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Quench Protection Study for Focusing Solenoids of Superconducting Sections of HINS Linac

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I. Introduction

Quench protection of focusing solenoids for the first superconducting section of HINS linac (SS1) has been addressed in [1] and [2]. At that time (summer 2007), the solenoid base design was ~160 mm long with ~40% quench current margin. After the situation with superconducting strand availability changed at the end of 2007, a new design was made: the one with more modest margin, but with much less strand required. Introduction of steering dipoles also required some rethinking of the design concept, which, in turn, resulted in a different steering coil fabrication approach. Two prototypes of the solenoid were fabricated and tested. The first one (type 1, without steering coils) was built to test the design concept described in [3] and to verify that the desired level of fringe magnetic field can be reached. The results of the test were described in [4]. The second prototype was equipped with steering dipoles (type 2) and was built to verify that the steering coil fabrication techniques work as we hoped and that the introduction of these coils does not increase the fringe field above some allowable level [5].

Based on the results obtained in [1] and [2], the quench protection issues during tests of the prototypes were addressed similar to how it was done when the CH section solenoids were tested (e.g. see [6] and [7]). A dump resistor value of ~1.8 Ohm was found optimal in [1] to keep the temperature in the solenoid below 300 K and the voltage to ground below 400 V (having in mind the 500 V voltage used during the hipot test on the cold system).

One of the findings in [1] was that protection of the solenoids for the second superconducting section of HINS (SS2) would require special attention because the dump resistance-based protection technique is not going to ensure the needed low levels of the voltage to ground and the bucking coil (BC) temperature. This conclusion was based on the preliminary design of SS2 solenoid, which had longer main coil (MC) and higher inductance and stored energy. As a result, the expected maximum temperature and voltage to ground of the SS2 solenoid were significantly higher than that of the SS1 system, which were already close to their limits of 300 K and 400 V.

Meanwhile, following design modifications made for the SS1 focusing lens [3], a new design of the SS2 solenoid was proposed [8] that took advantage of the experience gained during SS1 lens fabrication and testing. This design used rectangular strand with higher critical current to lower the coil inductance; simultaneously, a lower quench current margin was accepted, that also led to lower inductance and reduced stored energy of the solenoid.

In this note, the quench analysis approach developed in [1] and [2] is applied to the modified designs of the focusing solenoids SS1 and SS2.

II. Focusing Solenoid Description

Table 1 compares parameters of focusing solenoids for the superconducting sections of HINS linac. The data for the "old" design of the SS1 system analyzed in [1] is included for comparison.

Table 1. Superconducting Section Focusing Solenoids

Parameter	**SS-1 "Old"**	**SS-1 "New" (T2 #1)**	**SS-2**
Nominal current (A)	135	174	193
Quench current (A) @ 4.2 K	203	220	254
Max. stored energy (kJ)	8.3	6.7	11.2
Main Coil			
Strand bare (mm)	Dia. 0.808	Dia. 0.808	1 x 0.6
Strand insulated (mm)	~0.840	~0.863 (max)	1.08 x 0.66
Number of layers	29	28	30
Turns in each layer	166	125 / 124	166
Number of turns	4835	3486	4980
Length (mm)	144	108	188
Inner Diameter (mm)	40	40	40
Outer diameter (mm)	85.3	84.2	84.2
Inductance (H)	0.388	0.244	0.335
Bucking Coil			
Strand bare (mm)	Dia. 0.5	Dia. 0.5	Dia. 0.5
Strand insulated (mm)	Dia. 0.525	Dia. 0.525	Dia. 0.525
Number of layers	42	39	36
Turns in each layer	10	11 / 10	10 / 9
Number of turns	420	410	342
Length (mm)	5.4	6.0	5.4
Inner Diameter (mm)	39	LE / RE: 45.0 / 44.0	46
Outer diameter (mm)	79.6	LE / RE: 81.1 / 79.9	79.1
Inductance (H)	0.013	0.0147	0.0115

The inductance of the new SS1 solenoid (as described in [3]) is significantly lower than that of the "old" design. It is much closer now to the CH section solenoids, which is 0.215 H. More over, the inductance of the new SS2 solenoid is still lower that the inductance of the SS1 "old" design. This is because strand with larger cross-section is used in the device and because similar number of turns is spread over longer distance. This gives some hope that using the dump resistance can help in the case of the SS2 solenoid protection as it did for the SS1 solenoid. The complication is that as the current in the SS2 solenoid is higher, the stored energy is significantly higher than in the SS1 system at lower current.

