**

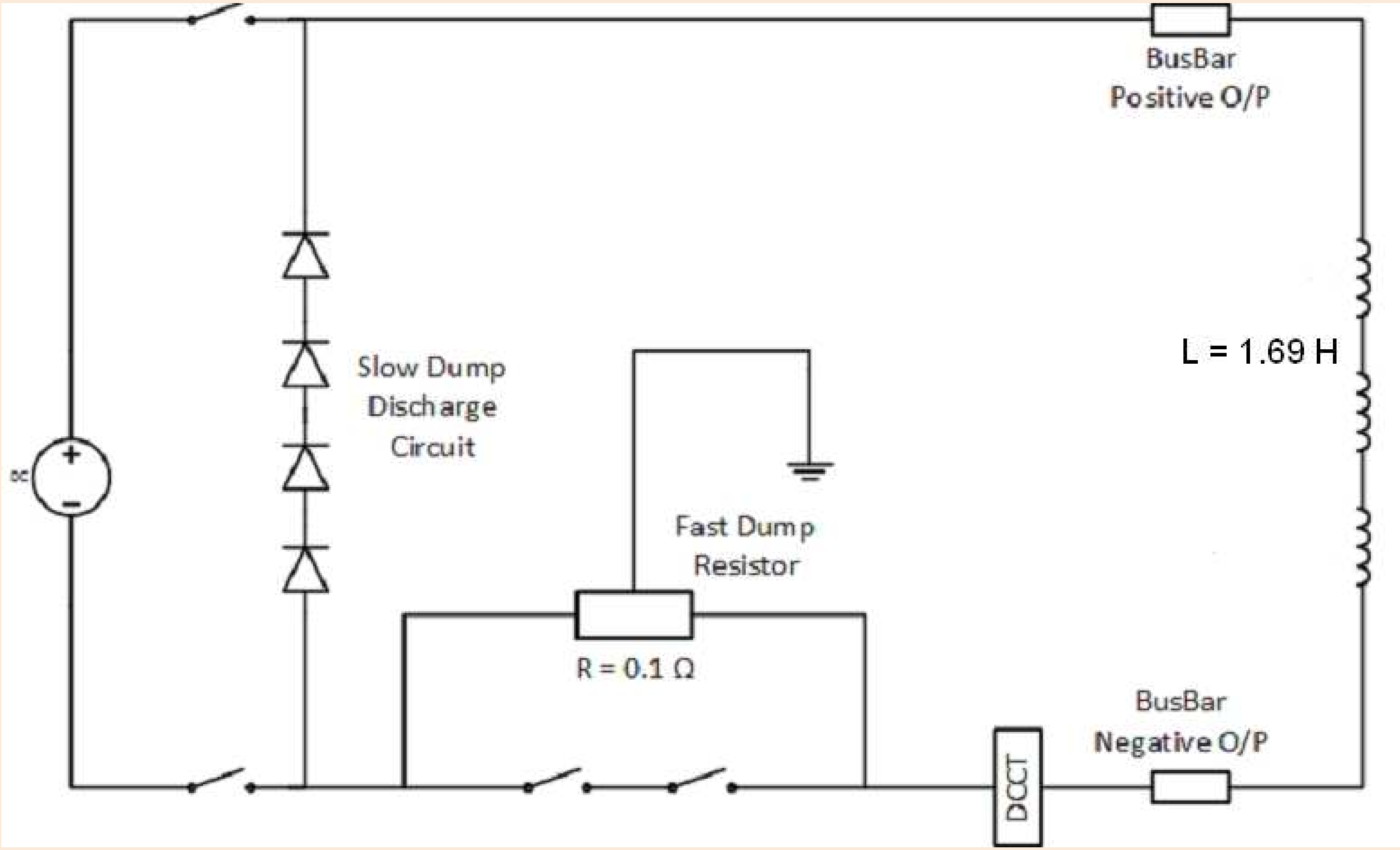
Average temperature at short circuited quench in the solenoid:

60 K - solenoid

76 K – SC winding



- ***Powering circuit***



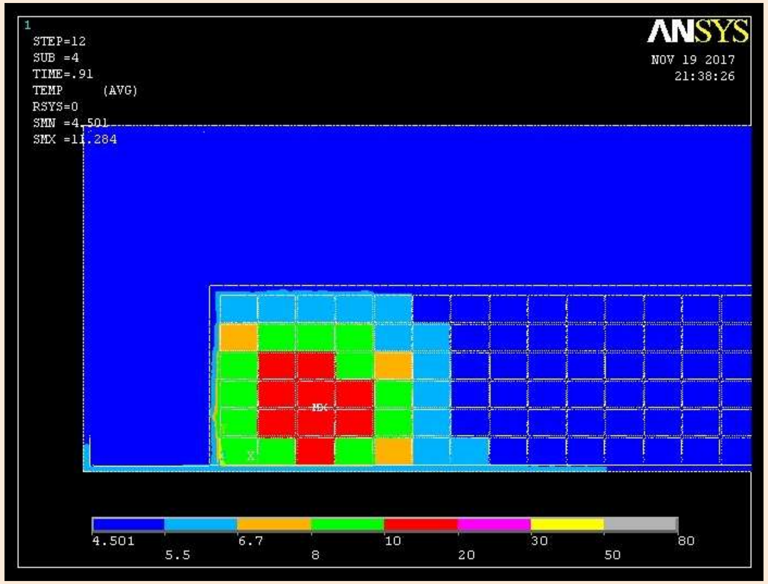
the discrimination time is ~ 1 s, at Al matrix RRR=328

the threshold voltage is ~ 5 V

Quench calculations

- 2D ANSYS calculations of the normal zone propagation
- Matlab quench code with input parameters from ANSYS calculations
- Influence of RRR on the quench parameters

