Quench calculations of the SPD detector solenoid

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Outline

Purpose of the work

Main parameters of the magnet

Homogeneous energy dissipation in the solenoid

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Purpose of the work

A superconducting magnet can go into a normal state for various reasons.

If the magnet completely goes into a normal state, then most likely there will be no problems.

The most dangerous scenario is when one or more turns go into a normal state. In this case, local overheating and uneven distribution of electrical voltage occur, which can lead to the destruction of the magnet.

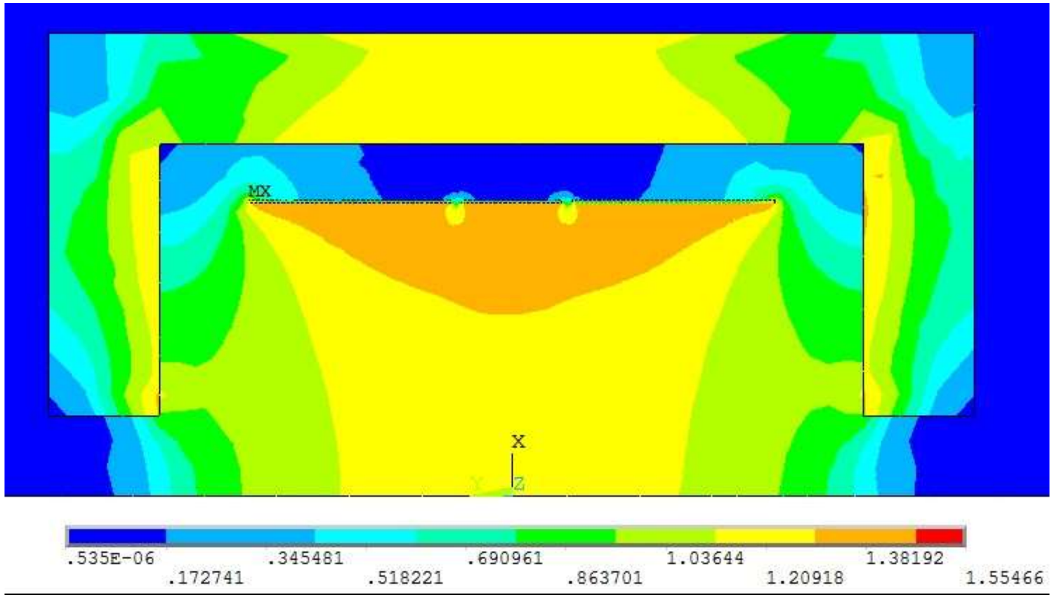
The purpose of the work is to calculate the maximum temperature and electrical voltage in the worst case scenario. And to assess the influence of the solenoid design elements on these parameters: aluminum strips and support cylinder.

To give requirements to the dump resistor protection system

Main parameters of the solenoid

Solenoid parameters	Values
Inner diameter of the winding, mm	3662
Outer diameter of the winding, mm:	3756
Total length of the solenoid, mm	3330
Number of turns in the solenoid (2*150+2*75+ 2*150)	750
Number of layers	2
Length of one turn, m	11.5
Operating current Io, A	5200
Test current, Io*1.05, A	5460
Magnetic field on the coil Bmax, T	1.55
Io/Ic ratio along the load line, %	
Operating temperature, K	4.5
Temperature of current sharing, K	6.7
Stored energy of the magnet, MJ	25.6
Cold mass, kg	5240
Cold mass of the SC cable without insulation, kg	2280
Inductance of the magnet at full current, H	1.89
E/M ratio for cold mass, kJ/kg	4.9
E/M ratio for SC cable mass, kJ/kg	11.2

quench parameters

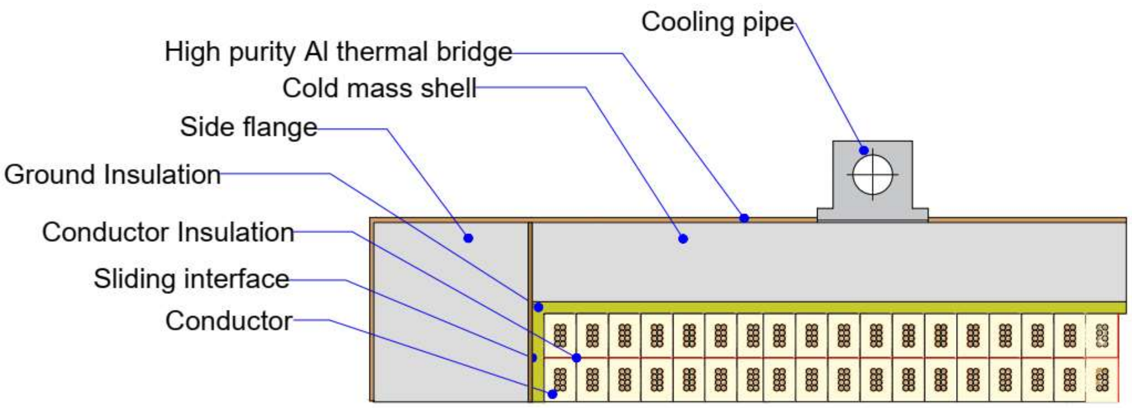


Magnetic field map (ANSYS 2D, Babs)

Cold Mass (design)

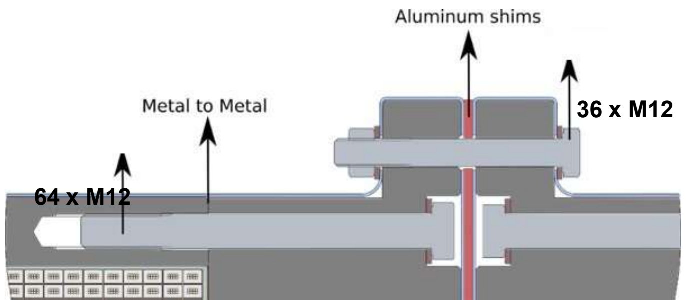
2x 2 layers - 300 turns
1x 2 layers - 150 turns

Magnetic field - 1 T
Current - 5.2 kA



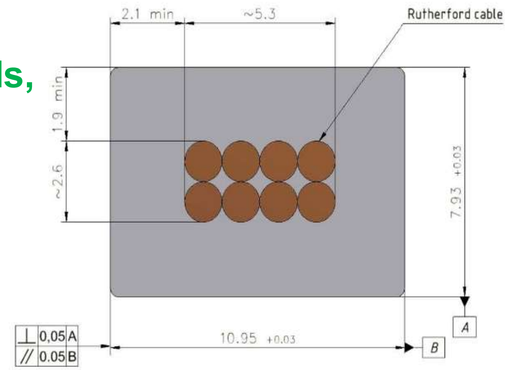
Conductor mechanical and electrical parameters.

Thickness (after cold work) at 300 K	mm	7.93	± 0.03
Width (after cold work) at 300 K	mm	10.95	± 0.03
Critical current (at 4.2 K, 5 T)	A	> 14690	
Critical current (at 4.5 K, 3 T)	A	> 16750	
Overall Al/Cu/sc ratio		10.5/1.0/1.0	
Aluminum RRR (at 4.2 K, 0 T)		> 600	
Al 0.2% yield strength at 300 K	MPa	> 30	



Rutherford cable, 8 strands, extruded in Al matrix

10.95 мм x 7.93 мм,
NbTi / Cu d=1.4 мм



Rutherford cable is used to wind the coils. If necessary, we will use special shims between the sections of the coils.