Because cross-section of the strand in the main coil became larger, higher current is used to power the solenoid, and the thickness of the bucking coils must be made smaller to adjust for the increased current density in the strand of the bucking coils.

Main design features of the SS1 and SS2 systems are shown in Fig. 1 and Fig. 2.

The main coil of the SS2 solenoid consists of two windings separated by an intermediate barrier. This provision allows more flexibility when a protection solution is to be found. But before exploring other options, the simple approach of protection by a dump resistor must be re-evaluated.

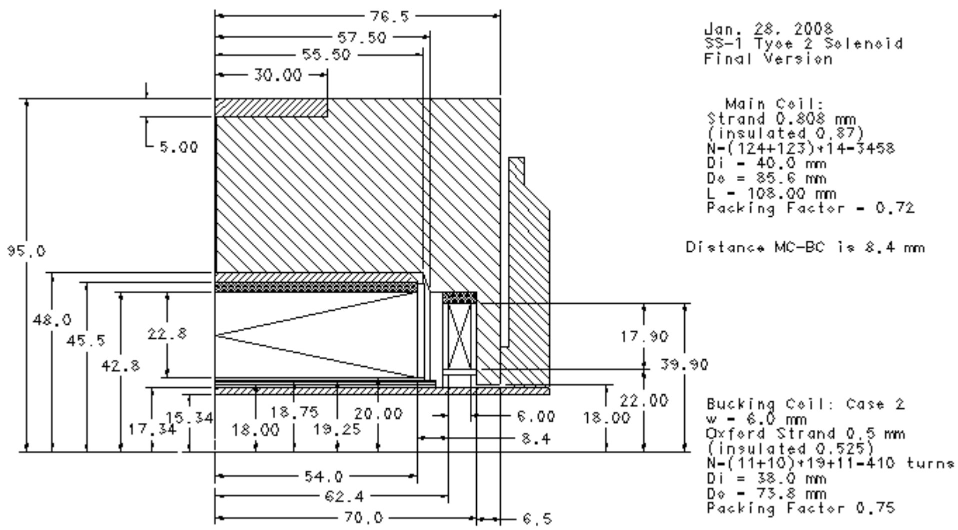

Fig. 1. SS1 prototype type 2 solenoid design [3] (only one half of the solenoid is shown)

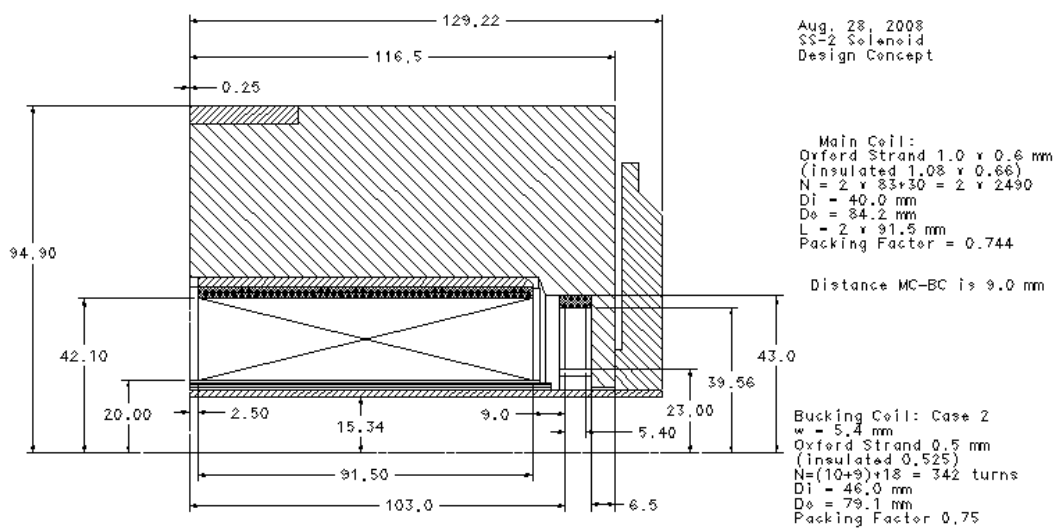

Fig. 2. SS2 prototype type 2 solenoid design [8] (only one half of the solenoid is shown)