Normal zone propagation



The ANSYS 2D calculation of the transversal velocity of the normal zone.

RRR ~350 in the SC cable

Heat generation 2.7*10^5 W/m^3

The velocities of the nz propagation are:

- 6.9 m/s along the cable;

- 0.079 ... 0.18 ... m/s;

The Al strips of high purity accelerate the normal zone spreading.

The hot spot in the SC cable joints

The SC cable joints will be on the outer parts of the solenoid where the magnetic field is minimal.

The heat generation in such joint will be more than 2 times less taking into account the dependence of the aluminum RRR on the magnetic field.

The higher RRR the higher relative RRR decrease in the 2 T magnetic field.

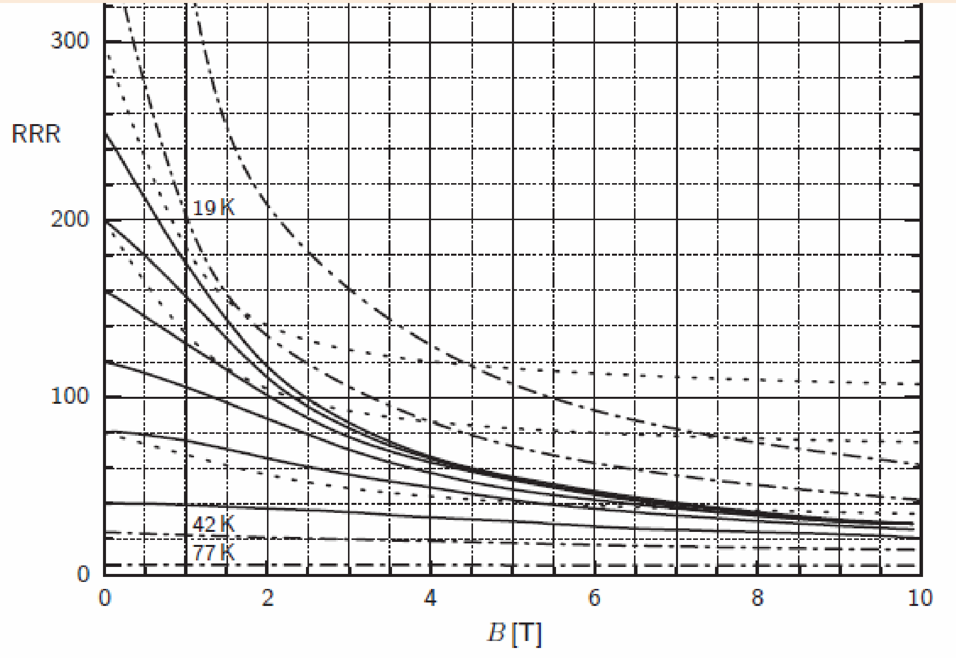
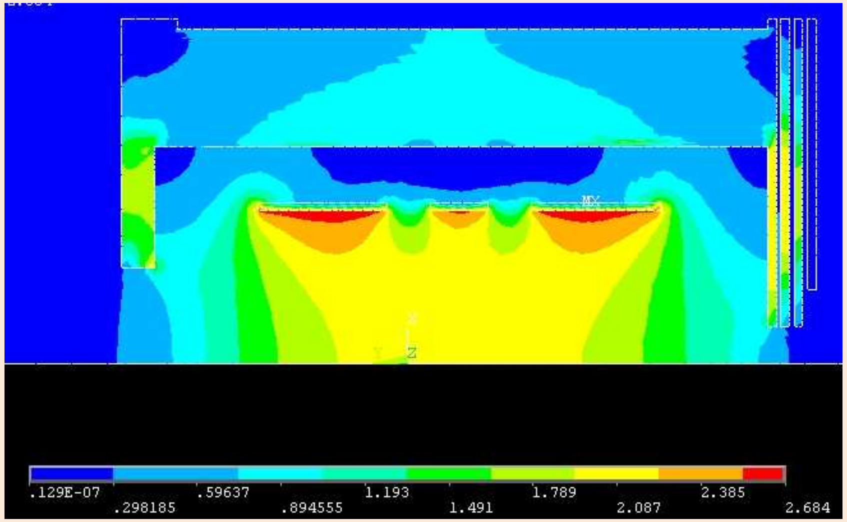


Fig. A4.2 RRR vs. magnetic field plots: copper (solid) and aluminum (dotted), both at 4.2 K, and silver (dash-dotted, with temperatures indicated—RRR = 735 at 0 T). At 77 K, field-dependence of RRR for copper is similar to that of silver.



