SSR2 Focusing Lens Quench Protection Study:
Dump Resistors Connected in Parallel to Coils of the Lens.

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As indicated in earlier studies (see [1]), it is marginally possible to protect SSR2 focusing lens [2] by employing a dump resistor connected in series to the lens, like it was done in [3] and [4] for the CH-type and SSR1-type lenses. The protection was made possible due to a special design of this lens that has the main coil consisting of two thermally insulated halves electrically connected in series with a grounded connection point. As in the previously explored cases of CH and SSR1 lenses protection (see [3] and [4]), a switch was required in the circuit to disconnect a power supply immediately after quench detection and to introduce a dump resistor in the current discharge circuit.

There exists another quench protection circuit configuration where dump resistors are permanently connected in parallel to the coils of a focusing lens. When one of the coils of a lens is quenching (that is transition from the superconducting to the normal state is in process), a voltage drop appears across this coil due to resistance of the normal zone, and current starts flowing through the corresponding dump resistor. As the current in the quenching coil changes, inductive voltage develops on all other coils of the lens. This voltage results in current flowing through the dump resistors connected to other coils of the lens. This protection scheme looks attractive because it can significantly simplify quench protection hardware and make it more reliable. Two configurations of this quench protection circuit will be studied in this paper:

a) dump resistors connected in parallel to the bucking coils (**BC**),

b) dump resistors connected in parallel to both halves of the main coil (**MC**).

Because in each of the two configurations quenching can happen in the coil equipped with the dump or in the coil without it, the next four cases need to be investigated:

1. Quenching bucking coil with dump resistors connected in parallel to the bucking coils of the lens (case BC-BC).
2. Quenching half of the main coil with dump resistors connected in parallel to the bucking coils (case MC-BC).
3. Quenching bucking coil with dump resistors parallel to both halves of the main coils (case BC-MC).
4. Quenching half of the main coil with dump resistors connected in parallel to both halves of the main coils (case MC-MC).

As shown in [1], quenching bucking coils of a lens can potentially generate more problems than quenching main coil, which, if fabricated with proper care, is self-protected. That's why we need to study the cases of quenching bucking coil first, but after this study, we need to verify that quenches in the main coil with the chosen dump resistor connection scheme do not result in unwanted effects. So, the second and the last study cases verify main coil self-protection condition in each of two configurations of the quench protection circuit. Optimal configuration and corresponding dump resistor values will be chosen based on the results of this modeling.

Similar to what was done in [1], we will study the SSR2 focusing lens in the next configuration: the lens is built of a main coil consisting of two halves that are wound separately and do not have direct thermal contact and two bucking coils (Fig. 1).

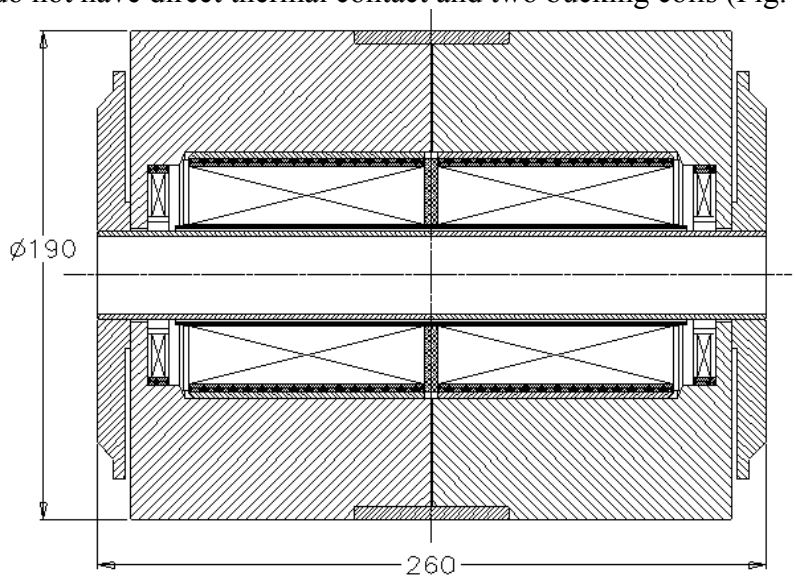


Fig. 1. SSR2 focusing lens design concept

Connection to the ground is made between the two halves of the main coil. When a quench in one of the coils is detected (when a voltage misbalance is detected between the two halves of the lens), the power supply is phased out but not disconnected, allowing the circuit current flowing uninterrupted. We will further accept that in all the schemes analyzed below, the current in the circuit flows in the clockwise direction. The dump resistances ***Rd*** are connected in parallel to the bucking coils or the halves of the main coil. In the quenching coil, resistance ***Rc*** changes with time. Currents in the coils without dump resistors are the same as the circuit current ***I***. We will always assume that the quench originates in the first coil of a pair BC1-BC2 or MC1-MC2. Currents in BC-s or MC-s equipped with dump resistors will be ***I1*** (for the quenching coil) and ***I2***. Currents in the dump resistors will be ***Id1*** (for the dump of the quenching coil) and ***Id2***.

Stars near the ends of the inductance symbols in the circuit schemes below show that the bucking coils and main coils have opposite directions of magnetic field. While performing the discharge circuit analysis, this feature will be reflected by assigning the negative sign to corresponding mutual inductance. These inductances are calculated in the way it was done in [1]; corresponding tables are provided in the input file of the modeling code as array constants.

Because in the most common case three of the four coils have different currents (***I***, ***I1***, and ***I2***), calculation of the magnetic field in the quenching coil becomes more difficult. To save on amount of additional modeling to be made to find the field, a series of sample calculations were made corresponding to different current ratios ***I1/I*** and ***I2/I***. During the modeling, at every time step, these ratios were evaluated and the corresponding field distribution in the quenching coil was found.

Quench propagation analysis was made using a code similar to that in [3] and [4]. The next main modifications to this code were made:

1. The part of the code that calculated initial conditions was eliminated; now this part is done within the main body of the program.
2. The field shape on turns in the quenching coil is parameterized using current ratios ***I1/I*** and ***I2/I*** **,** and at each time step, the interpolation procedure is used to find the field value based on previously calculated currents ***I***, ***I1***, and ***I2***.

Block scheme of the modified code is shown in Fig. 2.

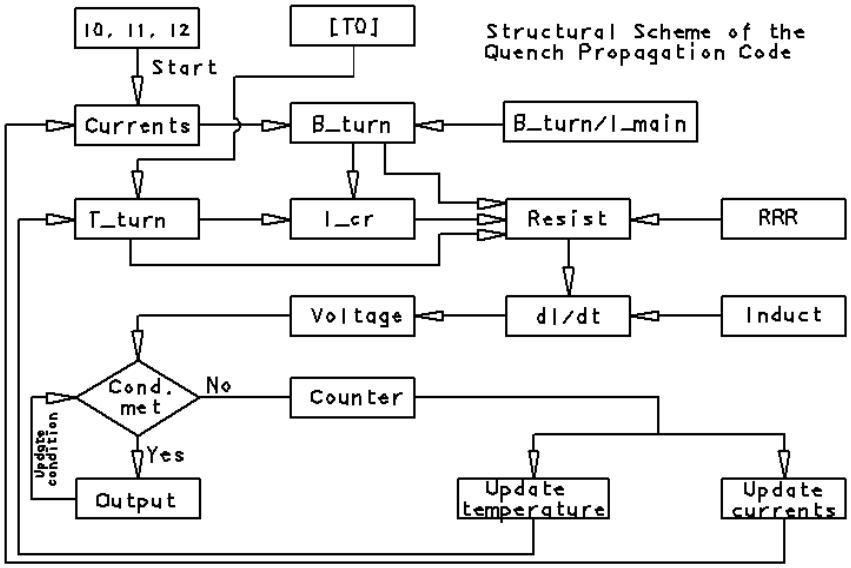


Fig. 2. Block scheme of the quench propagation code

I. Dump resistors connected in parallel to both bucking coils of the SS2 lens; quench happens in one of the bucking coils – case BC-BC

Block diagram of a quench detection and protection system for this case is shown in Fig. 3. This figure also shows the current discharge circuit.

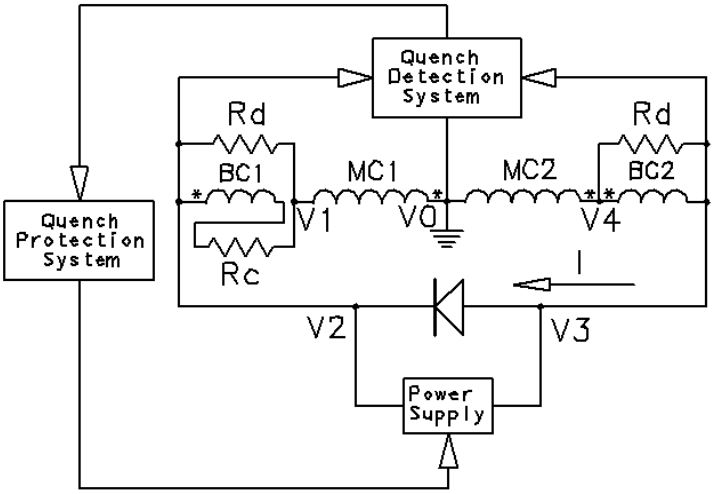


Fig. 3. Quench detection/protection functional scheme and current discharge circuit for the case of quenching bucking coil with dump resistors connected in parallel to both bucking coils.