III. Modeling Quench Propagation.

It makes sense to re-evaluate quench propagation and related protection issues for the new design version of SS1 section solenoid first to be sure that protection steps used during testing of this solenoid were adequate.

1. Quench propagation study for the new design version of SS1 solenoid

As was done in [1], a series of quench protection program [2] runs was made with different values of the dump resistance. The closed current discharge circuit (after quench is detected and power supply phases off) consists of the series-connected dump resistor, main coil (MC), bucking coil #1 (BC1), and bucking coil #2 (BC2). Connection to ground is made between the dump resistor and BC2. As shown in [1], this configuration provides the lowest voltage to ground at quench, which is the ultimate goal. Also shown in [1] is that in this case the highest voltage is generated in the bucking coil connected to ground (that is BC2) if the quench is initiated in the middle of the inner side of this coil.

Main results obtained by running the program are summarized in Table 2. V1 is the voltage to ground at the point between BC1 and BC2; V2 is voltage to the ground at the point between BC2 and MC; V3 is the voltage at the point between the MC and the dump resistor, and V3mod is the voltage drop across the dump resistor. A 200 A current was used for all the runs, which is close to the maximum current obtained in [5], where the measured LHe temperature was ~4.4 K.

Table 2. New SS1-T2 BC Quench Data

Rdump (Ohm)	V1max (V)	V2max (V)	V3mod (V)	Tmax (K)	R_BC (Ohm)	Edump (kJ)	Etot (kJ)
0	584	553	0	207	7.3	0	5.5
0.5	464	435	100	183	6.1	1.1	5.5
1.0	364	338	200	162	5.1	2.1	5.5
1.5	285	261	300	144	4.2	2.9	5.5
2.0	220	197	400	128	3.5	3.5	5.5

Without a dump resistor, we can have maximum voltage to ground of ~600 V, which is higher than the hipot voltage of 500 V and hence unacceptable. The maximum temperature reaches 207 K. Adding a dump resistor to the solenoid current discharge circuit results in some relaxation of the maximum voltage developed in the BC, but instead the voltage across the dump resistance develops. Fig. 3 below shows how the voltage to the ground changes in these two parts of the circuit. The optimum value of the dump resistor in this case is ~1.5 Ohm; this value of the dump resistor was used during the SS1 prototype solenoids testing summarized in [4] and [5].

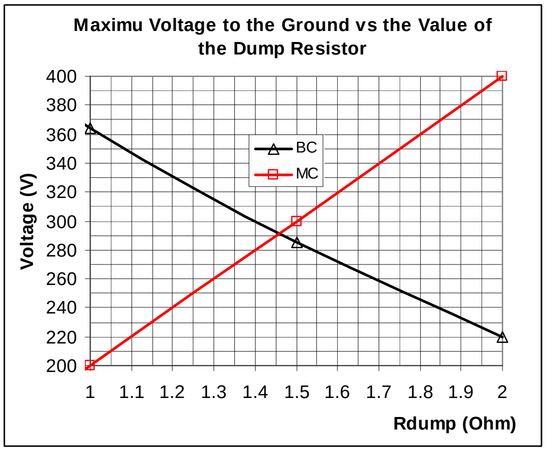

Fig. 3. Voltage to ground after quenching in the SS1 solenoid BC

With the optimal dump, the maximum voltage to ground is ~290 V, which seems OK. Total energy stored in the system at 200 A is 5.5 kJ, and with Rdump = 1.5 Ohm ~53% of this energy is dissipated in the dump resistor, that is outside of the cryostat. The maximum temperature in the bucking coil with the optimal dump resistor is 144 K.