MatLab calculations

The solved equations are:

For the aluminum of the cable RRR = 328

Al support cylinder has 3 mOhm*cm of resistivity. Its characteristic time is ~ 1 s.

Damp resistor Rd = 0.1 Ohm.

Beginning temperature of the solenoid is 10 K.

The solenoid will be completely normal after ~ 2 s of quench beginning.

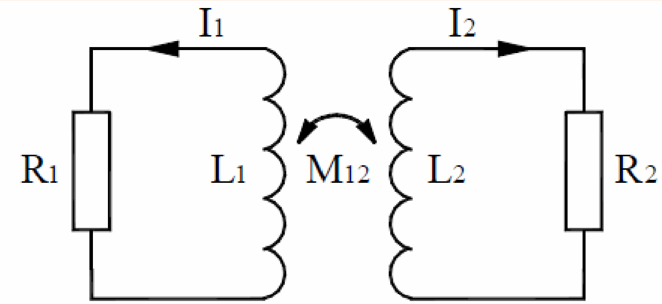
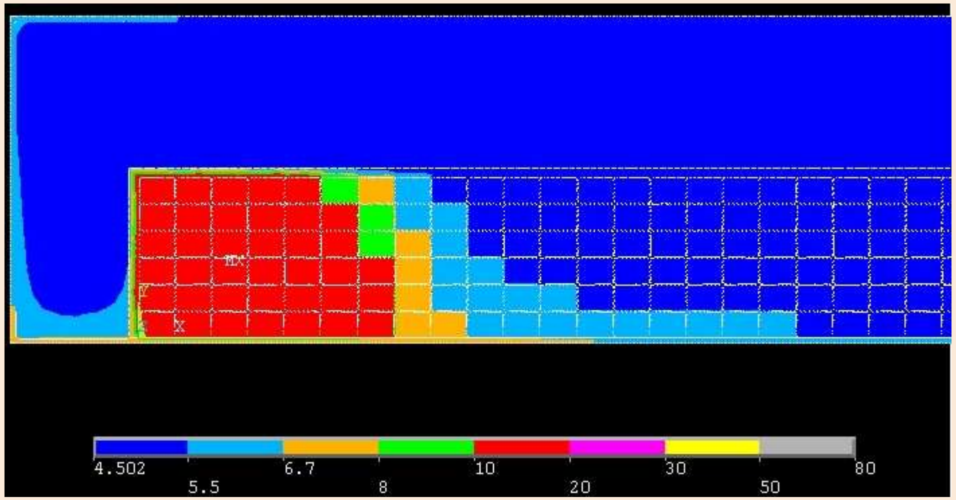


Fig.. Scheme of the coupled circuits.

The equations to be solved are:

$$I_1R_1 + L_1\frac{dI_1}{dt} + M\frac{dI_2}{dt} = 0\,;\; I_2R_2 + L_2\frac{dI_2}{dt} + M\frac{dI_1}{dt} = 0\,.$$

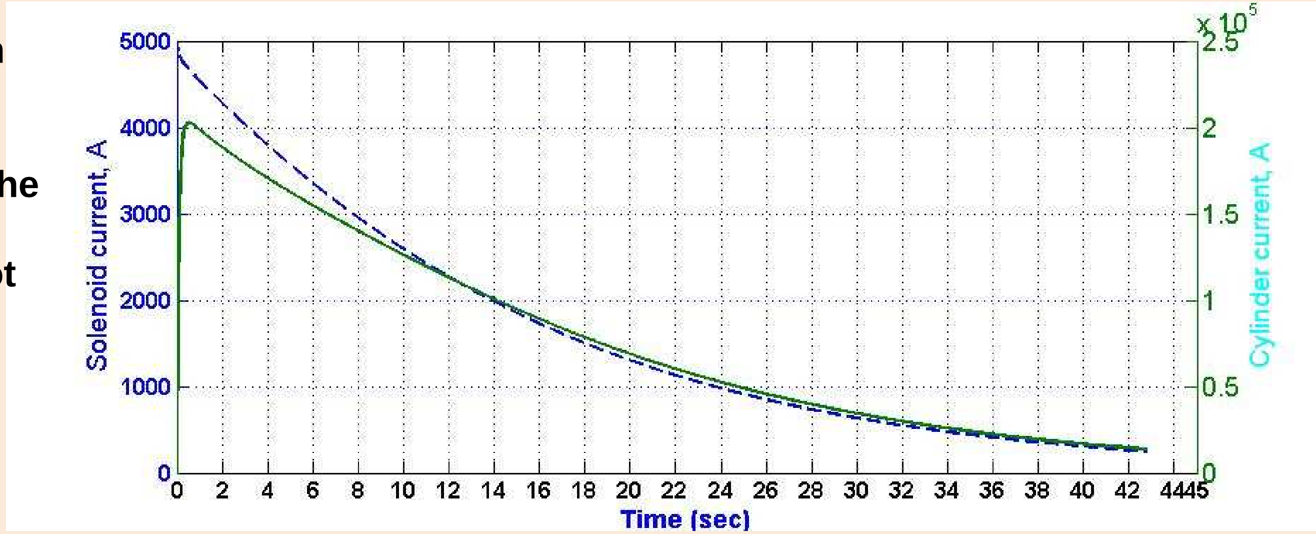


While the SC winding temperature is <20-25 K the Al resistance is constant and the current decay is negligible.