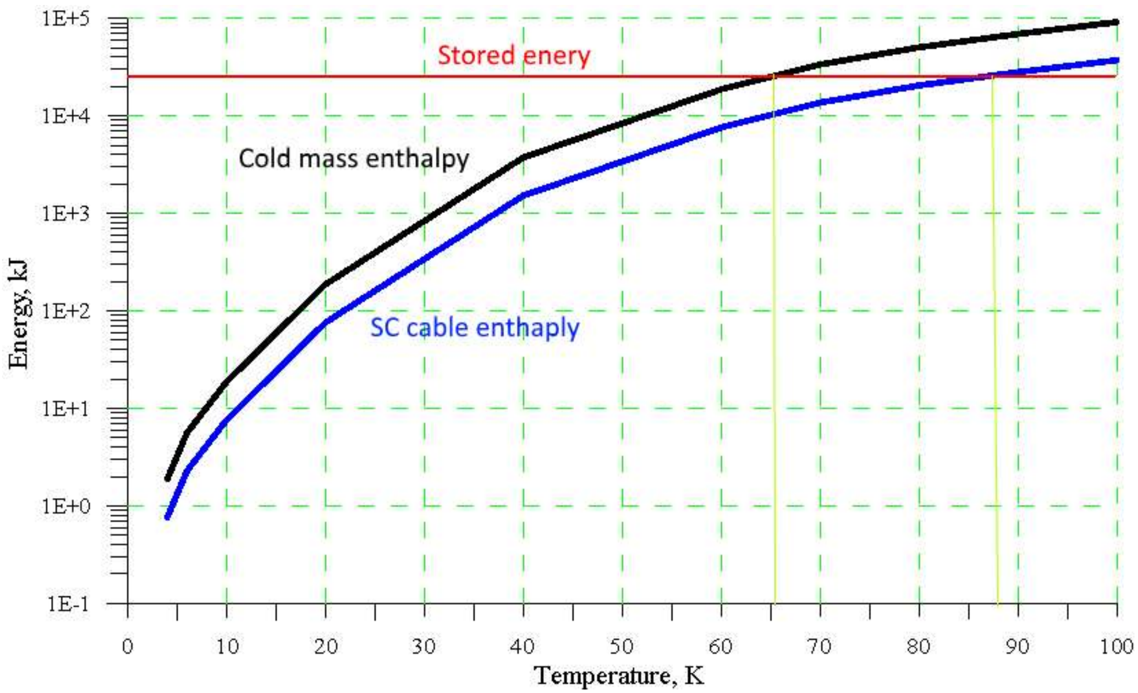
Homogeneous energy dissipation

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	2280	0.76
Total solenoid	5283	1.87

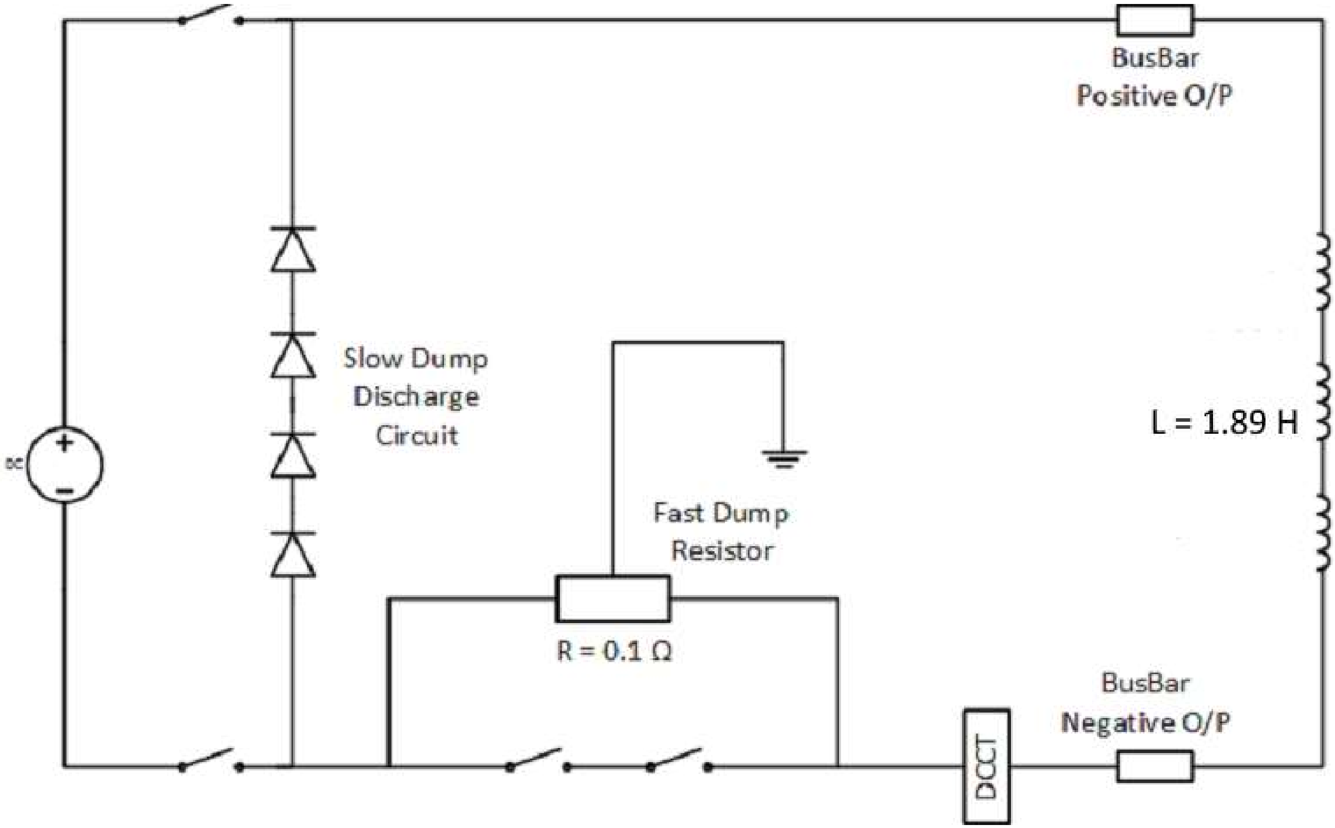
Average temperature at short circuited quench in the solenoid:

~65 K in the whole cold mass

~ 88 K in the SC cable only



- ***Powering circuit***



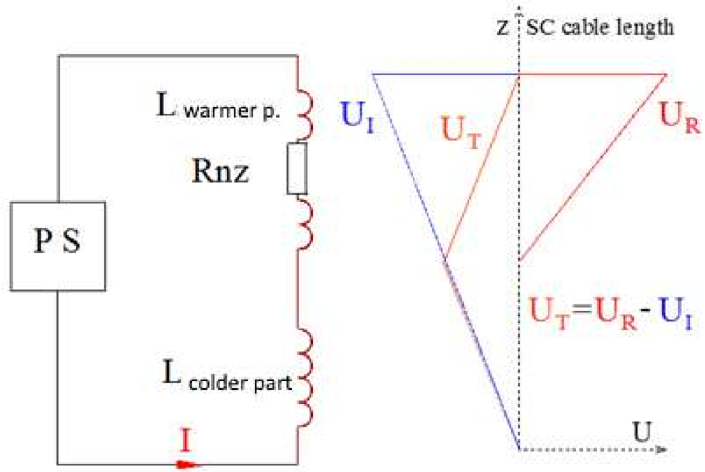
the discrimination time is ~ 1 s, at Al matrix RRR=328

the threshold voltage is ~ 0.1 V

Quench calculations steps

- 2D ANSYS calculations of the normal zone propagation. This calculation gives time when total solenoid becomes normal and maximal temperature at this time.
- Matlab quench code with input parameters from ANSYS calculations.
- Influence of RRR of the cable on the main quench parameters.
- The hot spot is calculated directly
- The calculated resistive voltage should be interpreted with respect to the maximal voltage between the superconducting winding and ground insulation (support cylinder)

The resistive voltage in the winding during a quench is distributed no uniformly while the inductive voltage is uniformly. The difference between these voltages produce the voltage between the winding and the ground .



The hot spot in the SC cable joints

One of the reason of the premature quench is the hot spot appearance in the winding – it must be evaluated during the designing of the solenoid.

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.

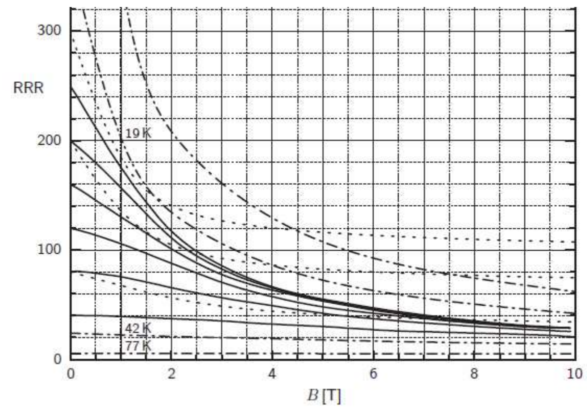
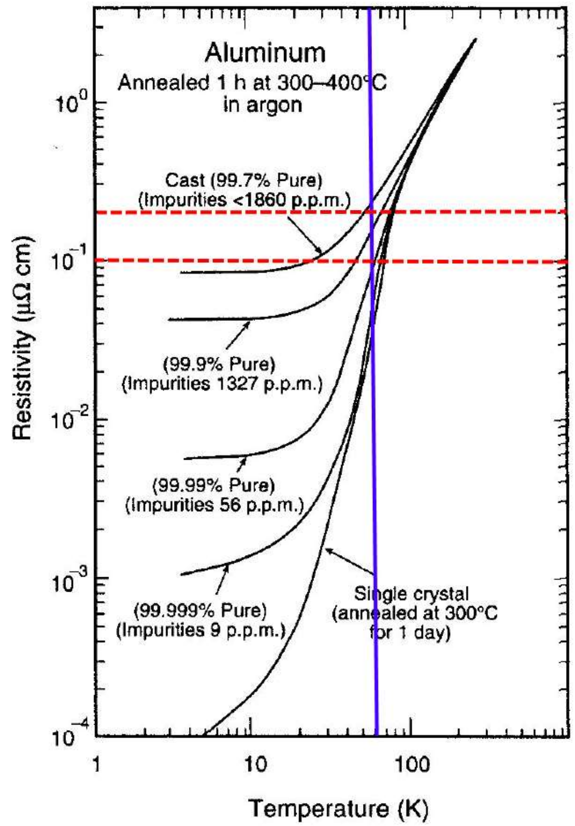


Fig. A4.2 RRR vs. magnetic field plots: copper (solid) and aluminum (dotted), both at 4.2 K, and silver (dash-dotted, with temperatures indicated—RRR = 735 at 0 T). At 77 K, field-dependence of RRR for copper is similar to that of silver.