As was expected for the SS1 section solenoid, protection against excessive voltage and temperature does not differ much from what was done for the CH systems. Adjusting the value of the dump resistor in the current discharge circuit to its optimal value results in the acceptable quench protection solution. It worth to mention though that the maximum allowed voltage of 500 V was taken quite conservatively and can probably be increased. Analysis of one of the protection system failures that happened during the solenoid testing in [4] shows that the solenoid has survived the quench event in the bucking coil without being protected by a dump resistor.

2. Quench propagation study for the new design version of SS2 solenoid

Comparing the data in Table 1, we see that the expected quench behavior of SS2 focusing lens must be close to that found in [1] for the "old design" of the SS1 system with the same starting current. This statement is supported by the graphs in the Fig.4 to Fig.6, that show the circuit current, maximum temperature in the quenching bucking coil, and the maximum voltage to ground with Rdump = 0 at I0 = 200 A, which is close to the operating current of the SS2 solenoid in accordance with Table 1. These figures must be compared with the corresponding figures in [1].

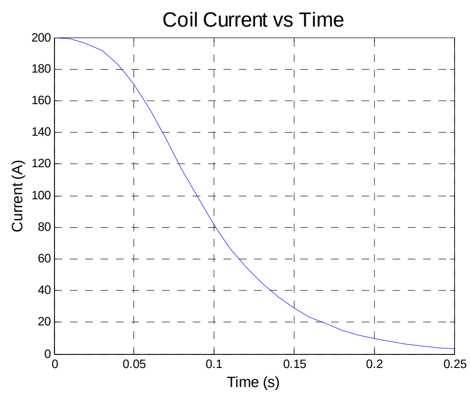

Fig. 4. Current decay after quench in the SS2 bucking coil; Rdump = 0; I0 = 200 A.

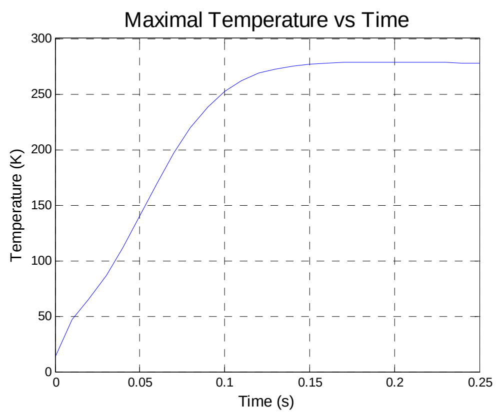

Fig. 5. Temperature rise in the quenched bucking coil; Rdump = 0; I0 = 200 A.

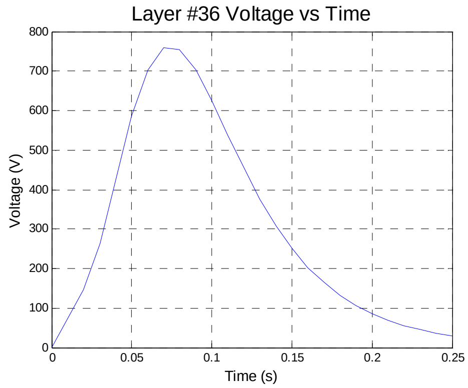

Fig. 6. Maximum voltage to ground in the bucking coil of SS2 solenoid during quench; Rdump = 0, I0 = 200 A.

Although the maximum temperature is still within the allowable range (<300 K), the maximum voltage is too high and some measures must be undertaken to make it lower. Here we investigate to what extent using the dump resistor can help to lower the voltage and temperature. Table 3 summarizes main results obtained by running the same quench protection code. The quench was initiated in the middle of the inner side of the bucking coil connected to a power supply.

Table 3. SS2 BC Quench Data; I0 = 200 A

Rdump (Ohm)	V1max (V)	V2max (V)	V3mod (V)	Tmax (K)	R_BC (Ohm)	Edump (kJ)	Etot (kJ)
0	703	680	0	259	8.7	0	7.15
0.5	578	557	100	230	7.3	1.3	7.15
1.0	471	452	200	204	6.3	2.4	7.15
1.5	381.5	364	300	181	5.3	3.4	7.15
2.0	306	290	400	161	4.5	4.16	7.15

Fig. 7 shows how voltage to the ground changes in the discharge circuit.

