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# Using a Dump Resistor for Protection of Focusing Solenoids in the CH Section of the HINS Linac Front End

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Analysis of events is a case of a quench in the main coil or in the bucking coils of a focusing solenoid in the absence of a dump resistor in the solenoid discharge circuit has been made in [1]. According to this analysis, the worst case scenario (the maximum temperature and voltage) happens when quench starts in one of the bucking coils, in the area where the magnetic field is close to zero, and when the main coil and the bucking coils are connected in series. In this case, the maximum temperature in the bucking coil is approaching 180 K and the voltage level on the outer layer of the coil reaches ~ 500 V. The maximum temperature in the coil can be made lower if to use an external (dump) resistance to remove part of the energy out of the solenoid. On the other hand, right choice of a place where to make ground connection can help in keeping voltage to ground low through all the circuit.

Two circuit configurations will be analyzed in this note. For both of them, the maximal current can not exceed the quench current in the main coil: I = 250 A.

**The first circuit configuration** is shown in Fig. 1. Two variations of the circuit correspond to quenching in the bucking coil (a) or in the main coil (b).

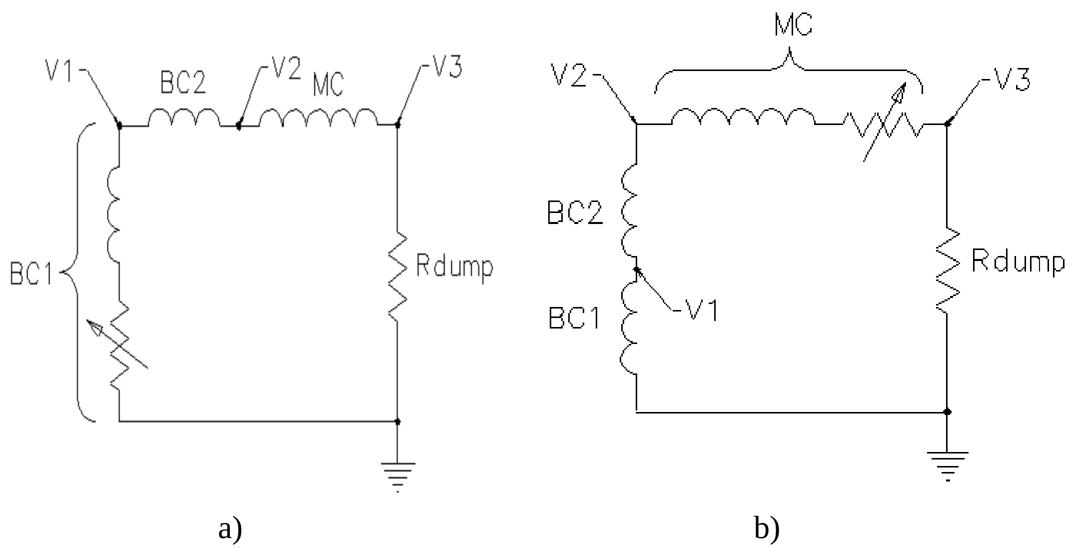



Fig. 1: Circuit configuration # 1: a) quench in the bucking coil; b) quench in the main coil

For this configuration, the ground connection is made between the bucking coil and the dump resistor. V1, V2, and V3 are voltages in the corresponding points relative to the ground after quench develops. If the inner layer of the bucking (or main) coil is closer to the ground, higher voltage can develop when the quench starts in this layer because resistive voltage is less compensated by the inductive voltage, which is opposite in sign if the current is decaying (dI/dt < 0). We will assume later that quench starts in the inner layer of the winding. While analyzing the process of quenching, we will use a discharge circuit from Fig. 1 (“a” or “b”) and scan the value of the dump resistor starting from Rdump = 0. In the two cases when quench happens in the bucking or in the main coil, voltages V1, V2, V3, and the maximum voltage in the quenched coil will be found as well as the maximum coil temperature. Also, a fraction of energy dissipated in the dump resistor is an important property to know. It is assumed that the current in Fig. 1 circuit flows counterclockwise, so the resistive part of the voltage seen in the quenching bucking coil (relative to the ground) is positive.