Распространение нормальной зоны RRR=125

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

RRR ~125 in the SC cable

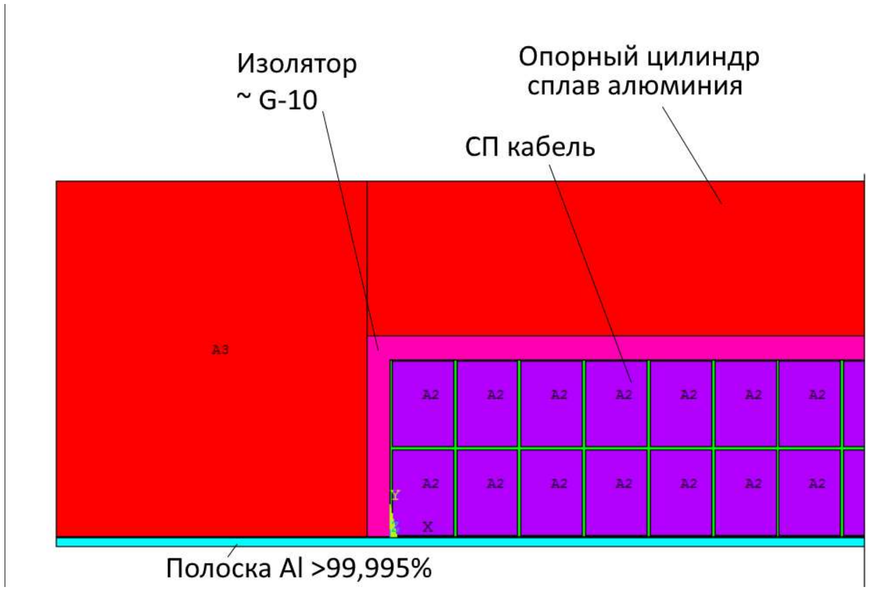
Heat generation 8.6*10^5 W/m^3

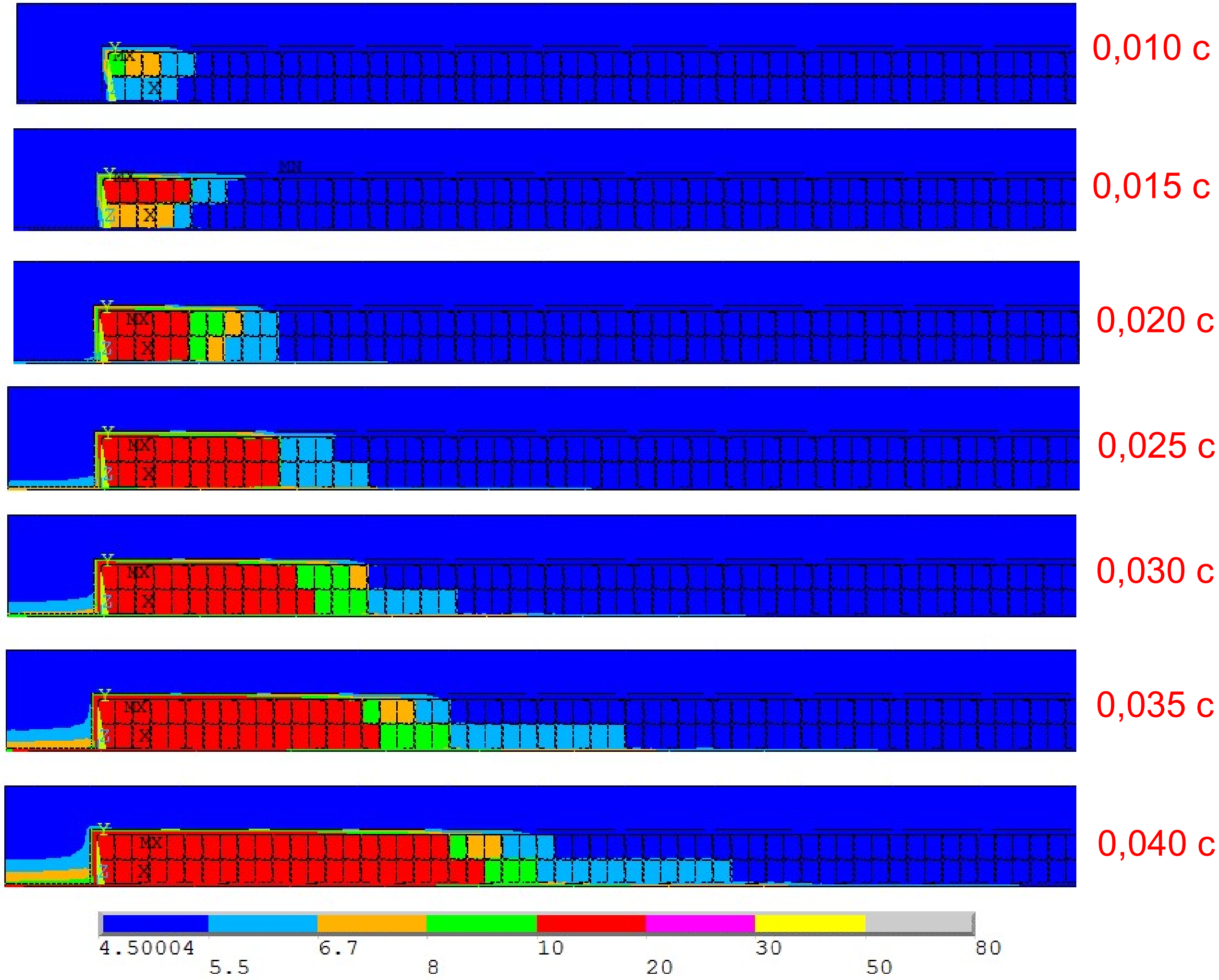
The velocities of the nz propagation are:

- 6.9 m/s along the cable;

- 0.079 ... 0.18 ...0.8 … m/s;

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





Tmax ~ 25 K when the whole solenoid become normal

Распространение нормальной зоны RRR=328

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

RRR ~328 in the SC cable

Heat generation $2.1*10^5$ W/m^3

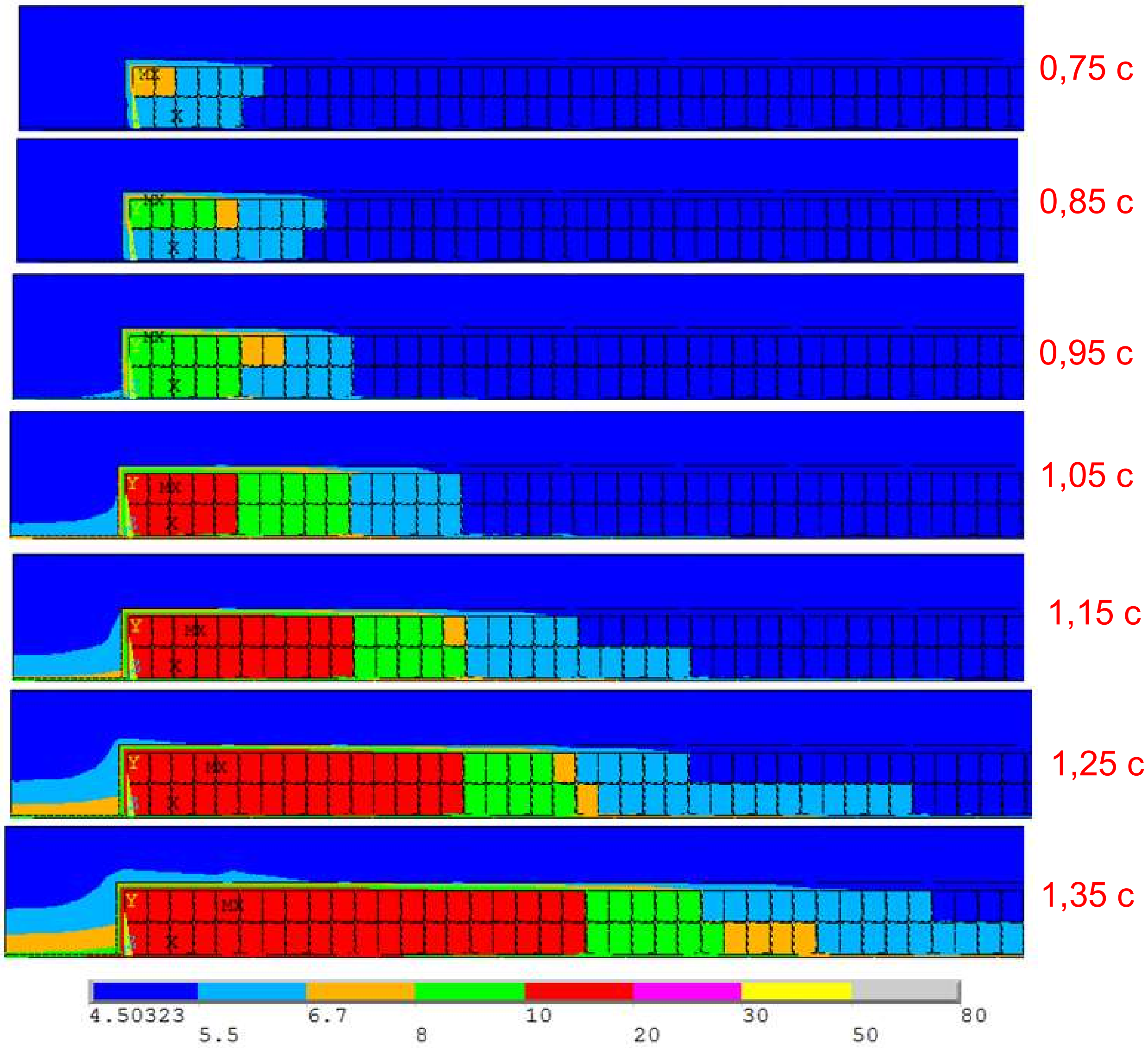
The velocities of the nz propagation are:

- 6.9 m/s along the cable;

- 0.079 ... 0.18 ... 0.8 … m/s;

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

Tmax ~ 20 К when the whole solenoid become normal



MatLab codes calculations

Решались уравнения:

For the aluminum of the cable RRR = 328

Aluminum support cylinder (АМГ5, 5056 American alloy) has electrical resistivity of 3 mOhm*cm.