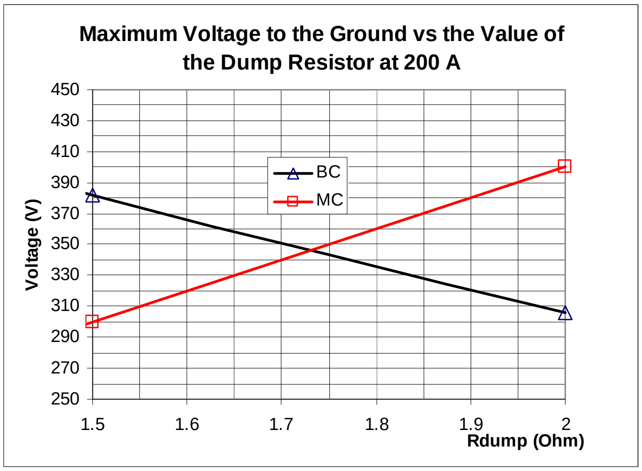

Fig. 7. Voltage to ground in the SS2 solenoid BC as function of a dump resistor value; I0 = 200 A

The optimum value of the dump resistor in this case is ~1.73 Ohm (it was 1.85 Ohm for the old version of the SS1 solenoid). With this 1.73 Ohm resistor, the expected maximum voltage to ground is ~346 V, which seems acceptable. With the 1.5 Ohm resistor, which is used for the SS1 solenoid, the expected maximum voltage is ~ 380 V in the bucking coil, which is also acceptable. The maximal temperature expected with the optimal resistance in the circuit is ~170 K. The energy removal efficiency in this case is ~52% (the energy stored at 200 A is 7.15 kJ).

So, at nominal current, the focusing solenoid of the SS2 section of the HINS linac proposed in [8] can be protected with the use of a dump resistor.

The situation is different during solenoid training, when one needs to go up to the maximum current of ~250A. Table 4 summarizes the main results obtained by running the quench protection code.

Table 4. SS2 BC Quench Data; I0 = 250 A

Rdump (Ohm)	V1max (V)	V2max (V)	V3mod (V)	Tmax (K)	R_BC (Ohm)	Edump (kJ)	Etot (kJ)
0	1220	1180	0	360	11.8	0	11.2
0.5	1063	1027	125	328	10.6	1.4	11.2
1.0	925	890	250	300	9.5	2.7	11.2
1.5	803	770	375	274	8.5	3.9	11.2
2.0	696	665	500	250	7.6	4.9	11.2
2.5	602	572	625	229	6.8	5.9	11.2
3.0	520	491	750	210	6.1	6.7	11.2

Fig. 8 shows how voltage to the ground changes in the discharge circuit.

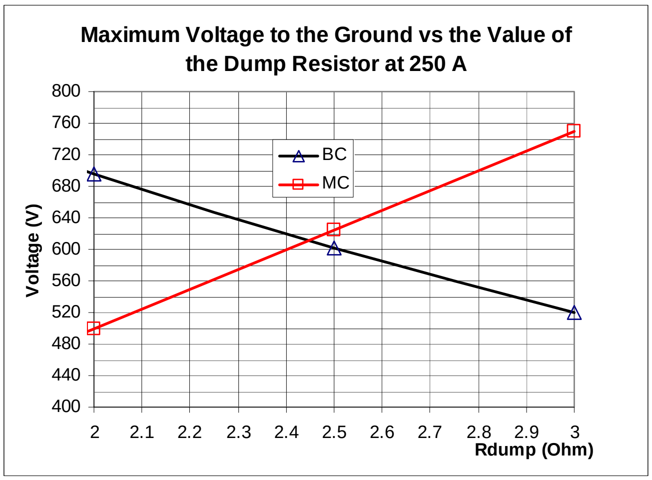

Fig. 8. Voltage to ground in the SS2 solenoid BC as a function of the dump resistor value; I0 = 250 A

Much higher energy stored in the solenoid at higher current results in significant increase of the coil temperature and voltage to ground. In case of a quench in one of the bucking coils, voltage to ground is higher than 600 V even if the value of the dump resistor is chosen close to its optimal value of 2.45 Ohm. Figures 9 to 12 below show how the current, the quenching coil resistance, the voltage to ground, and the coil temperature change during the quenching with Rdump = 2.45 Ohm. Fig. 13 shows the coil temperature map in the end of the quenching process.