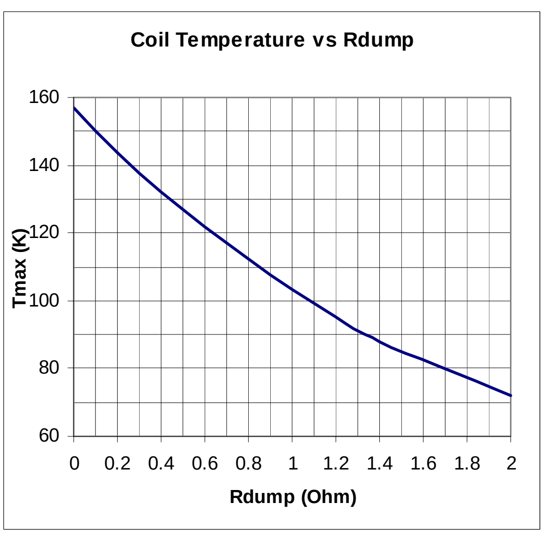
Let's consider a **quench in the first bucking coil** (BC1), which is the closest to the ground. The location of the quench starting point is in the middle of the first layer. This modeling can be made by using slightly modified MATLAB-based program for quench propagation analysis [2]. The table below provides the data corresponding to quenching BC1.

Table 1: Quench in BC1. Case 1

| Rdump (Ohm) | V1 (V) | V1m (V) | V2 (V) | V2m (V) | V3 (V) | Tm (K) | Rcoil (Ohm) | E (J) | Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 350 | 0 | 310 | 0 | 157 | 3.5 | 0 | 0 |
| 0.2 | -5 | 285 | -10 | 250 | -50 | 143.8 | 3.03 | 840 | 0.1635 |
| 0.4 | -10 | 228 | -20 | 195 | -100 | 132.3 | 2.6 | 1600 | 0.312 |
| 0.6 | -15 | 182 | -30 | 155 | -150 | 121.8 | 2.2 | 2250 | 0.436 |
| 0.8 | -20 | 142 | -40 | 116 | -200 | 112.4 | 1.85 | 2800 | 0.545 |
| 1 | -25 | 112 | -50 | 84 | -250 | 103.4 | 1.5 | 3270 | 0.636 |
| 1.2 | -30 | 88 | -60 | 61 | -300 | 95 | 1.28 | 3625 | 0.705 |
| 1.4 | -35 | 70 | -70 | 43 | -350 | 88 | 1.07 | 3920 | 0.765 |
| 2 | -50 | 30 | -100 | 7 | -500 | 72 | 0.64 | 4500 | 0.877 |

The total energy absorbed by the dump resistor E should be compared with the energy stored in the system before the quench $E0 = Ltot*I0^2 / 2 = 5140$ J, where Ltot is a sum of the inductances of all the three coils in the solenoid. The energy extraction **efficiency** is a ration E/E0.

Graphs in the figures below illustrate the data in Table 1. Fig. 2 shows how the maximum temperature in the coil and the coil resistance in the end of the cycle change with the value of the dump resistor.



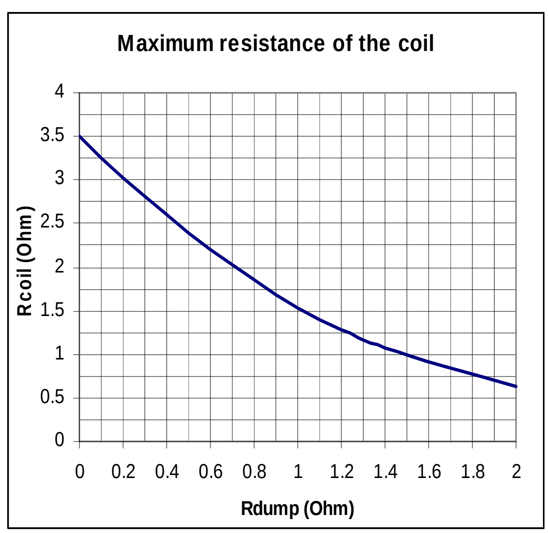




Fig. 2: Maximum temperature in the BC1 and the coil resistance in the end of the cycle as a function of the dump resistor value