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.

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

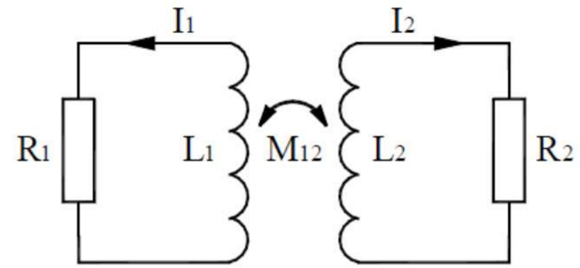
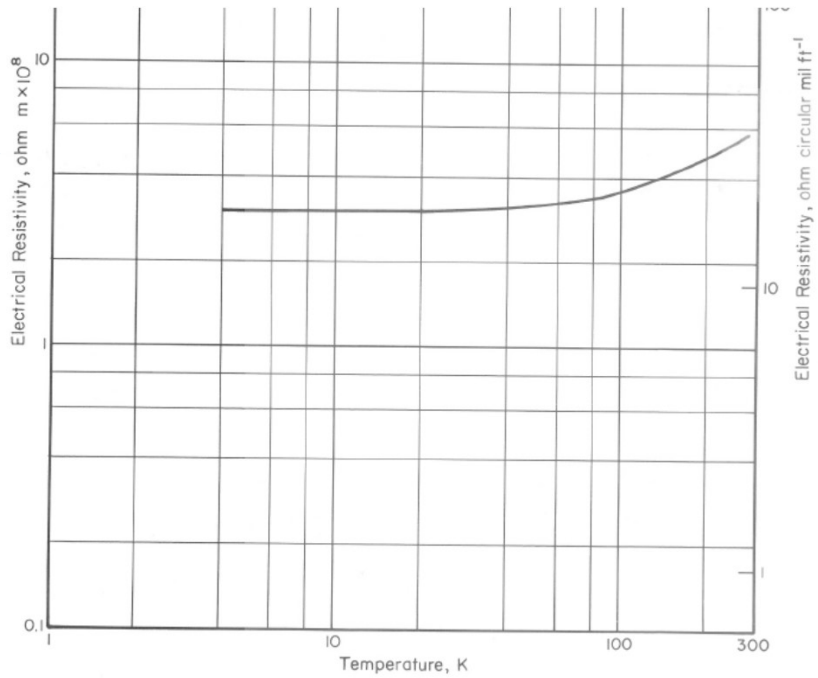


Fig.. Scheme of the coupled circuits.

The equations to be solved are:

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



Main operation parameters RRR328, Rd = 0.1 Ohm

The RRR parameters were taken at lower values then of raw aluminum which would be ~ 600, because the RRR will be degraded during winding process.

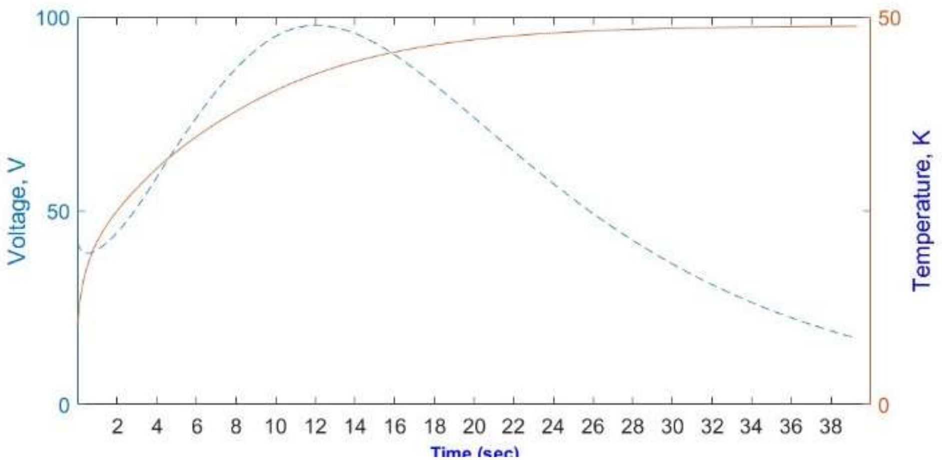
Quench at Rd = 0.1 Ohm

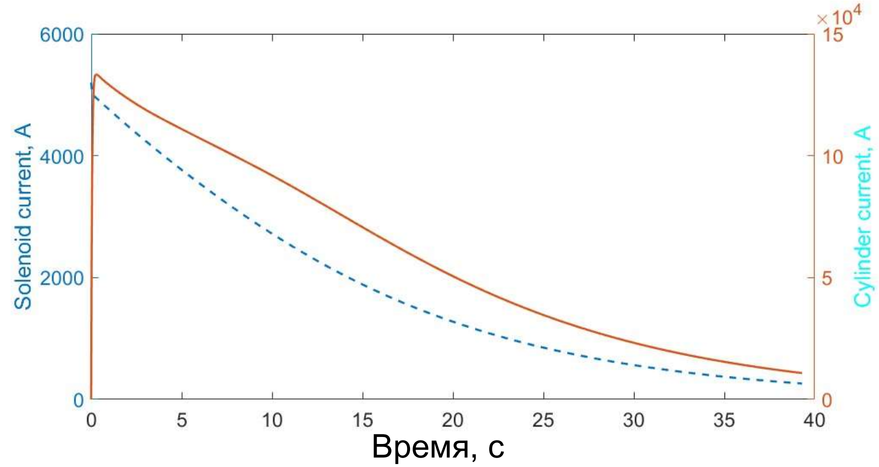
The external resistance was activated when the temperature at the hot spot reached 20 K.

The induced current in the support cylinder raised up to 0,15 MA – that is low comparing with the total winding current 5200*750 = 3,9 MA.

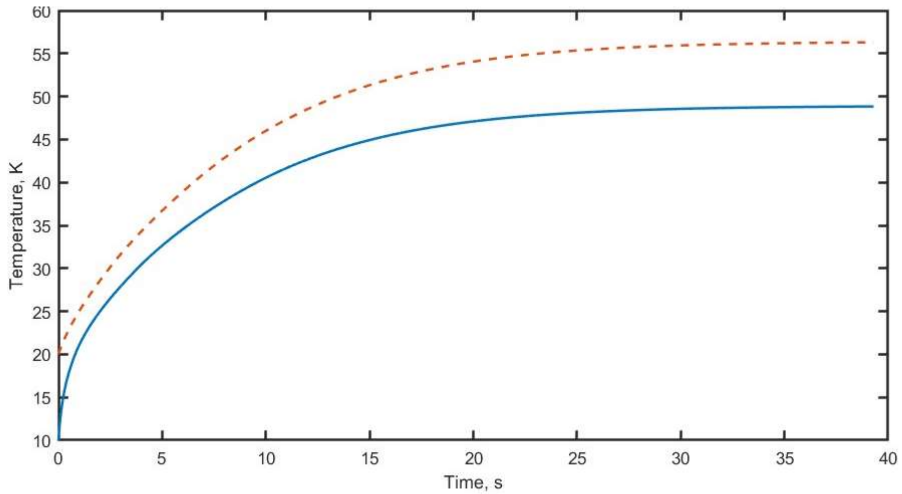
The raising of the temperatures is shown on the Figure below right: in the solenoid up to 49 K and in the hot spot up to 57 K.