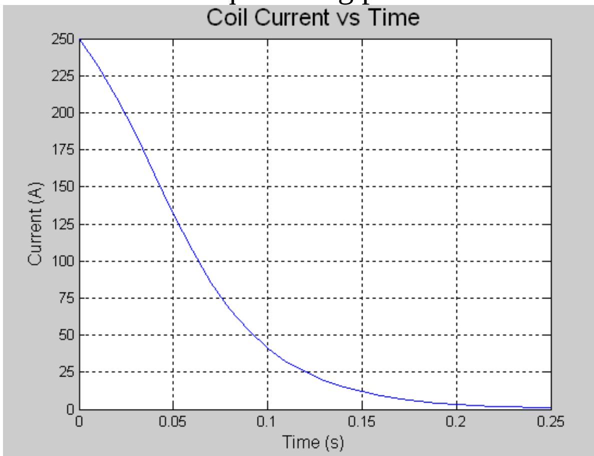

Fig. 9. Current decay after quenching in the bucking coil;
I0 = 250 A; Rdump = 2.45 Ohm

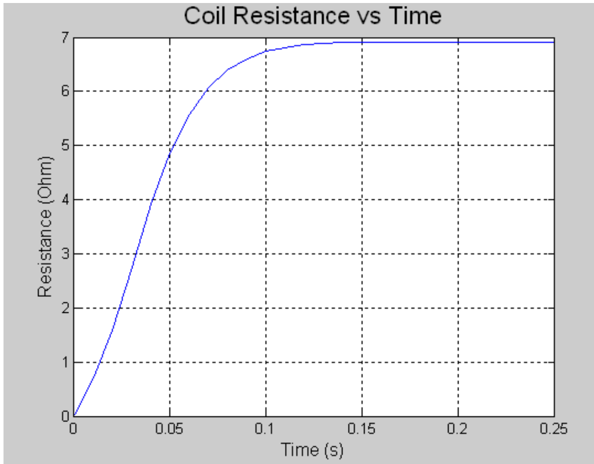

Fig. 10. Change of the coil resistance during quenching in the bucking coil;
I0 = 250 A; Rdump = 2.45 Ohm

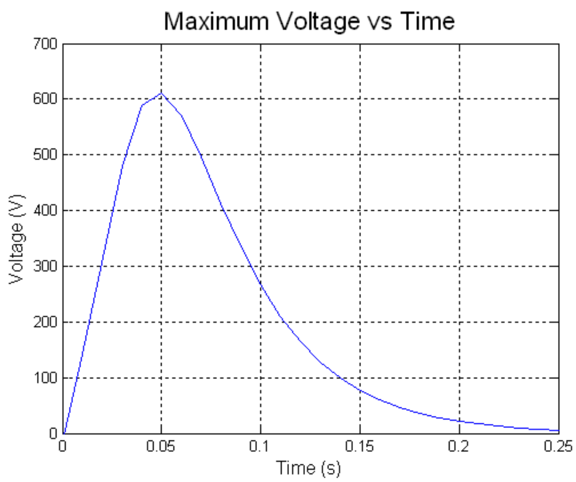

Fig. 11. Voltage to ground in the solenoid during quenching;
I0 = 250 A; Rdump = 2.45 Ohm