As expected, the temperature drops when the value of the dump resistor grows because of the growth of the energy removal efficiency; Fig 3 shows the corresponding graph. In the case of a quench in the bucking coil, the energy removal efficiency can be made quite significant by increasing the value of Rdump. To save more LHe, lower final temperature is preferred, so one would tend to increase Rdump if the voltage V3 can still be tolerated. The temperature growth correlates with the growth of the resistance of the coil after quenching.

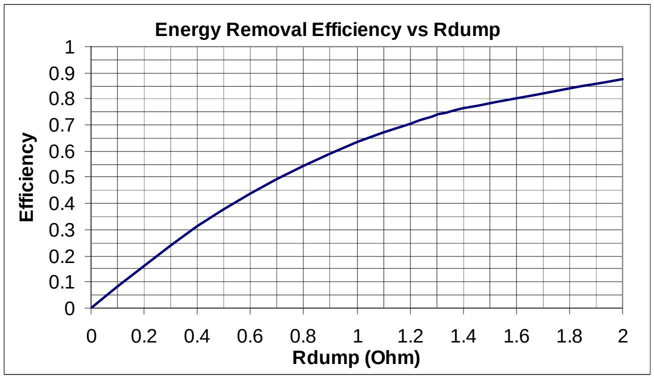



Fig. 3: Energy removal efficiency as a function of a value of the dump resistor

Maximum voltages in different points of the circuit in Fig. 1 are shown in Fig. 4 as functions of Rdump.

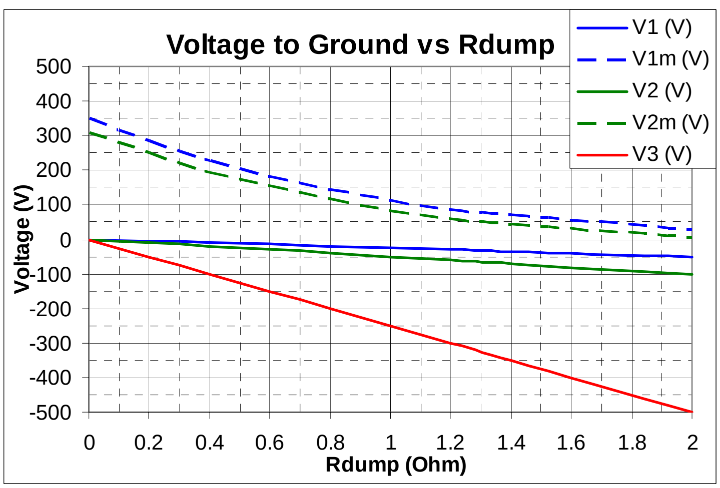



Fig. 4: Maximum voltage levels at different points of the circuit in Fig. 1-a

Location and timing of where and when the maximum voltage can be expected changes depending on Rdump. For V1 and V2 and with Rdump < 1.4 Ohm, the maximum voltage is reached approximately at t = 65 ms; for larger Rdump, the maximum voltage of ~ 100 V takes place in the very beginning of the discharge cycle (t = 0). For V3, the maximum voltage is always observed in the very beginning of the cycle.

While Rdump is small, the maximum voltage of the order of ~300 – 350 V is expected in the coils BC1, BC2 and part of MC. When Rdump > 0.7 Ohm, a part the main coil MC closest to the dump resistor sees higher voltage, which increases as Rdump increases.