Resistive voltage raise up to 97 V – Figure below.





The induced current in the cylinder is only ~ 1.5*10^5 A with respect to the whole current in the solenoid ~ 3.9*10^6 A.



Main operation parameters RRR328, Rd = 0 Ohm (fail in dump resistor system)

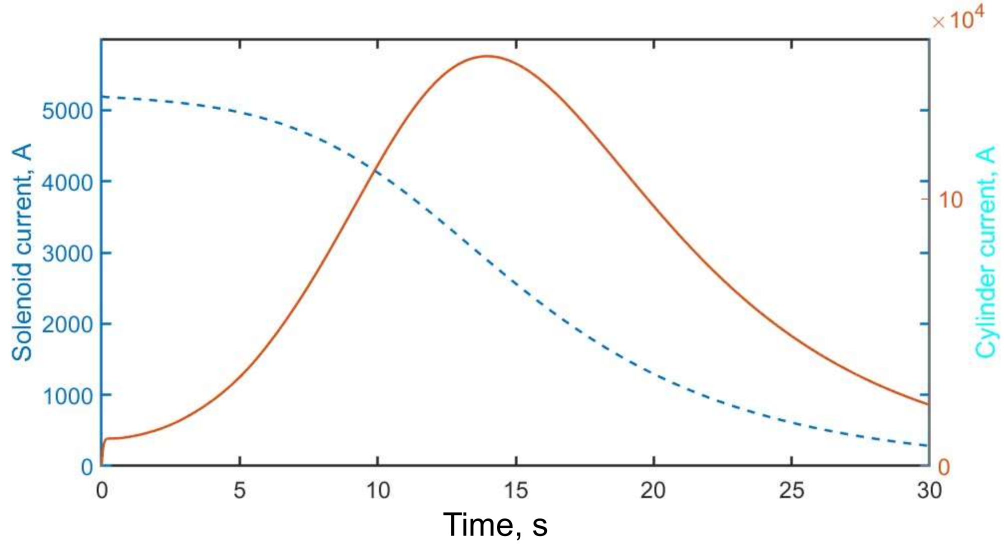
Quench at Rd = 0.1 Ohm

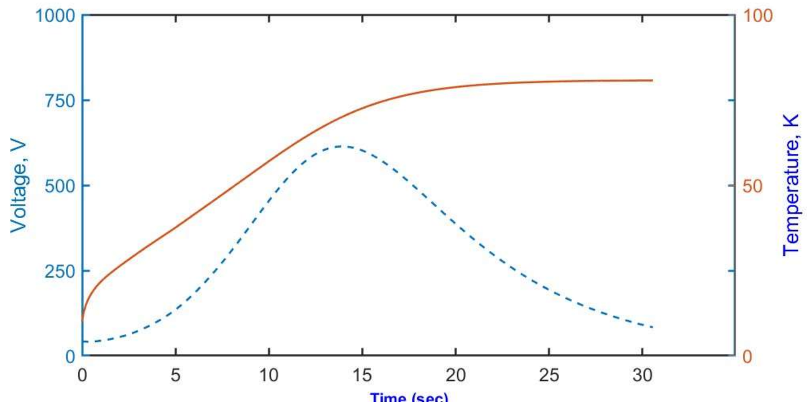
The external resistance was activated when the temperature at the hot spot reached 20 K.

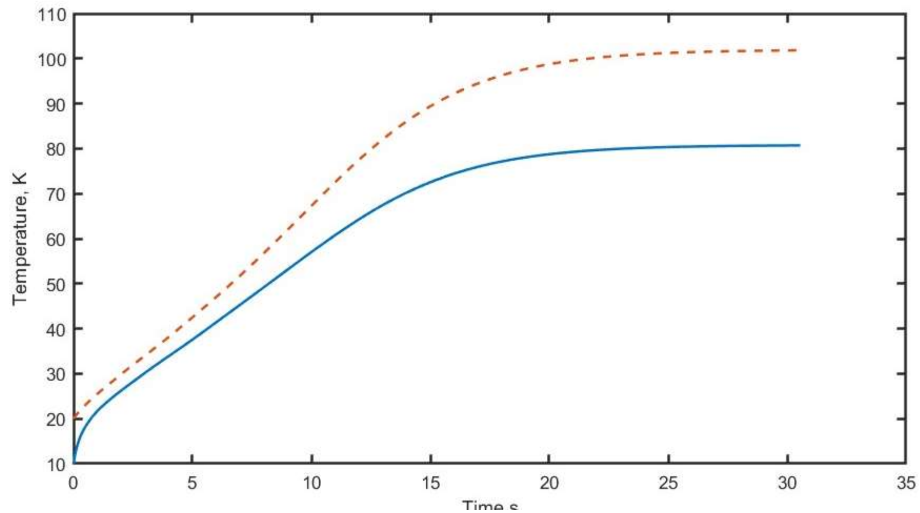
The induced current in the support cylinder raised up to 0,01 MA – that is even less than previous comparing with the total winding current 5200*750 = 3,9 MA.

The raising of the temperatures is shown on the Figure below right: in the solenoid up to 80 К and in the hot spot up to 103 К.

Resistive voltage raise up to 600 V – Figure below.







Main operation parameters RRR328, Rd = 0.1 Ohm – influence of the support cylinder

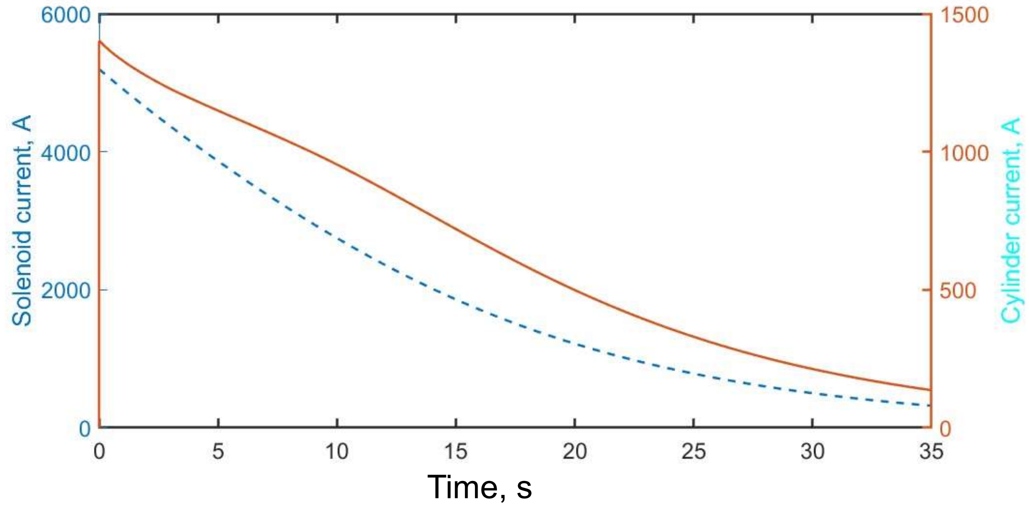
Quench at Rd = 0.1 Ohm. The resistance of the support cylinder was decreased by two orders.