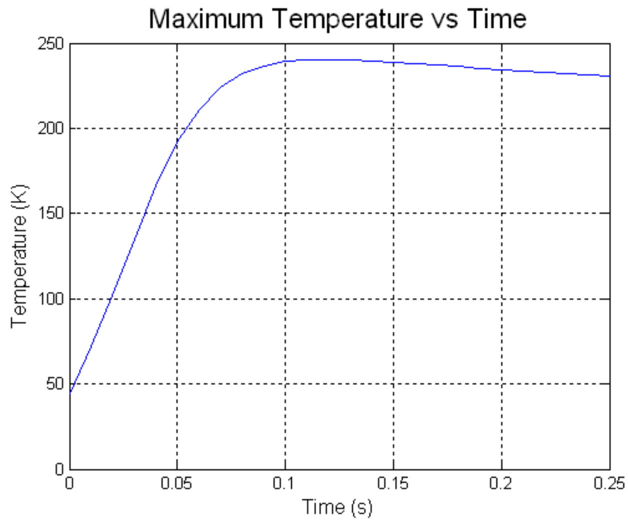

Fig. 12. Maximum temperature in the bucking coil during quenching;
I0 = 250 A; Rdump = 2.45 Ohm

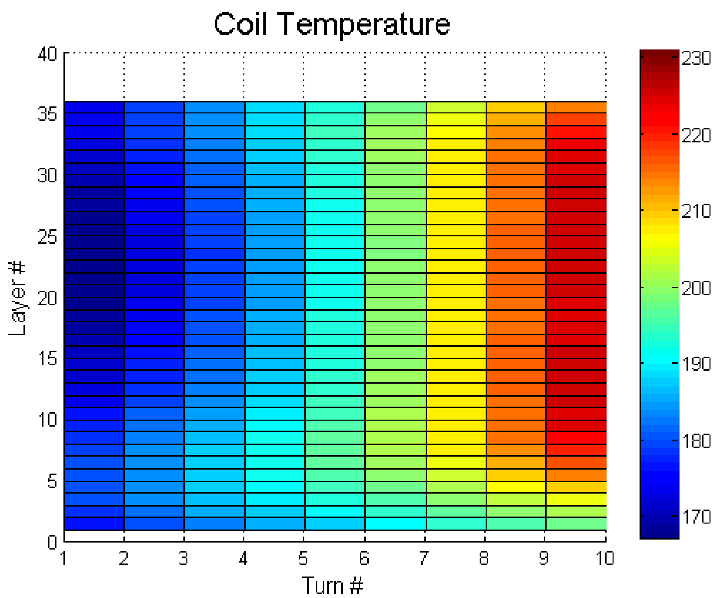

Fig. 13. Temperature map in the bucking coil after quench;
I0 = 250 A; Rdump = 2.45 Ohm

IV. Summary and Conclusion

It still seems possible, with some caution, to use a dump resistor based quench protection technique during operating and testing of solenoids for SS2 section. To prevent damage of the solenoid during testing, a higher hipot voltage must be used, e.g. 800 V, during cold check-up of the system before training. Also the value of the dump resistor must be chosen close to the optimal value of 2.45 Ohm (e.g. 2.5 Ohm) for the maximum current of 250 A. Then at lower current, maximum voltage to ground will be defined by the potential drop on the dump, that is always lower than at 250 A.

Besides using a dump resistor, there exist other options to protect the quenching system. The most radical (although the most expensive) way of protection is using separate power supplies for the main coil and the bucking coils. Another option is using cold diodes connected in parallel to each coil to provide a circuit for the current to bypass a quenching coil. Quench heaters can be used to dissipate the stored energy over the total system. Finally, an opportunity provided by the split main coil can also be explored to simplify quench detection.

This study was made using the analysis tool that was developed in [9] and used in [1] and [2] for the SS1 system study. This tool has some features that are not so well justified. For example, mutual inductance between the layers of coil winding is found using a handbook formula, which, although convenient, is not so accurate. Mutual inductances between the main coil and the bucking coils are totally neglected in this analysis. This adds some uncertainty to the result. Goals for the next phase of this protection study can be established as:

1. Find and implement more precise methods of mutual inductance evaluation.
2. Introduce more elaborate circuit analysis that would allow different protection options to be explored.
3. Introduce an option with simultaneous quenching in several coils of the solenoid.

References:

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