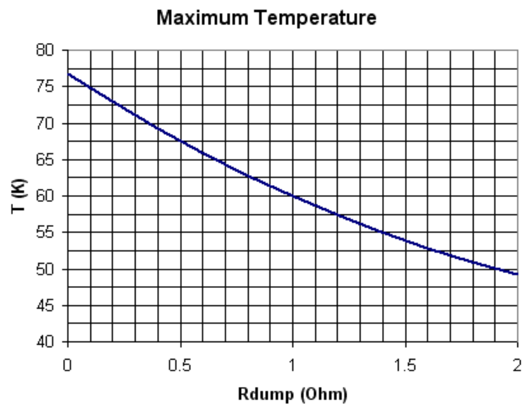
Minimal voltage level in the circuit is ~ 170 V and is reached at Rdump = 0.67 Ohm. Extraction efficiency in this case is ~ 0.47.

Table 2 shows data corresponding to the **quenching main coil**.

Table 2: Quench in MC. Case 1

| Rdump (Ohm) | V1 (V) | V1m (V) | V2 (V) | V2m (V) | V3 (V) | Tm (K) | Rcoil (Ohm) | E (J) | Efficiency |
|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | -21.5 | 0 | -43 | 0 | 76.8 | 2.54 | 0 | 0 |
| 0.4 | -7.5 | -20.75 | -15 | -41.2 | -100 | 69.3 | 1.98 | 2320 | 0.3 |
| 0.8 | -14 | -21 | -28 | -42 | -200 | 62.8 | 1.57 | 4000 | 0.52 |
| 1.2 | -21 | -23 | -42 | -46 | -300 | 57.4 | 1.29 | 5150 | 0.67 |
| 1.6 | -27.5 | -27.5 | -55 | -55 | -400 | 52.9 | 1.1 | 5950 | 0.78 |
| 2 | -34 | | -68 | | -500 | 49.2 | 0.97 | 6500 | 0.84 |

The data is illustrated in the graphs below.



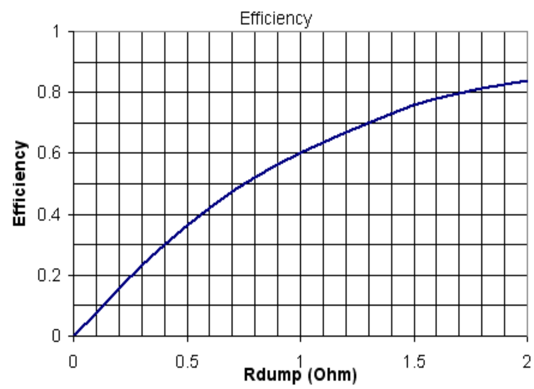




Fig. 5: Temperature in the main coil and energy extraction efficiency

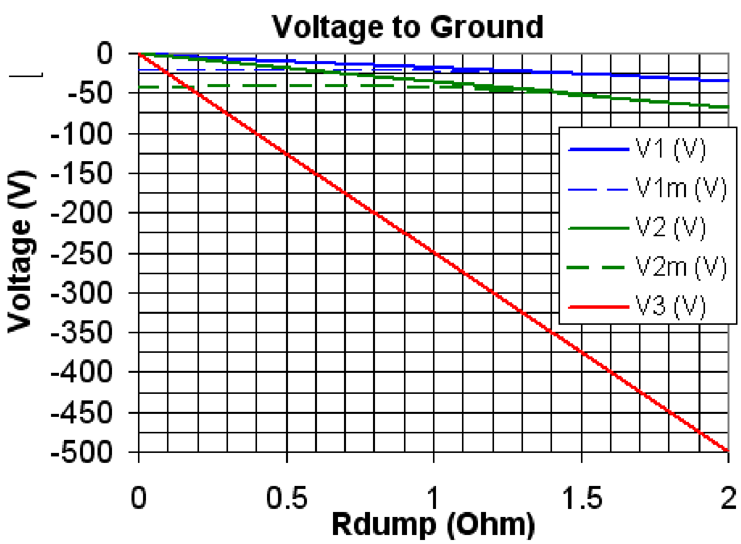
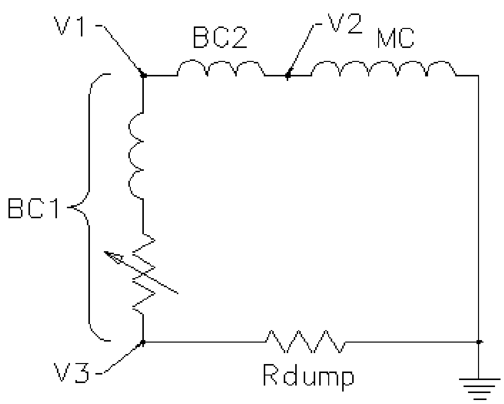