Quench calculations results 1

The quench at Rd = 0.1 Ohm

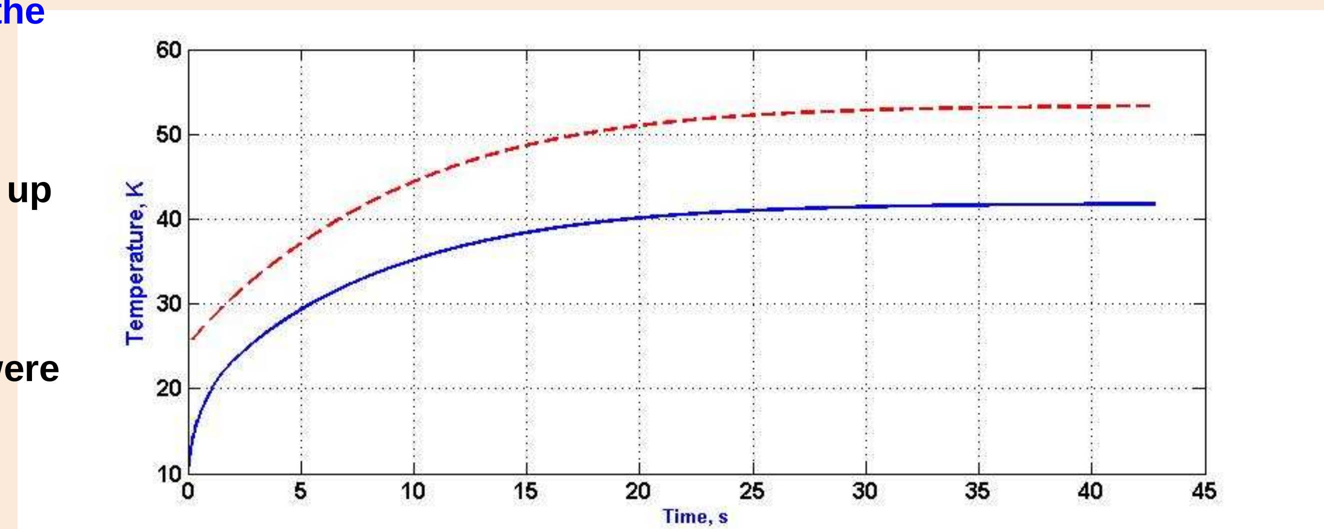
The Rd was activated after the hot spot reached 25 K, this shows the increasing the hot spot temperature during the current decay.



The support cylinders were accounted that is shown on the top Figure.

The induced current in the cylinder is only ~ $2*10^5$ A with respect to the whole current in the solenoid ~ $5.7*10^6$ A.

The bottom figure shows the hot spot temperature and the solenoid temperature.



The resistive voltage rises up to 50 V.

The quench calculations were stopped at 250 A of the solenoid current.

Quench calculations results 2

The quench at Rd = 0 Ohm

The uniform quench of the solenoid when the hot spot reached 25 K, this shows the increasing the hot spot temperature during the current decay.

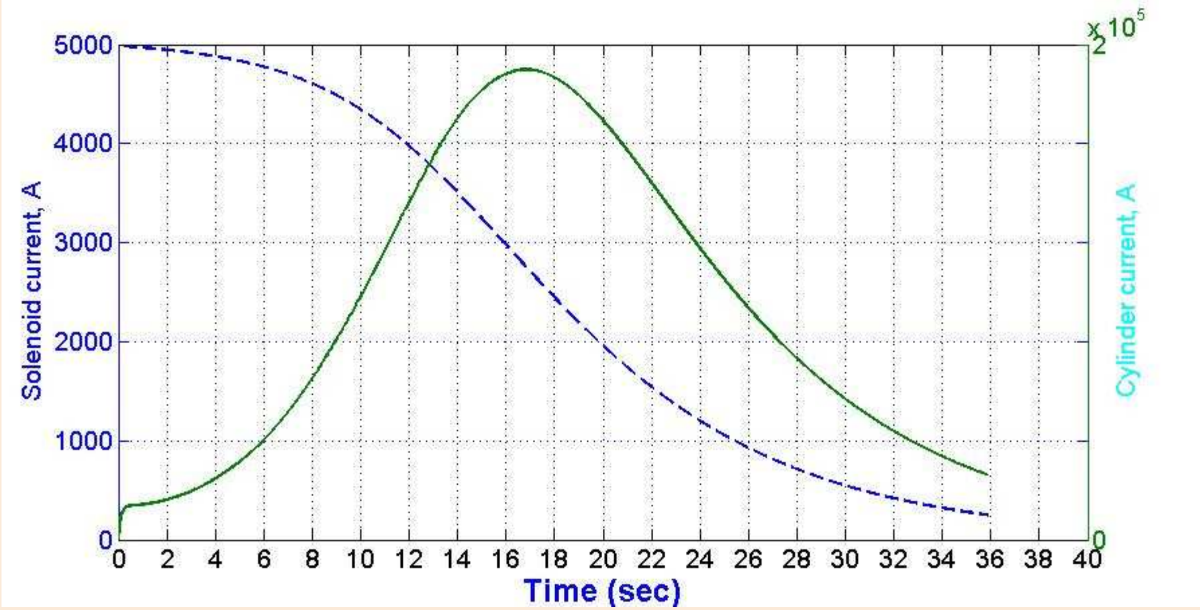
The support cylinders were accounted in the calculations that is shown on the top Figure with green line.