To describe the current discharge process in the circuit in Fig. 3, we need to find the currents in the main coil ***I*** (circuit current), and in the two bucking coils: ***I1*** and ***I2***. The currents in the dump resistors ***Id1*** and ***Id2*** can be found as a difference between the circuit current and the corresponding bucking coil current. Differential equations that describe the circuit are shown below:

$$\frac{dI}{dt} = \frac{I1 \cdot Rc \cdot (M1B1 + M1B2) + (I1 + I2 - 2I) \cdot Rd \cdot RB}{2 \cdot \left[(LM + M1M2) \cdot (LB + B1B2) - (M1B1 + M1B2)^2\right]}$$

$$\frac{dI1}{dt} = \frac{I \cdot (LB - B1B2) - I1 \cdot \frac{(Rc + Rd)}{Rd} \cdot LB + I2 \cdot B1B2}{(LB^2 - B1B2)^2 / Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LB + B1B2}$$

$$\frac{dI2}{dt} = \frac{I \cdot (LB - B1B2) + I1 \cdot \frac{(Rc + Rd)}{Rd} \cdot B1B2 - I2 \cdot LB}{(LB^2 - B1B2)^2 / Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LB + B1B2}$$

In these and following equations, ***MiBj*** is the mutual inductance between the main coil "*i*" and the bucking coil "*j*" (values of *i* and *j* can be only 1 or 2). If $i = j$, the coils are located next to each other; if $i \neq j$, the coils are located on different sides of the lens. ***B1B2*** is the mutual inductance between the two bucking coils and ***M1M2*** is the mutual inductance between the two halves of the main coil. ***LB*** is the self-inductance of each bucking coil, ***LM*** is the self-inductance of each half of the main coil. ***RB*** is the reactance of the bucking coil and ***RM*** is the reactance of the main coil. As was mentioned before, all ***MiBj*** mutual inductances have negative sign. ***Rd*** is the resistance of the dump resistor; ***Rc*** is the resistance of the quenching (in this case, the bucking) coil. We need also to take into account that in the following equations

MiBj ≡ BiMj ≡ MjBi.

The next set of the initial conditions is imposed:

I(0) = I1(0) = I2(0) = I0.

Using the differential equation above, the initial current derivatives can be found: they are fully defined if the solenoid inductance matrix and the initial resistance of the quenching coil (***Rc***) are known. As in [1], the initial resistance is introduced by pointing to an array of turns in the coil with temperature exceeding the quench threshold; this is done in the input file of the modeling code.

Solving the system of equations above is straightforward. As it was done in [4], after each time step, heat propagation equations are applied to find new temperatures within the quenching coil and to check on the superconducting status of the coil's turns, which is defined by the current in the bucking coil, the turn temperature array, and the array of the magnetic field at the location of the turns. As was mentioned earlier, finding the magnetic field at the location of each turn is complicated by the fact that here the current in the bucking coil differs from that in the main coil, so the magnetic field distribution function (which was a constant function in our earlier studies) changes with time as the ratio between the current in the bucking coil and the main coil changes. Using a magnetic modeling program (in this case it was COMSOL, but it can be another program), a series

of field arrays was found for the system of coils in the SSR2 lens corresponding to several values of the ratio ***I1/I*** (0, 0.25, 0.5, 0.75, and 1.0), and an interpolation process was used to find the field in the bucking coil at each time step of the modeling process. In this particular case, it was accepted that the current in the second bucking coil is equal to the circuit current; because of the large distance between the bucking coils, this approximation helped to reduce amount of work without compromising the accuracy of the modeling. For other cases presented below, this assumption will not be used.

Information obtained after the first step allows modification of the turn resistance array with new data. Then layer and coil resistance is found and the voltages in the circuit are calculated:

$$V1 = dI/dt \cdot (LM1+M2M1) + dI1/dt \cdot B1M1 + dI2/dt \cdot B2M1;$$

$$V2 = V1 + I1 \cdot Rc + LB1 \cdot dI1/dt + B2B1 \cdot dI2/dt + dI/dt \cdot (M1B1+M2B1);$$

$$V4 = V2 + LB2 \cdot dI2/dt + B1B2 \cdot dI1/dt + dI/dt \cdot (M1B2+M2B2);$$

$$V0 = V4 + dI/dt \cdot (LM2+M1M2) + dI1/dt \cdot B1M2 + dI2/dt \cdot B2M2.$$

Two coil winding configurations were analyzed which were different in terms of where the winding of the coils starts and in which direction it progresses. Although the overall circuit scheme (Fig. 3) remains the same, the connections details are slightly different for these cases. In the original winding configuration, the circuit originating from MC1 enters BC1 through the bucking coil's central layer, while in the alternative configuration, MC1 connects to BC1 through the outer layer of the coil. Similarly, the connections to BC2 are changed. The difference in circuit voltages due to the winding/connection pattern change was found to be negligible.

According to [1], the resistance of the bucking coil after quench can reach ~10 Ohm. So, if to make Rd >> 10 Ohm, the modeling results should be similar to those obtained for the case studied in [1] with Rdump = 0. Figures 4 to 6 below show results of the quench propagation modeling with Rd = 1000 Ohm. These figures must be compared with Figures 3 to 6 in [1] to conclude that the results are indeed very close.

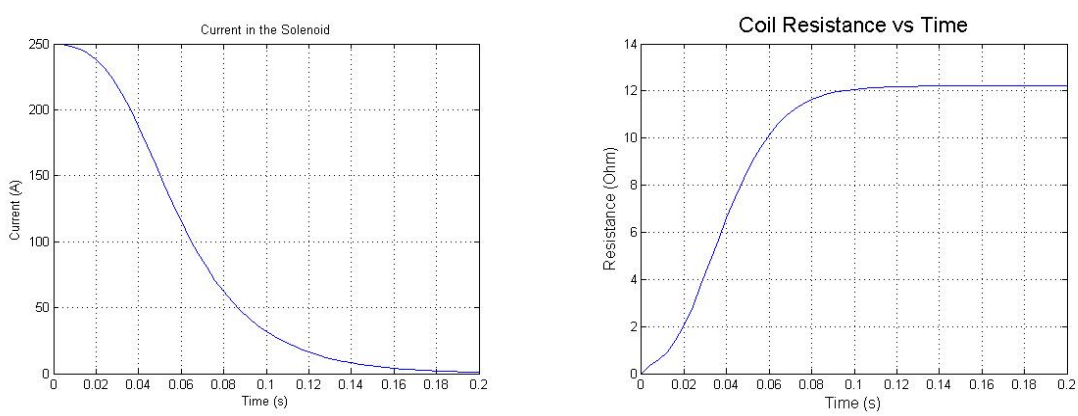


Fig. 4. Circuit current and quenching coil resistance; Rd = 1000 Ohm

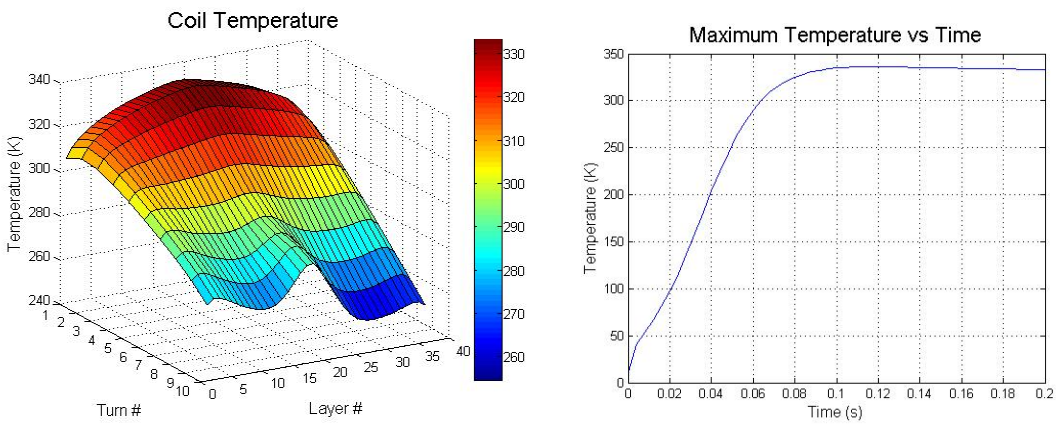


Fig. 5. Temperature in the coil after quench and maximum temperature during quench; Rd = 1000 Ohm

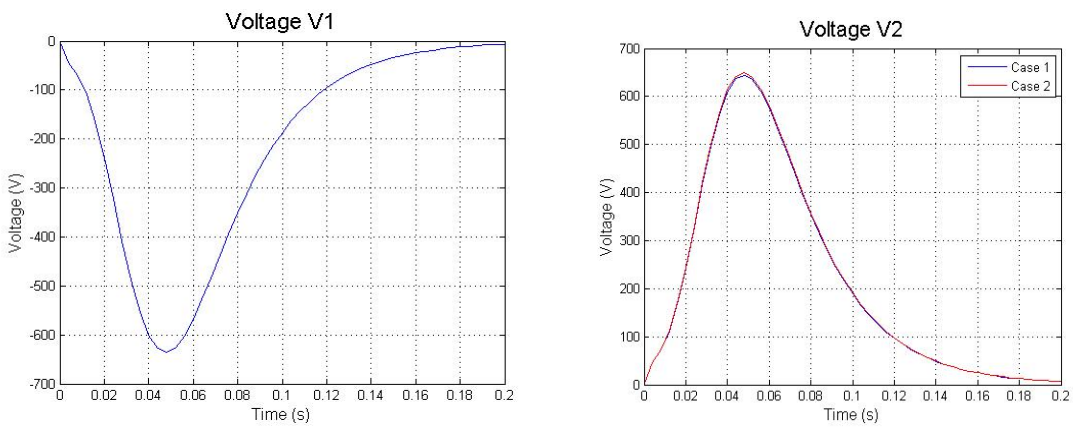


Fig. 6. Voltage to ground on the leads of the quenching coil; Rd = 1000 Ohm.

The close similarity of the results obtained by using two different approaches validates the new version of the code, so we can use it to investigate performance of the quench protection scheme. Table 1 below summarizes results of the modeling: maximum resistance of quenching coil, the coil temperature, voltage to ground in the points V1 and V2 of the circuit, voltage across the quenching coil (U), power in first dump resistor (Pd1), and the energy dissipated in the first dump resistor (Wd1) and in the quenching coil (Wc).