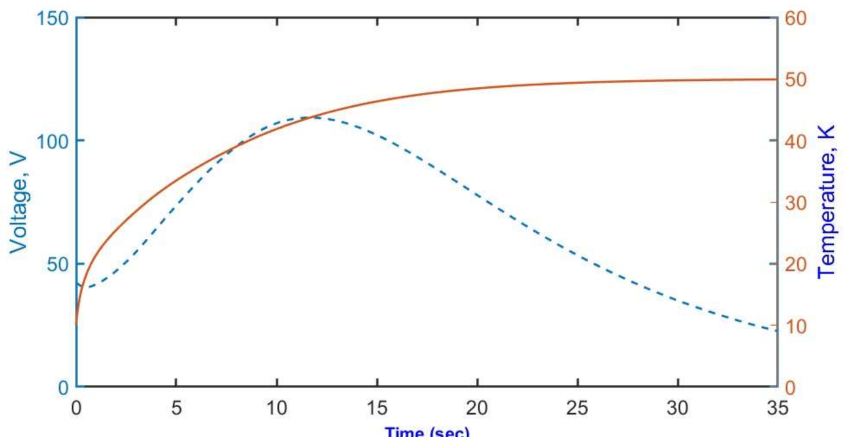
The induced current in the support cylinder raised up to 1.5 kA – negligible.

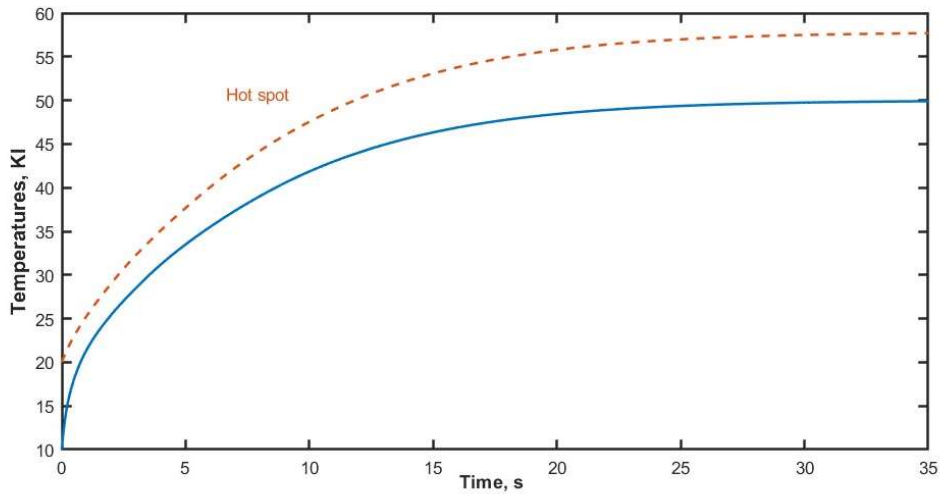
The raising of the temperatures is shown on the Figure below right: in the solenoid up to 50 K and in the hot spot up to 58 K.

Resistive voltage raise up to 110 V – Figure below that is 13% more than with the real situation.

So, we see the influence of the support cylinder resistance on the quench parameters of the solenoid.







Quench of the solenoid with very degraded parameter RRR130, Rd = 0.1 Ohm

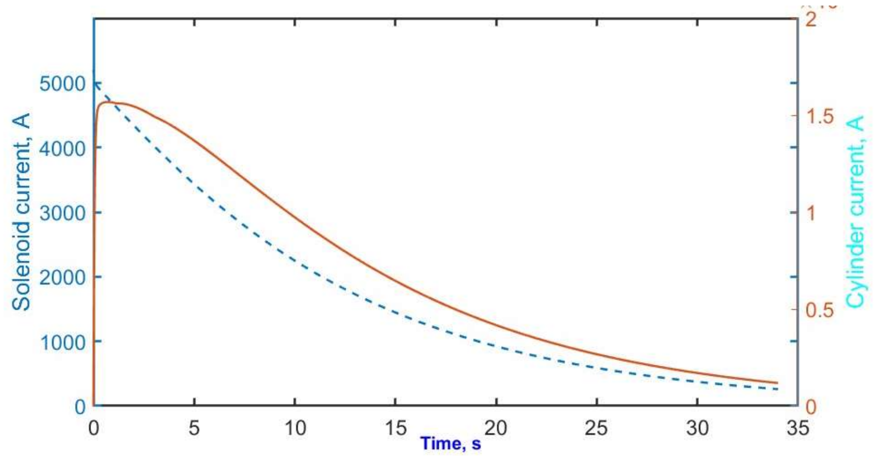
Quench at Rd = 0.1 Ohm

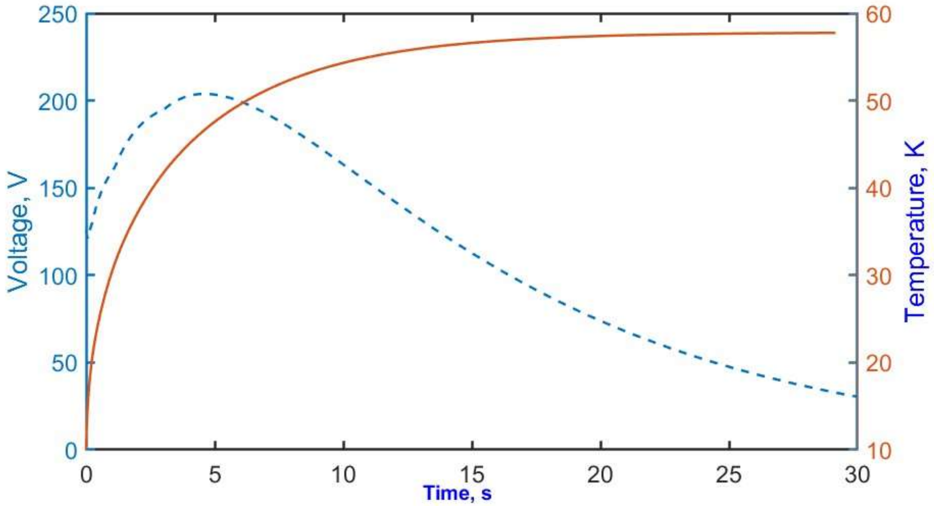
The external resistance was activated when the temperature at the hot spot reached 25 K.