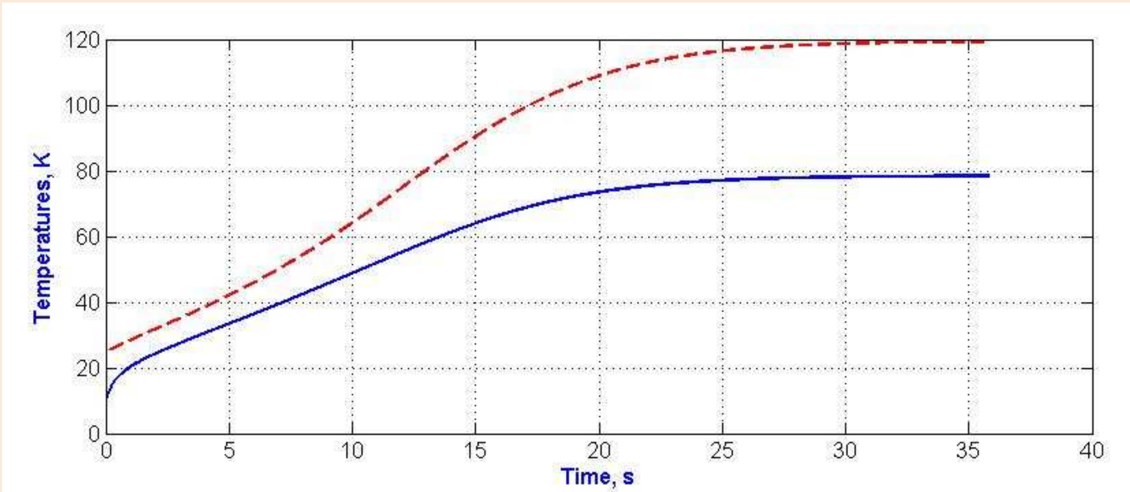
The bottom figure shows the hot spot temperature and the solenoid temperature.

The solenoid temperature is 79 K.

The hot spot temperature is 120 K.

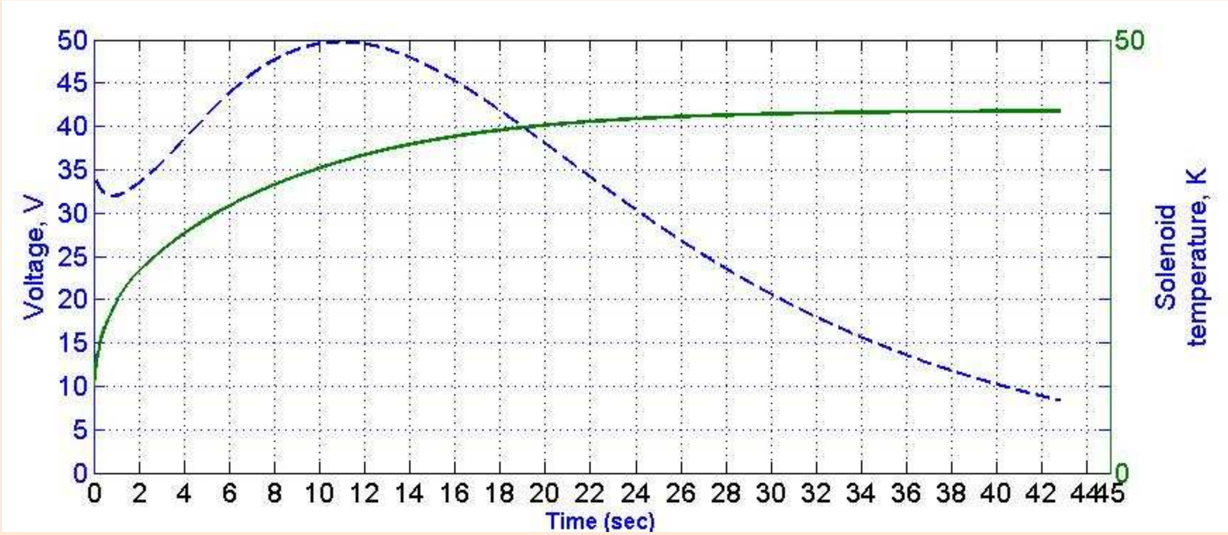
The resistive voltage rises up to 470 V.