Table 1. BC-BC case summary table (Fig. 3).

Rd (Ohm)	Process duration (s)	Rc_max (Ohm)	Tmax (K)	V1 (V)	V2 (V)	U (V)	Pd1 (kW)	Wd1 (kJ)	Wc (kJ)
1	1.5	4.51	189	-76.9	77.9	153.8	23.82	7.94	2.66
3	1.0	6.51	269	-167.9	170.7	338.5	38.55	6.12	4.71
6	0.6	7.89	327	-254.2	256.6	510.8	43.82	4.73	6.21

In this case, only the dump resistor connected in parallel to the quenching coil participates in the energy removal process; losses in the second dump resistor are negligible. Lower values for the dump resistors result in lower maximum temperature of

the quenching coil and lower voltages to ground and across the quenching coil. The current decay time increases with the dump resistance drop, so the inductive voltages become smaller. The lower limit of the dump resistance depends on the physical location of the dump resistors in the cryomodule; while choosing the resistance, one must take into account heat loss through the connecting wires, so the leads must have a sufficiently small cross-section and long length.

Graph in Fig. 7 visualizes some data from Table 1. Graphs in Fig. 8 and Fig. 9 compare profiles of the currents in the circuit and the voltages to ground at points V1, V2, V4, and V0. With smaller resistance of the dump resistor, the current decay constant becomes larger as the dump resistor effectively shunts the quenching coil's resistance.

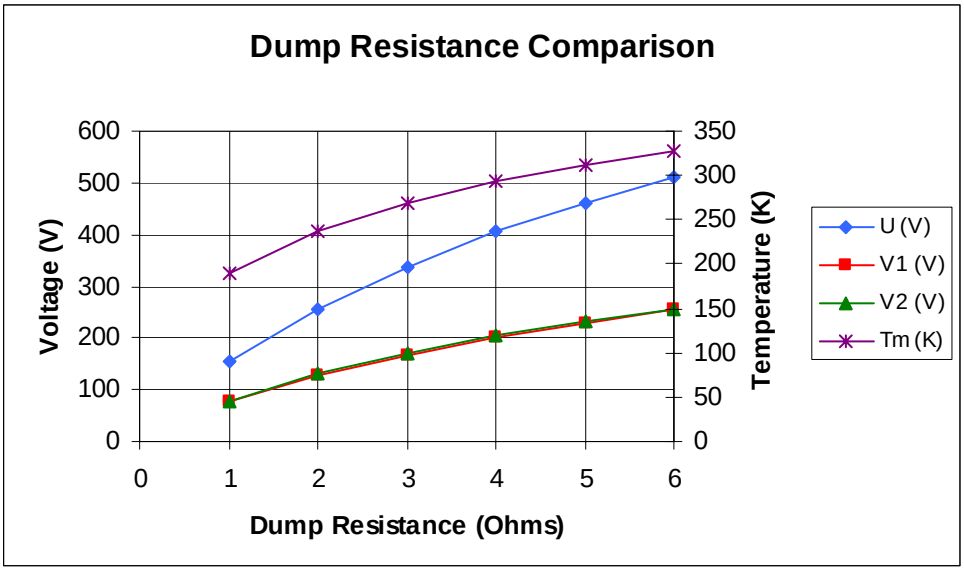
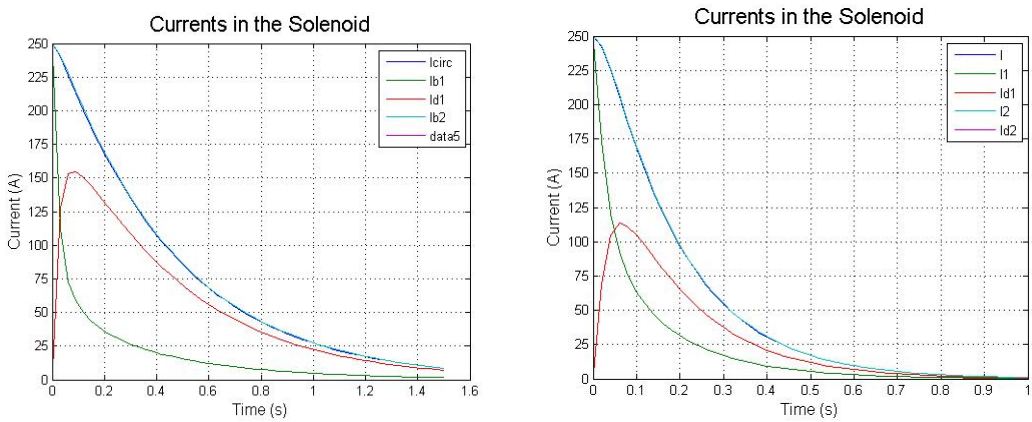
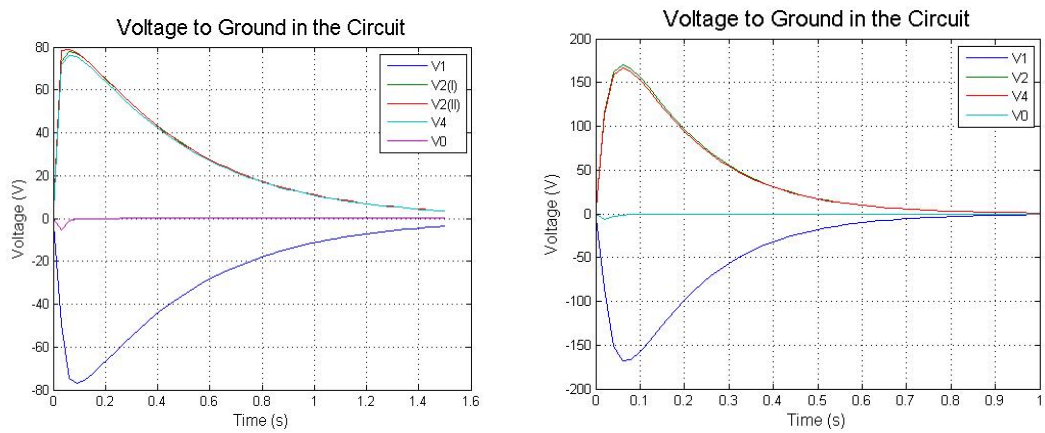


Fig. 7. Voltages in the circuit per Fig. 3 and the coil temperature as a function of the dump resistance.



a) b)

Fig. 8. Currents in the circuit in Fig. 3: a) Rd = 1 Ohm; b) Rd = 3 Ohm



a) b)

Fig. 9. Voltage to ground in the circuit in Fig. 1: a) Rd = 1 Ohm; b) Rd = 3 Ohm

We see that shunting bucking coils by resistors is a quite effective way to protect them in the case of a quench. The next logical step is to understand what can happen in the case when, with dump resistors connected in parallel to the bucking coils, the main coil is experiencing quenching.

II. Dump resistors are connected in parallel to both bucking coils of the lens; quench happens in one half of the main coil – case MC-BC.

The circuit scheme for the case is shown in Fig. 10.

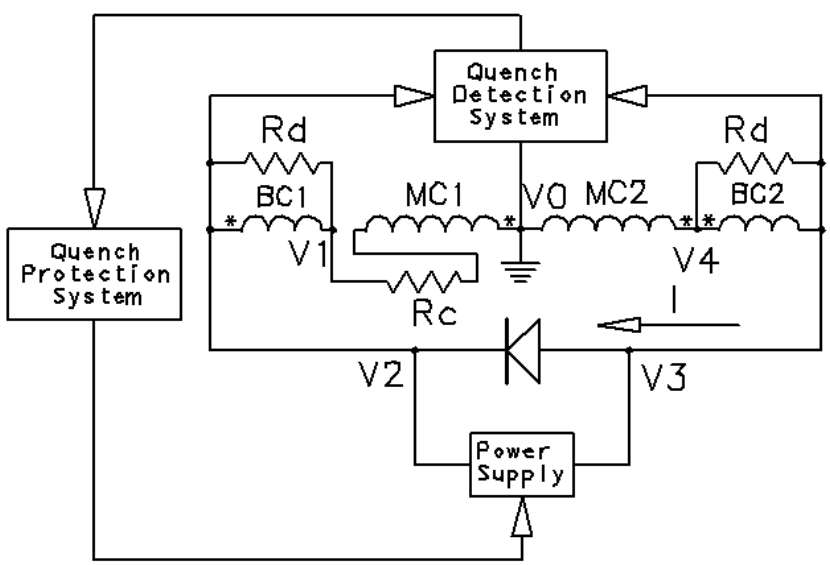


Fig. 10. Quench detection/protection functional scheme and current discharge circuit for the case of a quenching half of the main coil with dump resistors connected in parallel to both bucking coils.