Fig. 6: Voltage to ground for the circuit in Fig. 1-b

Comparing Fig. 4 and Fig. 6, we can conclude that when Rdump is small, voltage in the bucking coil can be high only if quench occurs in one of the bucking coils. When Rdump > 1 Ohm, the voltage on the main coil is higher wherever the quench occurs and tends to increase with Rdump. If to allow maximum voltage in the circuit ~ 330 V, we can get the energy removal efficiency of ~ 0.7 at Rdump = 1.3 Ohm. With this Rdump the temperature in the bucking coil will not exceed 90 K (if quench in the bucking coil) and the temperature in the main coil will not exceed 57 K (if quench in the main coil). In both cases, with this Rdump, we have the maximum voltage at t = 0 at the point between the main coil and the dump resistance (V3 in Fig. 1). **Making the point of a contact V3 at the outer layer of the main coil can help to reduce a danger of a failure in the vicinity of the beam pipe.**

If Rdump = 0.6 ohm (present configuration of the test stand #3), the maximum voltage expected is ~ 180 V at the point V1 when quench occurs in BC1. Energy removal efficiency is ~ 0.44.

**The second circuit configuration** to be investigated is when the ground is made between the dump resistance and the main coil. In this case, behavior of the coil resistance and maximum temperature do not change. Also the energy removal efficiency stays the same. Voltages in different points of the circuit (see Fig. 7) change though.



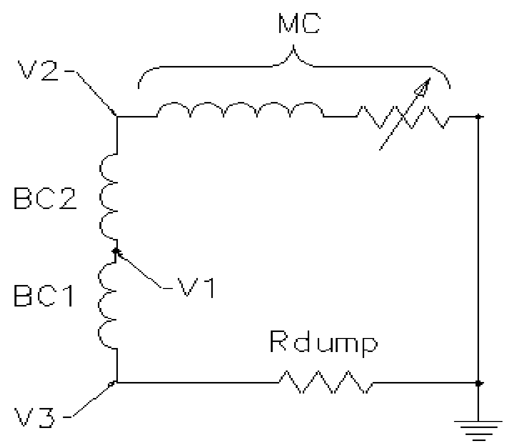




Fig. 7: Circuit configuration # 2: a) quench in the bucking coil; b) quench in the main coil

New voltages can be found by analyzing time dependant curves for voltages in the schemes of Fig. 1, but it was easier (and more reliable in the end) to run the quench code [2] with slightly modified expressions for the voltages. Table below provides data related to **quenching in the bucking coil**.

Table 3: Quench in BC. Case 2

| Rdump (Ohm) | V1 (V) | V1m (V) | V2 (V) | V2m (V) | V3 (V) |
|---|---|---|---|---|---|
| 0 | 0 | 350 | 0 | 310 | 0 |
| 0.4 | 94 | 290 | 80 | 255 | 100 |
| 0.8 | 180 | 260 | 160 | 230 | 200 |
| 1.2 | 270 | 285 | 240 | 250 | 300 |
| 1.6 | 360 | | 320 | | 400 |
| 2 | 450 | | 400 | | 500 |

Graphs in Fig. 8 illustrate the case.