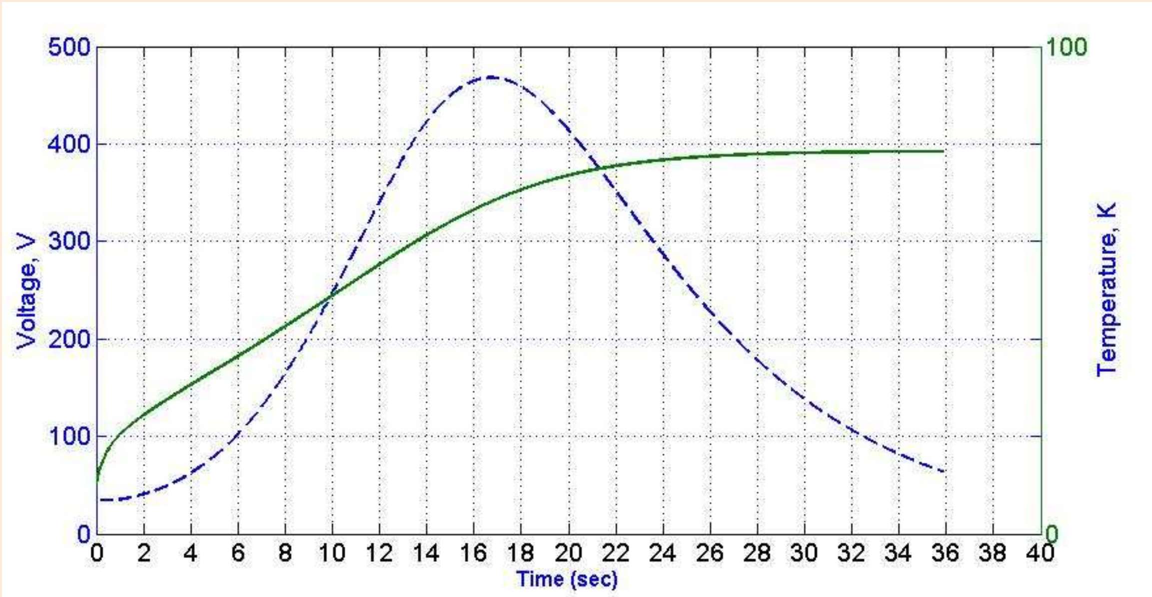


Quench calculations results 1 & 2
resistive voltage

The quench at Rd = 0.1 Ohm



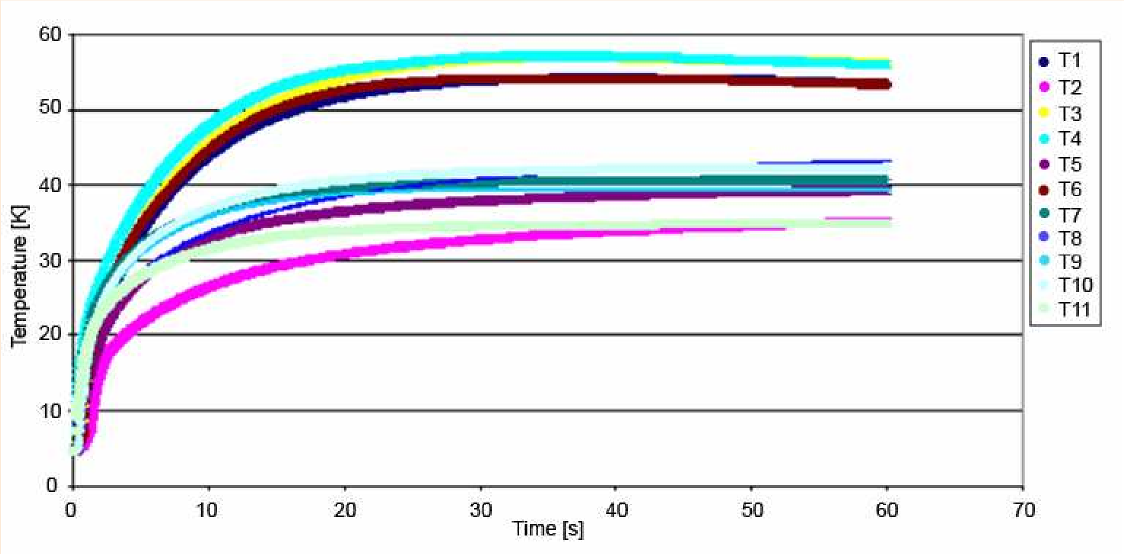
The quench at Rd = 0 Ohm



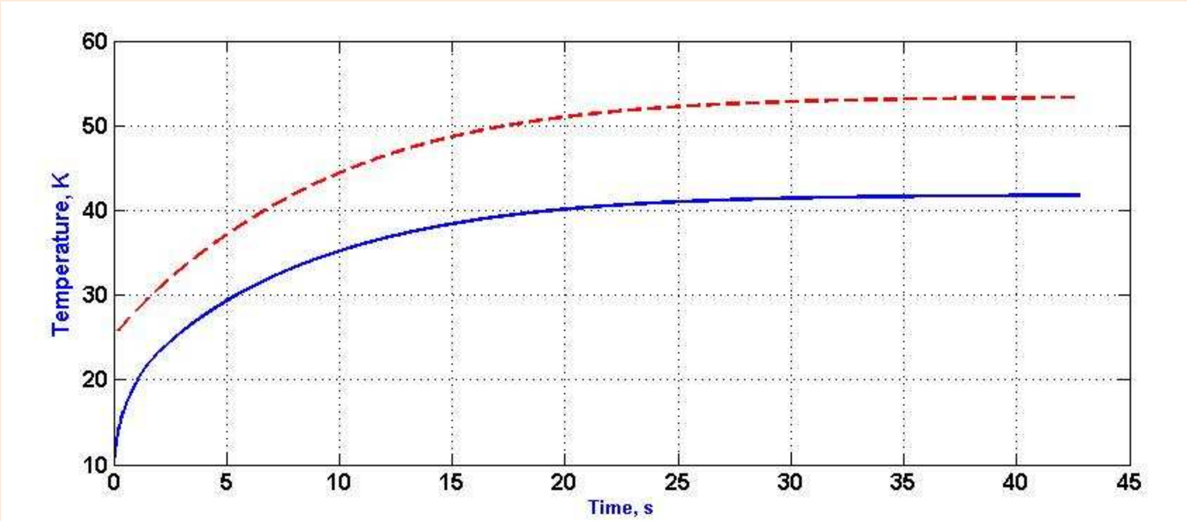
Comparison the quench calculations results with previous calculations

Nikkie Deelen report,

the solenoid and hot spot temperatures