To describe the current discharge process in the circuit in Fig. 10, we need to find the currents in both halves of the main coil, which are equal to the circuit current ***I***, and in the

two bucking coils: ***I1*** and ***I2***. The currents in the dump resistors ***Id1*** and ***Id2*** can be found as a difference between the circuit current and the corresponding bucking coil current. Equations describing the circuit in Fig. 10 are written below.

$$\frac{dI}{dt} = \frac{-I \cdot Rc \cdot (LB + B1B2) + (I1 + I2 - 2I) \cdot Rd \cdot RB}{2 \cdot [(LM + M1M2) \cdot (LB + B1B2) - (M1B1 + M1B2)^2]},$$

$$\frac{dI1}{dt} = \frac{I \cdot (LB - B1B2) - I1 \cdot LB + I2 \cdot B1B2}{(LB^2 - B1B2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LB + B1B2},$$

$$\frac{dI2}{dt} = \frac{I \cdot (LB - B1B2) + I1 \cdot B1B2 - I2 \cdot LB}{(LB^2 - B1B2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LB + B1B2}.$$

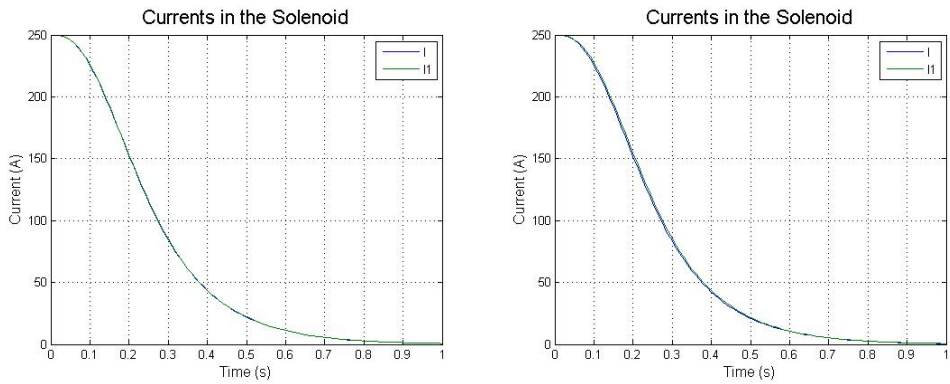
It is useful to notice that the current in the dump resistors depends on the voltage induced in the bucking coils by a changing current in the halves of the main coil. Because this current is the same for both halves, this inductive voltage is also the same; so we should expect ***I1*** = ***I2,*** and ***Id1 = Id2.*** This can simplify the equations above, but we used the full set of equations keeping in mind this property of the circuit to establish an additional checkup point. We indeed see that having the initial conditions as ***I = I1 = I2***, we come to equal ***I1*** and ***I2***.

The magnetic field in the quenching half of the main coil is modified by the current in the nearest bucking coil, which has a resistor connected in parallel. The algorithm of finding this field is similar to what was used in the BC-BC case. As before, knowing the temperature distribution in the coil, magnetic field, and the current at each time step, we can find turn resistance array and energy deposition, which allows modification of the temperature array in preparation for the next time step. As we know resistance, circuit equations can be solved to find all current derivatives and voltages in the coil.

Corresponding results are summarized in the Table 2 and Figures 11 and 12 below.

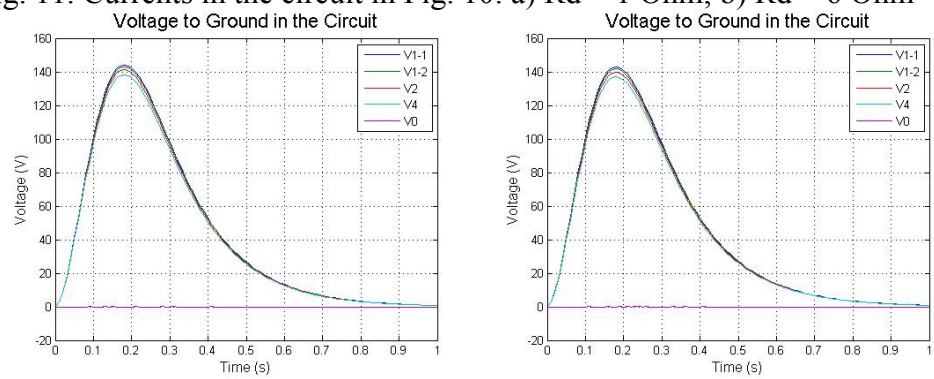
Table 2. MC-BC case summary table (Fig. 10).

Rd (Ohm)	Process duration (s)	Rc_max (Ohm)	Tm (K)	V1 (V)	V2 (V)	U (V)	Pd (W)	Wd (J)	Wc (kJ)
1	1	2.46	114	144	141	143	17.3	3.7	11.0
3	1	2.43	113	143	140	142	5.8	1.2	11.0
6	1	2.42	113	143	140	142	2.9	0.6	11.0



a) b)

Fig. 11. Currents in the circuit in Fig. 10: a) Rd = 1 Ohm; b) Rd = 6 Ohm



a) b)

Fig. 12. Voltage to ground in the circuit in Fig. 10: a) Rd = 1 Ohm; b) Rd = 6 Ohm

The dump resistors work with less efficiency when the quench occurs in the main coil, and we start seeing the dumps working only what the resistance is less than ~3 Ohm. Nevertheless, the critical parameters, such as the temperature and voltages, do not exceed safe levels.

Since the dump resistors have little effect on the propagation of the quench, the results of the modeling should be similar to the case studied in [1], when the resistance value was set equal to 0. Indeed, the graphs from both these cases are similar, as expected; the graphs below should be compared with similar graphs in [1].

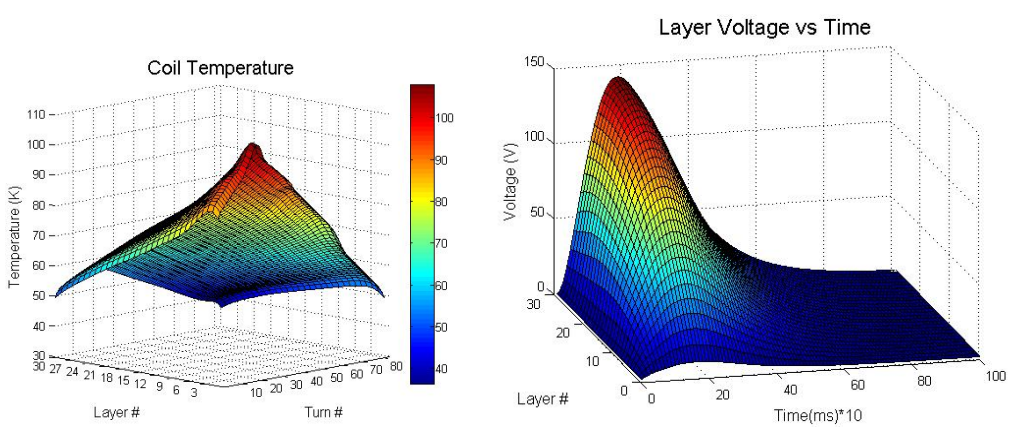


Fig. 13: Maximum temperature (a) and layer voltage vs. time (b); Rd = 6 Ohm

III. Dump resistors are connected in parallel to the main coils of the solenoid; quench happens in one of the bucking coils – case BC-MC

The second circuit configuration to explore features dump resistors connected to the main coil. Again we start with the case of quenching bucking coil, because here we expect a greater chance of possible problems.

The current discharge circuit fort this case is shown in Fig. 14.

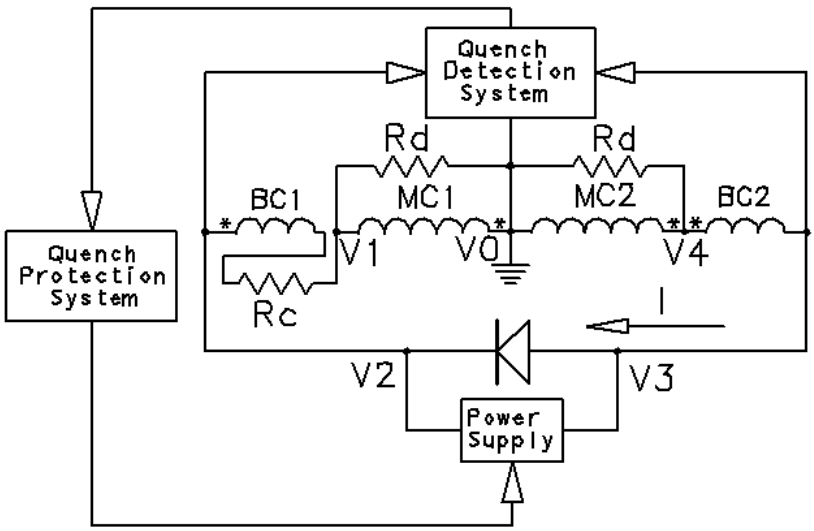


Fig. 14. Quench detection/protection functional scheme and current discharge circuit for the case of quenching bucking coil with dump resistors connected in parallel to both halves of the main coil.

Because the current in the dump resistors is only due to the inductive voltage in the main coil, we should expect full symmetry of the currents both in the main coil halves (MC1 and MC2) and in the dump resistors (Rd1 and Rd2). Not making this assumption from the very beginning, we can derive circuit equations similar to what was done earlier:

$$\frac{dI}{dt} = \frac{-I \cdot Rc \cdot (LM + M1M2) + (I1 + I2 - 2I) \cdot Rd \cdot RM}{2 \cdot [(LM + M1M2) \cdot (LB + B1B2) - (M1B1 + M1B2)^2]},$$

$$\frac{dI1}{dt} = \frac{I \cdot (LM - M1M2) - I1 \cdot LM + I2 \cdot M1M2}{(LM^2 - M1M2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LM + M1M2},$$

$$\frac{dI2}{dt} = \frac{I \cdot (LM - M1M2) + I1 \cdot M1M2 - I2 \cdot LM}{(LM^2 - M1M2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LM + M1M2}.$$

We indeed see that the equations for ***I1*** and ***I2*** with the identical initial conditions give equal currents. Observation of program results further validates the assumption that the currents in both of the main coils are equal. Magnetic field in the quenching bucking coil must be found taking into account the difference between the currents in the main coil and the bucking coil, which is accomplished by using parameterized magnetic field transfer functions, as was done earlier in this study. Because ***I1 = I2***, we can use one-

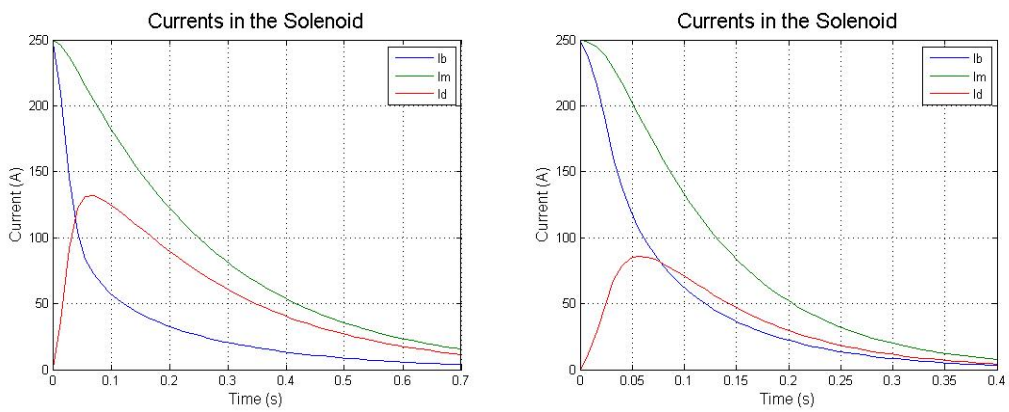
dimensional parameterization, which simplifies computation of sample arrays of the magnetic field. Table 3 summarizes the results of modeling this case.