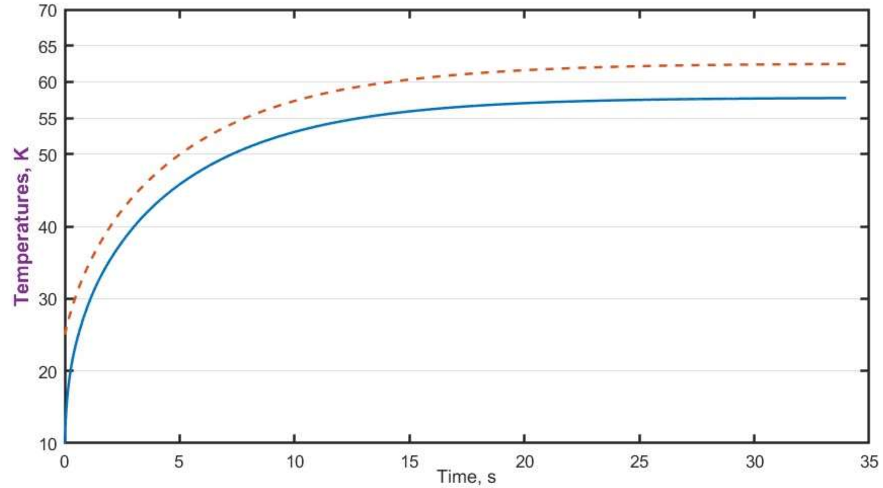
The induced current in the support cylinder raised up to 0,16 MA – that is low comparing with the total winding current of 3,9 MA.

The raising of the temperatures is shown on the Figure below right: in the solenoid up to 57 К and in the hot spot up to 63 К. At RRR328 they were К and 56 К correspondingly.

Resistive voltage raise up to 210 V – Figure below.







Quench of the solenoid with very degraded parameter RRR130, Rd = 0 Ohm

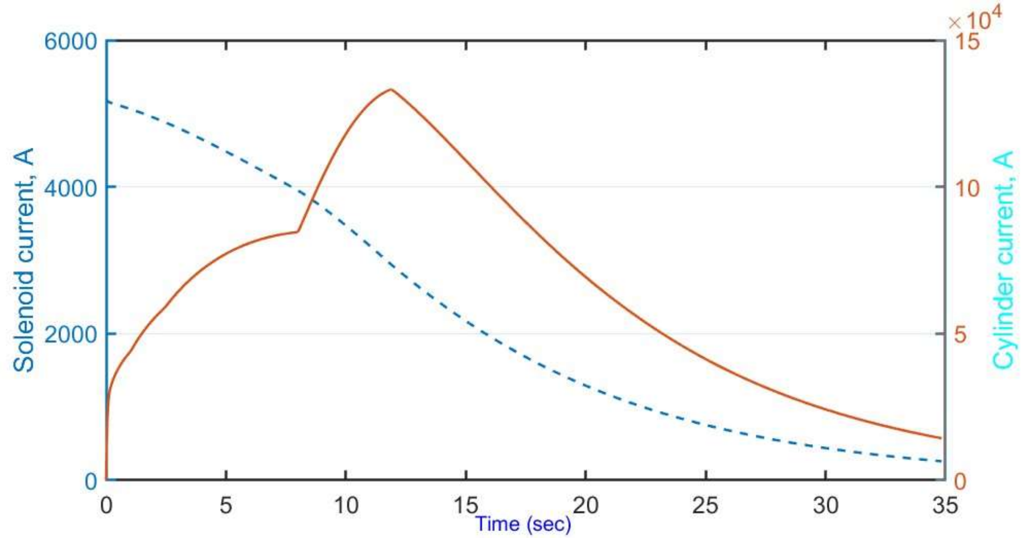
Quench at Rd = 0.1 Ohm

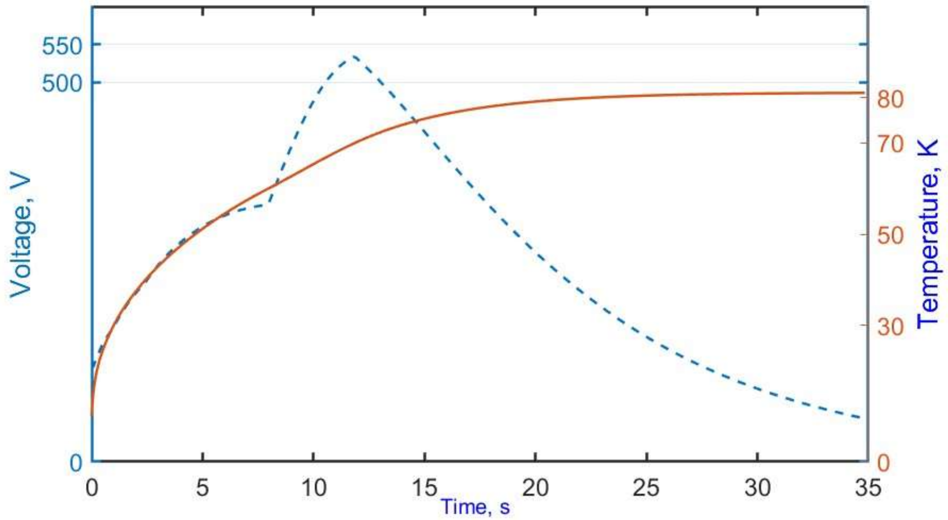
The external resistance was activated when the temperature at the hot spot reached 25 K.

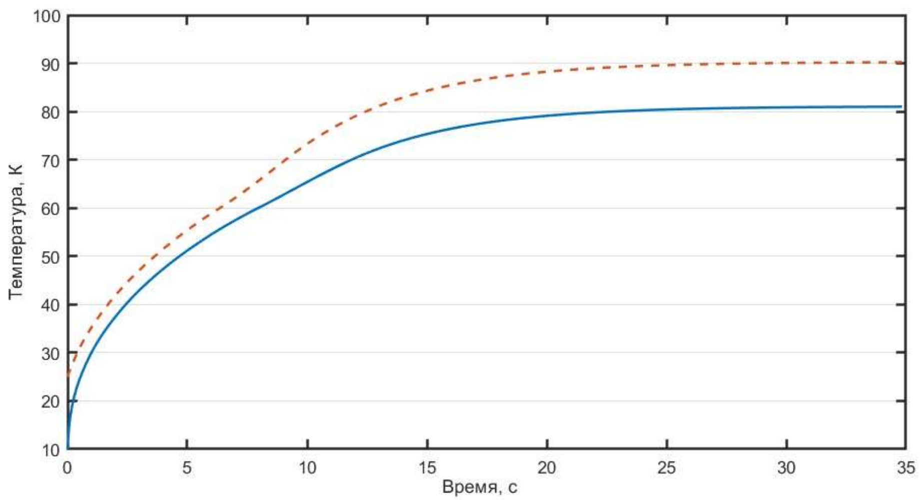
The induced current in the support cylinder raised up to 0,14 MA – that is low comparing with the total winding current of 3,9 MA.

The raising of the temperatures is shown on the Figure below right: in the solenoid up to 81 K and in the hot spot up to 90 K. At RRR328 they were 49 K and 56 K correspondingly.

Resistive voltage raise up to 540 V – Figure below.







Conclusions

- **Quench calculations of the transition to the normal state show that the solenoid generally operates in a safe mode.**
- **The temperature in the warm zone does not exceed 63 K, which corresponds to the permissible value. The critical temperature is considered to be 130-150 K. There are no problems with internal electrical voltage.**
- **The strips of ultra-pure aluminum play an important role in increasing the speed of propagation of the normal zone and reduce.**
- **May be it is worth to consider another aluminum alloy for the support cylinder with lower electrical resistivity – more calculations are needed.**
- **If there be low probability of failure in the quench protection system then the requirements to the high values of the RRR of the cable matrix would be decreased down to 130-100.**