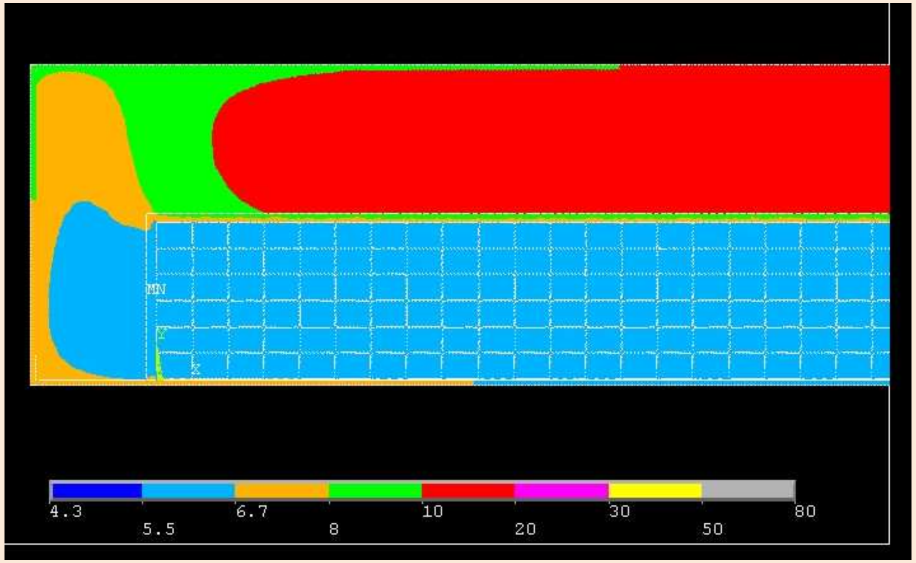


These calculations: hot spot and the solenoid temperatures



Comparison the quench calculations results with previous calculations – quenchback effect

Gabliella Rolando report: the quenchbcak takes 1.5 s to make the whole solenoid normal.

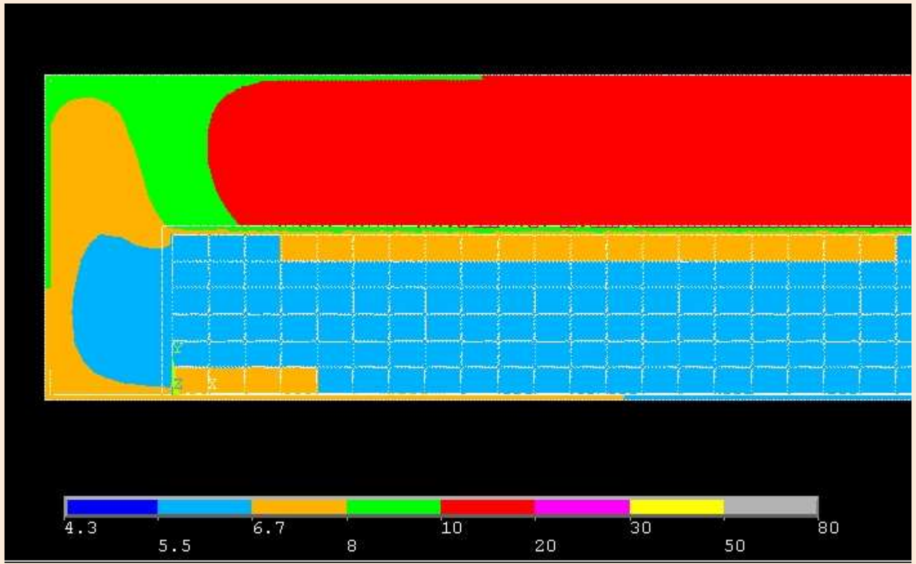


These calculations:

the first figure is at 2.3 s

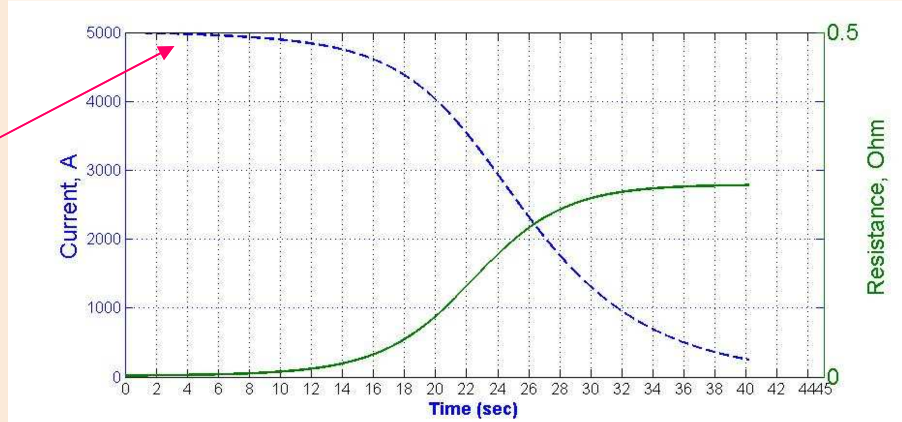
the second figure is at 2.4 s.

The heat generation was taken as $8*10^4$ W/m^3 that corresponds to $2*10^5$ A current in the cylinder.

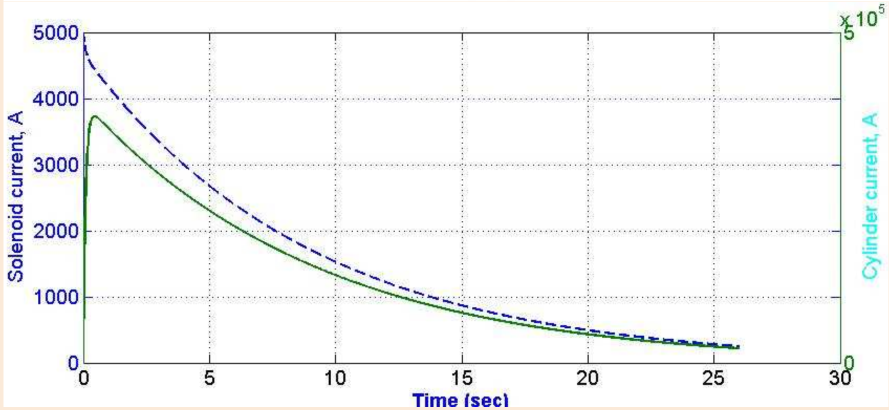


Quench calculations - influence of materials

RRR of Al stabilizer influence on the hot spot temperature. At RRR=1130 the current start to decay very slowly.

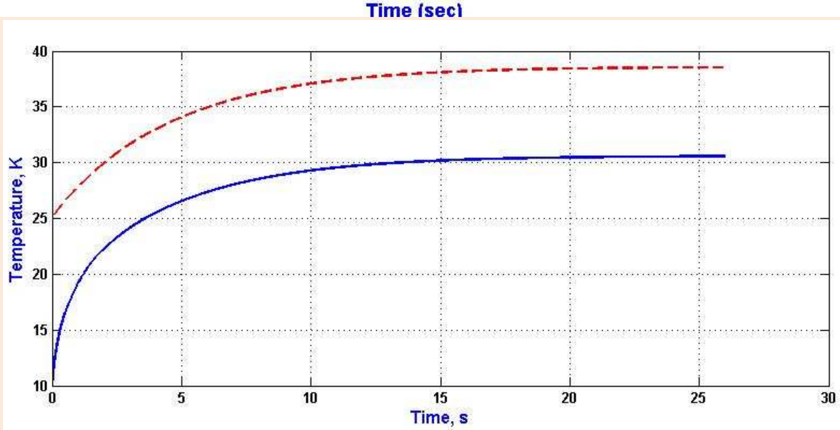


Dump resistor Rd = 0.1 Ω absorbs most energy of the magnet system.



At Rd = 0.2 Ω the current decay and the hot spot temperatures will be as shown on the two bottom figures.

In this case the current in the support cylinder is increased by a factor of 2. The solenoid and the hot spot temperatures changed as:



from 54 K to 38 K

from 42 K to 31 K respectively.

Conclusions

- **The quench calculations shows that the solenoid is safe as with active damp resistor as without it (short circuited solenoid).**
- **The hot spot temperature is expected to be about 55 K at 0.1 Ω of the damp resistor.**
- **The high purity Al strips will distribute the normal zone faster than the quench back effect.**
- **The demands to high RRR of the SC cable are unclear if the energy extraction system is supposed to work reliably.**