Table 3. Summary table of the BC-MC case (Fig. 14).

Rd (Ohm)	Process duration (s)	Rc_max (Ohm)	Tm (K)	V1 (V)	V2 (V)	U (V)	Pd (kW)	Wd (kJ)	Wc (kJ)
1	0.7 s	5.83	182	-132	140	267	35	6.7	4.13
3	0.4 s	7.94	235	-258	262	521	45	4.7	6.30
6	0.2 s	9.23	268	-356	361	717	42	3.3	7.66

The results in Table 3 indicate that this quench protection scheme can be used with dump resistor values of less than ~3 Ohms. At 3 Ohms, the maximum temperature does not exceed 240 K, voltage to ground is ~260 V, and the maximum voltage across the quenching coil is ~520 V. As in the BC-BC case, using lower values of the dump resistors results is a better efficiency of energy removal from the system.

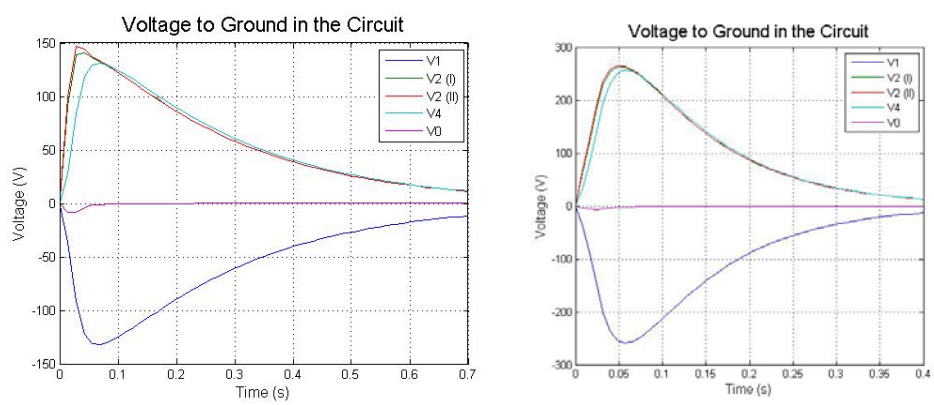
Fig. 15 shows traces of current in the circuit with 1 Ohm and 3 Ohms dump resistors.



a) b)

Fig. 15. Currents in the circuit in Fig. 14: a) Rd = 1 Ohm; b) Rd = 3 Ohm

Fig. 16 shows voltages to ground at several points in the circuit (Fig. 14) during quenching with the dump resistors of 1 Ohm and 3 Ohms.



a) b)

Fig. 16. Voltage to ground in the circuit in Fig. 14: a) Rd = 1 Ohm; b) Rd = 3 Ohms

The symmetric nature of this quench protection scheme suggests several advantages. For example, in this case, each dump resistor will dissipate the same amount of energy, while in the BC-BC case with dump resistors in parallel to the bucking coils, the resistors dissipate different amounts of energy. As we cannot predict which coil will quench, dump resistors in each of schemes under study must have the same resistance; connecting the resistors to the halves of the main coil will insure each of them handles the same power.

Change (decrease) of current in the quenching bucking coil induces voltage across the main coil with a polarity that generates current in the dump resistor directed in the opposite direction relative to the current in the main circuit. That's why in the case of quench protection with dump resistors connected in parallel to the main coils, the current in the main coil is always larger than that of the bucking coil, like it was in the BC-BC case. As a result, in the code we could use the same parameterized magnetic field distributions in the bucking coil that were utilized in the case with dump resistors connected in parallel to the quenching bucking coil.

IV. Dump resistors are connected in parallel to the main coils of the solenoid; quenching happens in one half of the main coil – case MC-MC.

The final case explores quenching in one half of the main coil with dump resistances connected in parallel to both halves. Mathematically, this case is similar to the BC-BC case where a dump resistor was connected in parallel to the quenching bucking coil. So, we expect circuit equations also be similar. The circuit scheme for this case is shown in Fig. 17.

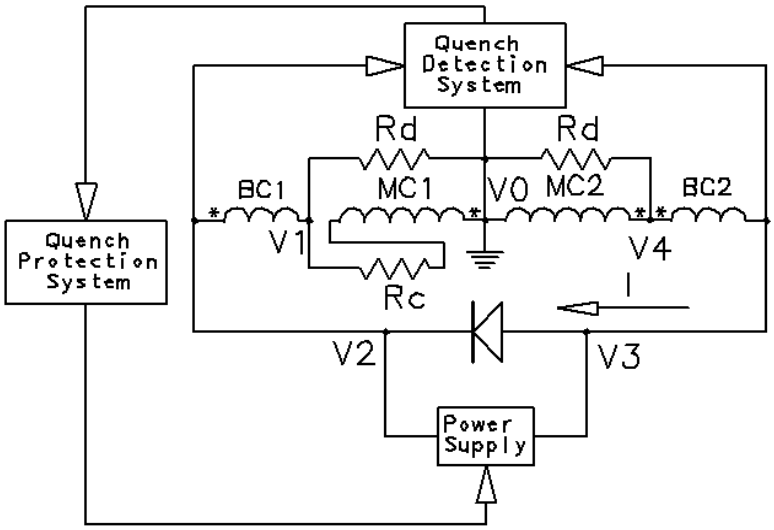


Fig. 17. Quench detection/protection functional scheme and current discharge circuit for the case of quenching one half of the main coil with dump resistors connected in parallel to both halves of the main coil.

To describe the current discharge process in the circuit in Fig. 17, we need to find the currents in the bucking coil which are equal to the circuit current ***I***, and in the two main coils: ***I1*** and ***I2***. The currents in the dump resistors ***Id1*** and ***Id2*** can be found as a

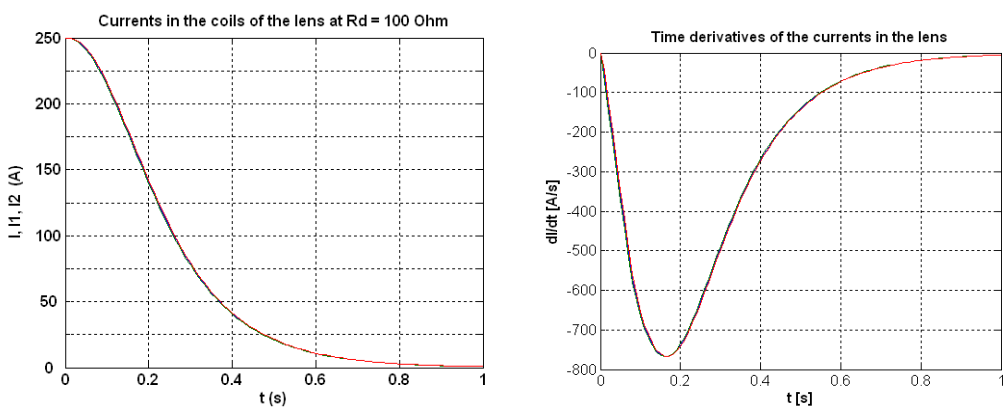
difference between the circuit current and the corresponding main coil current. Differential equations that describe the circuit are shown below:

$$\frac{dI}{dt} = \frac{I1 \cdot Rc \cdot (M1B1 + M1B2) + (I1 + I2 - 2I) \cdot Rd \cdot RM}{2 \cdot \left[(LM + M1M2) \cdot (LB + B1B2) - (M1B1 + M1B2^2)\right]}$$

$$\frac{dI1}{dt} = \frac{I \cdot (LM - M1M2) - I1 \cdot \frac{Rc + Rd}{Rd} \cdot LM + I2 \cdot M1M2}{(LM^2 - M1M2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LM + M1M2}$$

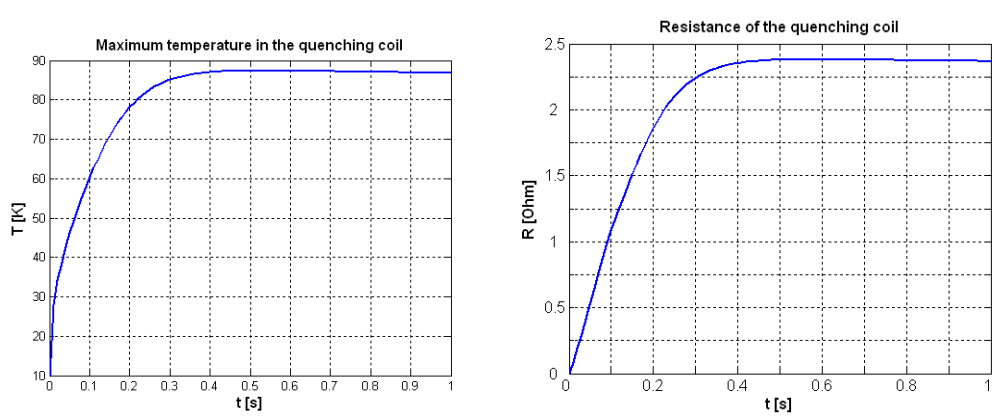
$$\frac{dI2}{dt} = \frac{I \cdot (LM - M1M2) + I1 \cdot \frac{Rc + Rd}{Rd} \cdot M1M2 - I2 \cdot LM}{(LM^2 - M1M2^2)/Rd} - \frac{dI}{dt} \cdot \frac{M1B1 + M1B2}{LM + M1M2}$$

Results obtained in this case with ***Rd*** → ∞ must converge to those obtained in [1] with ***Rd*** = 0. In both cases, normal zone propagation in the quenching half of the main coil is the only resistive component. Figures 18 to 22 below provide a summary of the results of simulation with ***Rd*** = 100 Ohm, which can be compared with corresponding graphs in [1] to conclude that the cases are quite similar.



a) b)

Fig. 18. Currents I, I1, and I2 in the lens (a) and their derivatives (b) at Rd = 100 Ohm.



a) b)

Fig. 19. Maximum temperature in the quenching MC1 (a) and the coil resistance (b) at Rd = 100 Ohm.

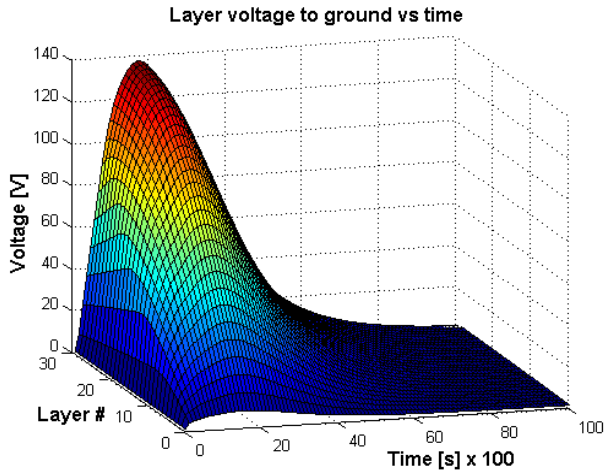


Fig. 20. Voltage to ground in the quenching coil at Rd = 100 Ohm

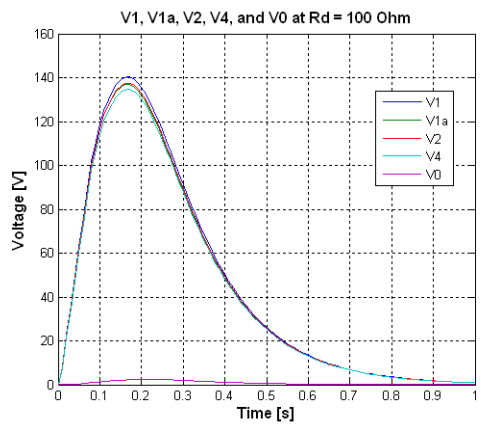


Fig. 21. Voltage to ground in sections of the circuit at Rd = 100 Ohm

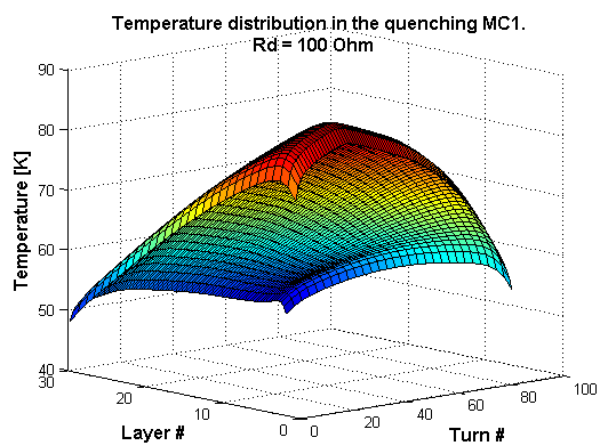


Fig. 22. Temperature distribution in the quenching main coil at Rd = 100 Ohm

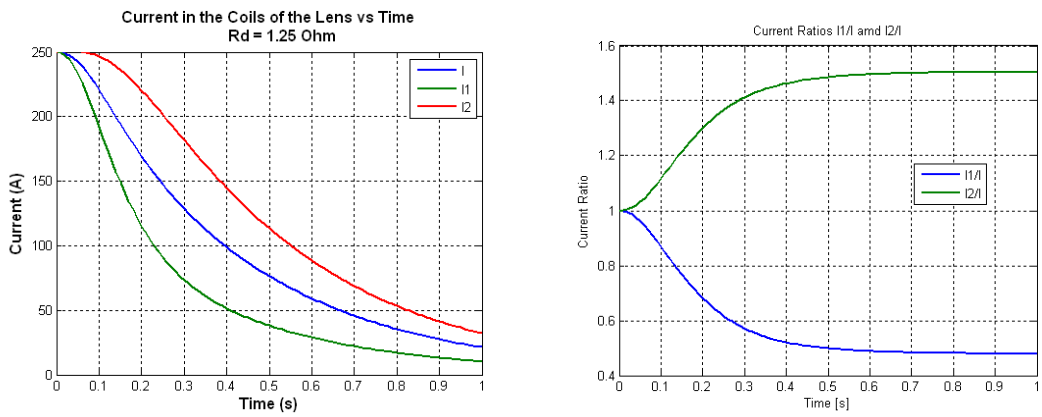
The main technical difference between the BC-BC and MC-MC cases is that in the BC-BC case we did not have so strong inductive coupling between the coils with attached dump resistances. Strong coupling in the MC-MC case is a reason why the current in the

part of the main coil that is not quenching cannot be considered equal to the circuit current. Instead, we will have three different currents, and magnetic field in the quenching half of the main coil must be found based not only on the self-current, but also on the currents in the bucking coils (with circuit current) and the neighboring half of the main coil. The magnetic field in the quenching coil becomes a function of two "current ratio" parameters; the range of current ratios ***I1/I*** and ***I2/I*** is shown in the table below as a function of the value of the dump resistor:

Table 4. Range of the current ratio parameter change

Rd (Ohm)	***I1/I***	***I2/I***
20	0.94	1.06
10	0.89	1.11
5	0.79	1.2
2.5	0.65	1.34
1.25	0.48	1.5

Fig. 23 below illustrates data in the Table 4.



a) b)

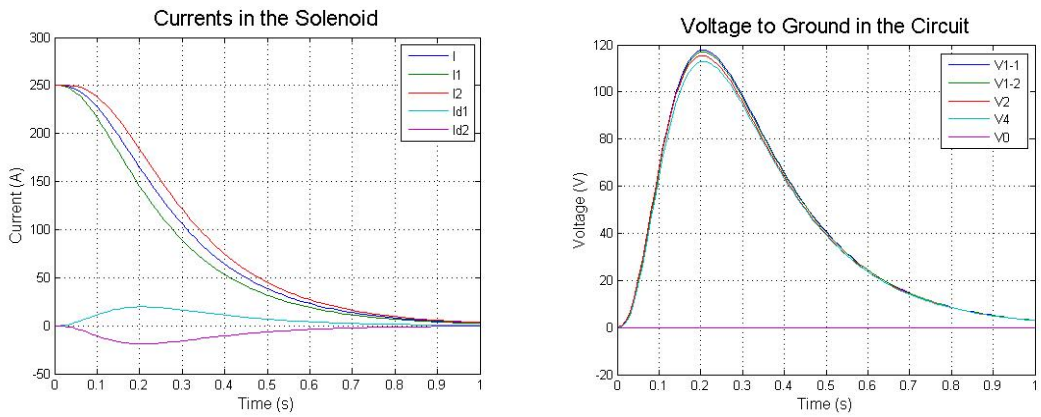
Fig. 23. Currents in circuit (a) and current ratio change (b) at Rd= 1.25 Ohm

Table 5 summarizes the modeling results for this case.

Table 5. Summary table of the MC-MC case

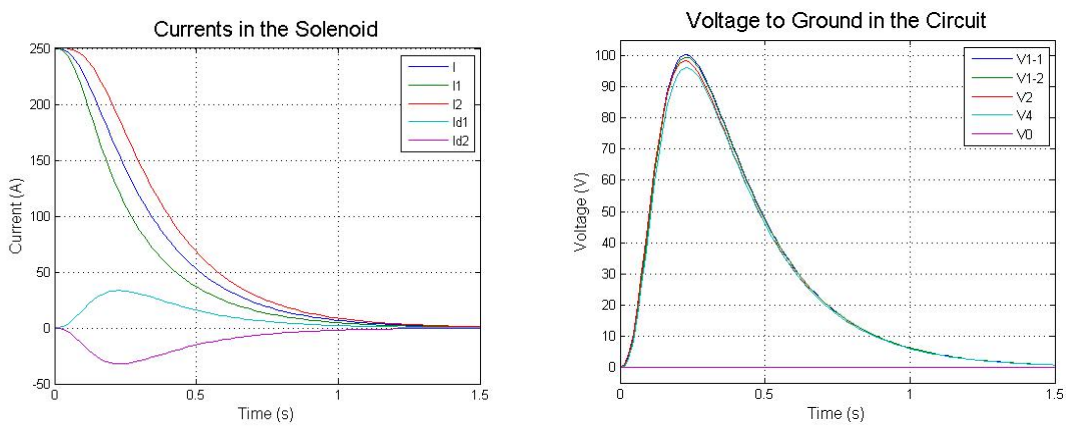
Time	Rd (Ohm)	Rm (Ohm)	Tm (K)	V1 (V)	V2 (V)	U (V)	Wd 1 (kJ)	Wd 2 (kJ)	Wc (kJ)
Total: 2 s Step: 1 ms	1	1.81	98	63.5	62	63.0	1.77	1.63	7.6
Total: 1.5 s Step: 1 ms	3	2.09	105	100	98	99.5	0.98	0.9	9.1
Total: 1 s Step: 1 ms	6	2.22	108	118	115	117	0.58	0.54	9.9

Figures below illustrate the data in the table showing the currents and voltages changing in time based on three chosen values of dump resistance.



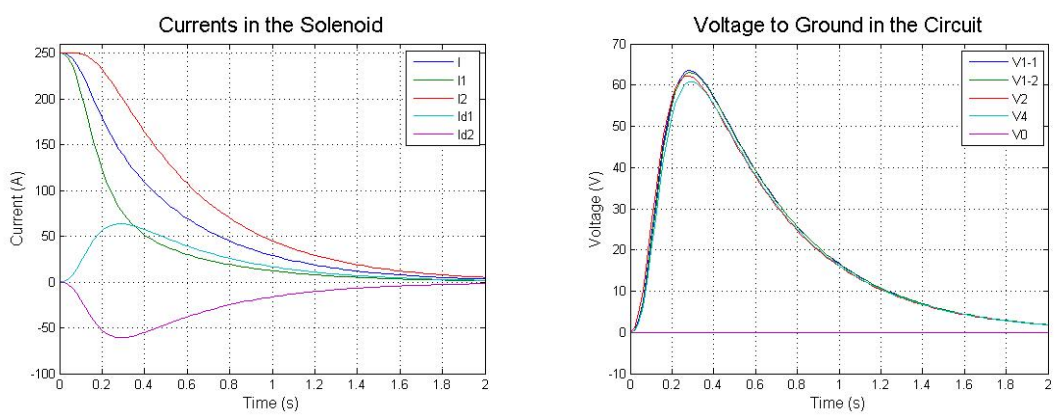
a) b)

Fig. 24. Currents (a) and voltages (b) in the circuit per Fig. 17; Rd = 6 Ohm.



a) b)

Fig. 25. Currents (a) and voltages (b) in the circuit per Fig. 17; Rd = 3 Ohm.



a) b)

Fig. 26. Currents (a) and voltages (b) in the circuit per Fig. 17; Rd = 1 Ohm.

In the case where the dump resistors are connected in parallel to the halves of the main coil and a quench happens in one of the halves, two 1-Ohm dump resistors dissipate ~30% of the total energy stored in the magnetic field.

V. Choice of the protection scheme for the SS2 coil system

To understand which protection scheme of the two we analyzed works better, let us to fill a table that compares key parameters: maximum temperature in quenching coils ***Tm***, maximum voltage to the ground in the circuit ***Vm*** and the voltage across the quenching coil ***Um***, and the energy dissipated in the dump resistors ***Wd1*** and ***Wd2***. The initial energy stored in the coil in all the cases was 11 kJ, which corresponded to the initial current ***I0***= 250 A.

Table 6. Case comparison table

Rd	Case:	**BC-BC**	**MC-BC**	**BC-MC**	**MC-MC**
1 Ohm	***Tm*** (K)	189	114	182	98
	Vm / Um (V)	80 / 160	140 / 140	140 / 267	63 / 63
	Wd1 (kJ)	8	0.002	3.35	1.77
	Wd2 (kJ)	0.002	0.002	3.35	1.63
3 Ohm	***Tm*** (K)	269	113	235	105
	Vm / Um (V)	170 / 340	140 / 140	260 / 520	100 / 100
	Wd1 (kJ)	6.1	0.001	2.35	1
	Wd2 (kJ)	0.001	0.001	2.35	0.9

We have a bit lower maximum temperature in a quenching coil in the cases when dump resistors are connected to the halves of the main coil (XX-MC), but higher voltage across the quenching coil, although within acceptable limits if the dump resistor value is below 3 Ohm. Extracted energy is distributed more evenly between the dumps in this case, and with a quenching main coil they still remove significant energy. So, it looks reasonable to use this connection scheme for protection. Each dump resistor must be able to dissipate ~4 kJ in about one second with the maximum current of ~150 A and the maximum voltage of ~500 V.

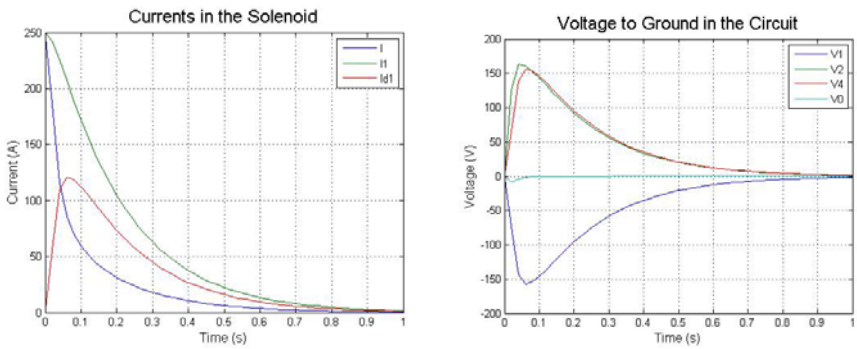
Type and value of the dump resistor were chosen based on availability in Fermilab stock: it was made by cutting spiral turns through a pipe made of a high resistivity alloy; nominal resistance of the assembly is R = 1.3 Ohm. Photo of the resistor is shown below.

Fig. 27. Dump resistor; R = 1.3 Ohm

VI. Analysis of the Chosen Quench Protection Scheme

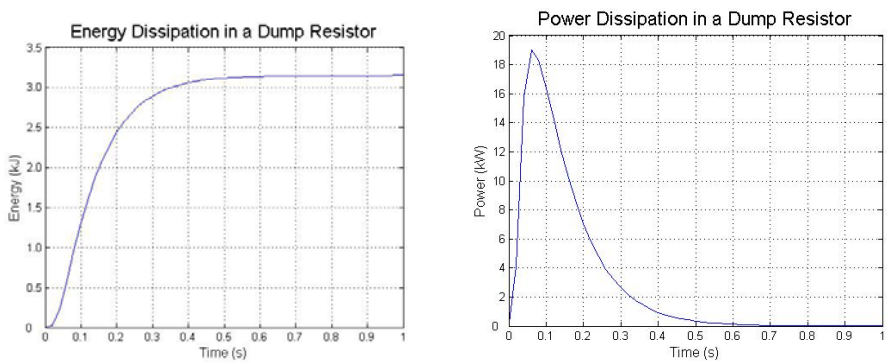
As indicated in the previous section, the quench protection scheme with the dump resistors connected in parallel to the halves of the main coil has been chosen for implementation during the SSR2 focusing lens test. Based on availability, a dump resistor with a resistance of 1.3 Ohms has been selected for use in the protection scheme.
This section presents the results of modeling quench propagation in the chosen protection circuit configuration; the two cases correspond to those shown in Fig. 14 and Fig. 17.

Figures and a table below summarize results of modeling for the case of quenching bucking coil (case BC-MC - Fig. 14).



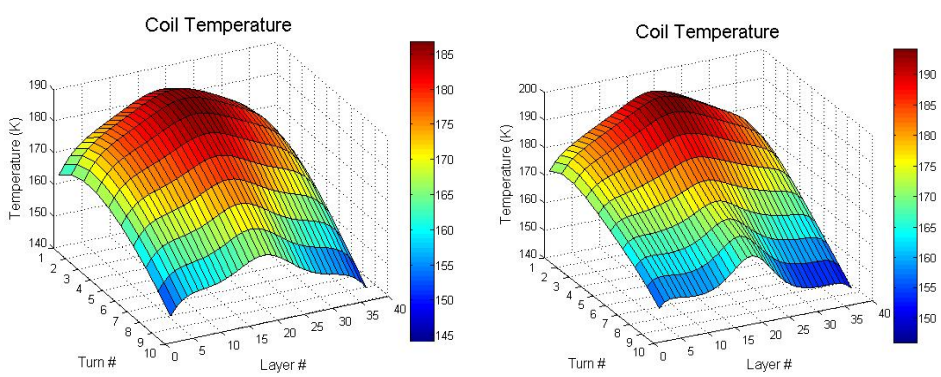
a) b)

Fig. 28. Currents (a) and voltages (b) in the circuit per Fig. 14; Rd = 1.3 Ohm.



a) b)

Fig. 29. Energy (a) and power (b) dissipation in the circuit per Fig. 14; Rd = 1.3 Ohm.



a) b)

Fig. 30. Temperature distribution in quenching coil, at 1 sec. (a) and at 0.38 sec. (b).

At t = 0.38 s, the maximum temperature in the quenching coil reaches its maximum value, as shown in the graph below.

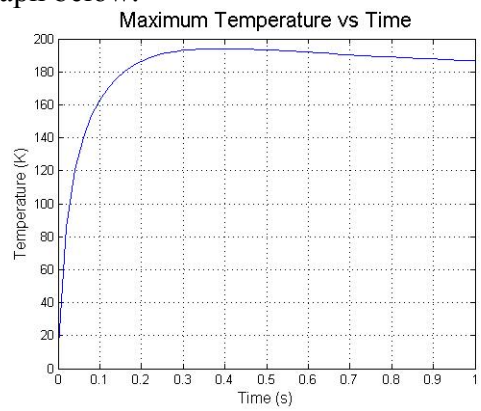
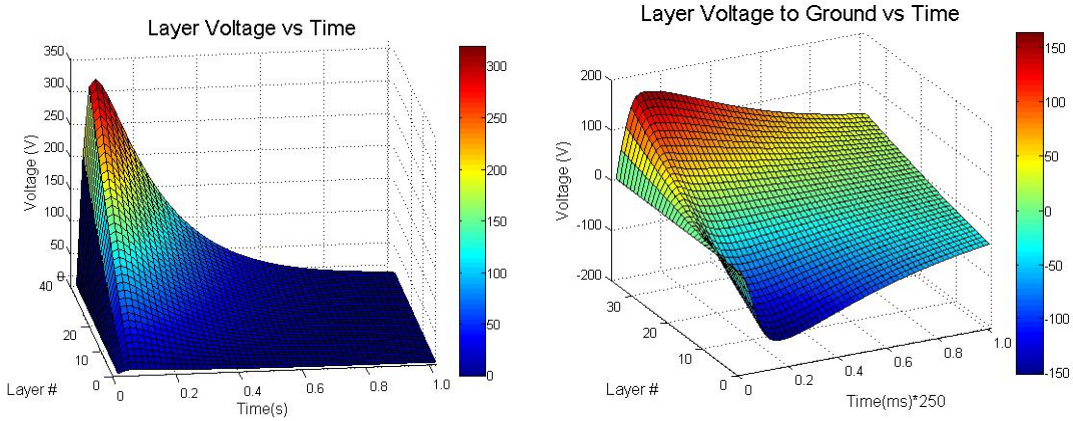


Fig. 31. Maximum temperature in the quenching coil vs. time

Graphs in Fig. 32 show the development in time of the layer-to-inner layer voltage and the layer-to-ground voltage for the quenching coil.



a) b)

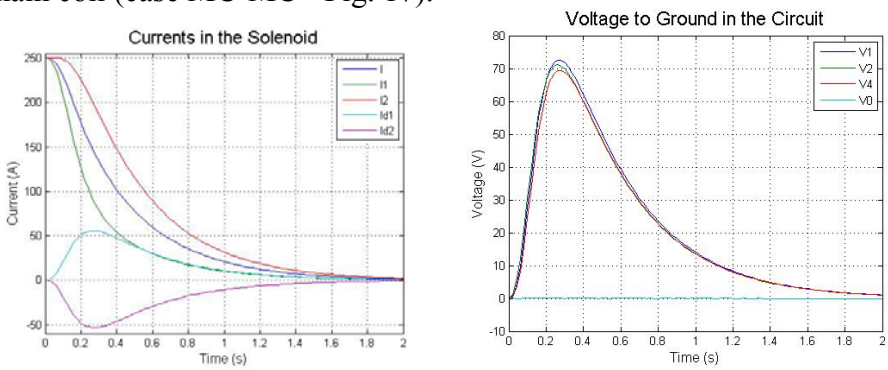
Fig. 32. Voltage in the layers of the quenching coil relative to the inner layer (a) and layer voltage to ground (b).

Table 7 summarizes the results of modeling obtained for this case.

Table 7. Summary table of the BC-MC case with Rd = 1.3 Ohms (Fig. 14).

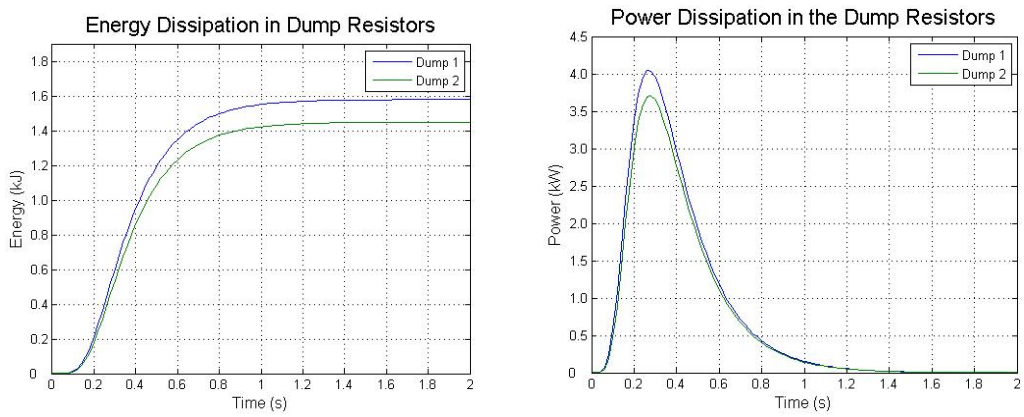
Rd (Ohm)	Max Rc (Ohm)	Max Tm (K)	Max V (V)	Max U (V)	Max Pd 1 (kW)	Max Pd 2 (kW)	Wd1 (kJ)	Wd2 (kJ)	Wc (kJ)
1.3	6.32	194	163	318	19.0	19.0	3.15	3.15	4.54

Figures and a table below provide a summary of the results for the case of quenching main coil (case MC-MC - Fig. 17).



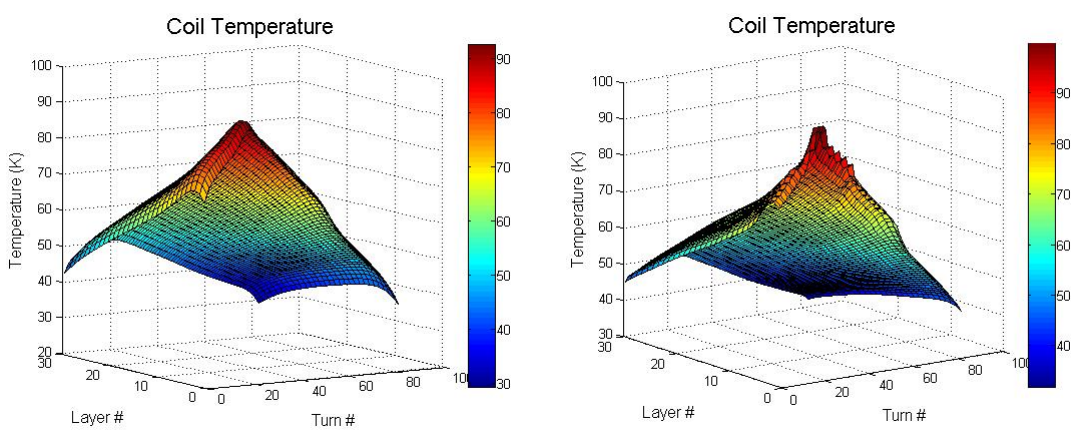
a) b)

Fig. 33. Currents (a) and voltages (b) in the circuit per Fig. 17; Rd = 1.3 Ohm.



a) b)

Fig. 34. Energy (a) and power (b) dissipation in the circuit per Fig. 17; Rd = 1.3 Ohm.



a) b)

Fig. 35. Temperature distribution in the quenching coil, at 2 sec. (a) and at 0.48 sec. (b).

Maximum temperature in the quenching coil reaches ~100 K at 0.48 s, as seen in the figure below.

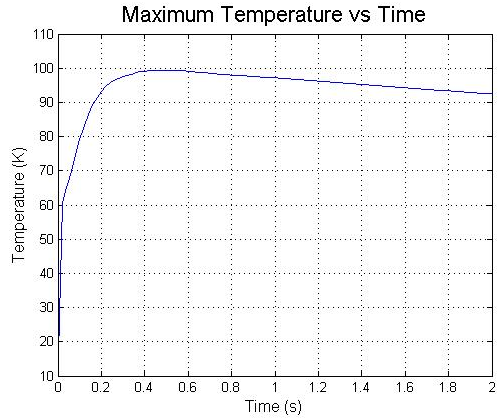


Fig. 36. Maximum temperature in the quenching coil vs. time

Graph in Fig. 37 shows development in time of the layer-to-inner layer voltage for the quenching coil.

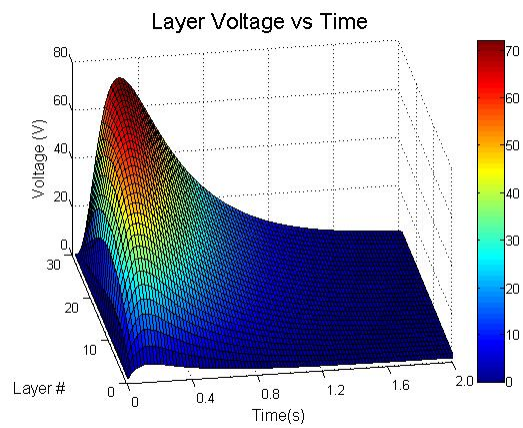


Fig. 37. Voltage in the layers of the coil relative to the inner layer

Table 8 summarizes results of modeling obtained for this case.

Table 8. Summary table of the MC-MC case with Rd = 1.3 Ohms (Fig. 17).

Rd (Ohm)	Max Rc (Ohm)	Max Tm (K)	Max V (V)	Max U (V)	Max Pd 1 (kW)	Max Pd 2 (kW)	Wd1 (kJ)	Wd2 (kJ)	Wc (kJ)
1.3	1.88	99.4	72.5	71.9	4.04	3.71	1.58	1.45	7.98

VII. Summary

During this study, we analyzed quench propagation / protection for the SSR2 focusing lens of the HINS proton linac front end. The core of the quench propagation module was upgraded to model cases with dump resistors connected in parallel to the main coils or the bucking coils of the focusing lens. Based on results of the analysis, quench protection scheme with the two dump resistors Rd = 1.3 Ohm connected in parallel to the halves of the main coil was chosen, and analysis of the final configuration was made. This analysis establishes background for configuring the quench protection system during SSR2 lens testing in IB1 environment.

The next phase of this work will address the most common case of the circuit configuration with dump resistors connected to all four coils of the lens, as well as quenching in several coils and delayed quenching.

References:

1. I. Terechkine, "SS2 Focusing Solenoid Quench Protection Study", TD-09-016, June 2009.
2. G. Davis, et al, "HINS Linac SS2 Section Prototype Focusing Lens Design, TD-09-003, FNAL, March 2009.
3. I. Terechkine, "Quench Protection Study for the Solenoids of Superconducting Sections of HINS Linac", TD-09-002, FNAL, February 2009.
4. I. Terechkine, V. Veretennikov, "Normal Zone Propagation in Superconducting Focusing Solenoids and Related Quench Protection Issues", IEEE Transaction on Applied Superconductivity, v. 18, No. 2, pp. 1325 – 1328, June 2008.