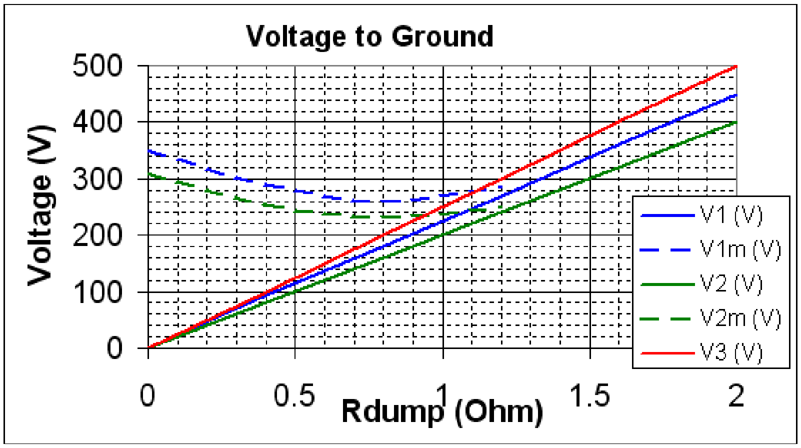



Fig. 8: Voltage to ground when quench starts in the bucking coil. Case 2

In this case, all the voltages relative to the ground are positive. The value of the dump resistor corresponding to the **lowest maximum voltage** in the circuit is ~ 0.8 Ohm; this voltage is ~ 260 V. The minimum is quite shallow, so higher value of Rdump can be chosen to increase efficiency of the energy removal, which is 0.55 in the point of minimum. Maximum voltage in this case will be defined mostly by the resistive voltage drop at the resistor.

Table 4 presents data in the case when the **quench starts in the main coil**.

Table 4: Quench in MC. Case 2

| Rdump (Ohm) | V1 (V) | V2 (V) | V3 (V) |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 0.4 | 92.5 | 87 | 100 |
| 0.8 | 185 | 173 | 200 |
| 1.2 | 275 | 260 | 300 |
| 1.6 | 370 | 345 | 400 |
| 2 | 460 | 425 | 500 |

Graphs in Fig. 9 illustrate the case.

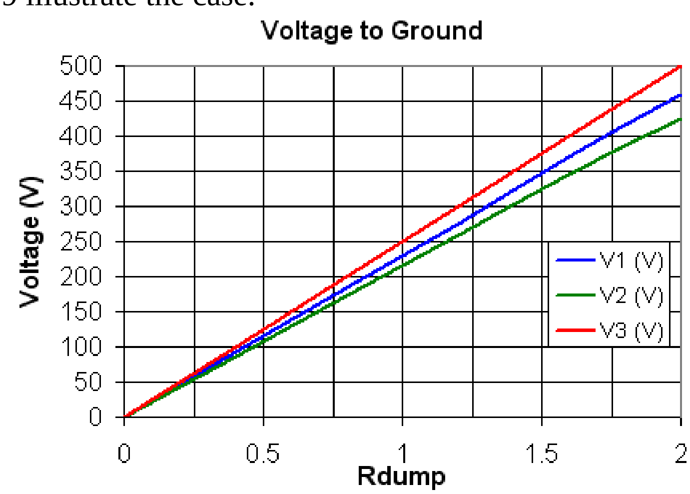



Fig. 9: Voltage to ground when quench starts in the main coil. Case 2

Comparing Fig. 9 and Fig. 8, we can come to the next conclusion: when Rdump < ~1 Ohm, voltage in the bucking coil is higher, but it does not go below ~ 260 V in this case if quench starts in the bucking coil. When Rdump > ~1 Ohm, voltages in the main coil and in the bucking coils tend to increase with Rdump. If to allow the maximum voltage in the circuit ~ 330 V, we can get the energy removal efficiency ~ 0.7 at Rdump = 1.3 Ohm. With this Rdump, temperature in the bucking coil will not exceed 90 K, and we will have the maximal voltage at t = 0 at the point between the bucking coil and the dump resistance (V3 in Fig. 7). It is not so important in this case where the point of contact is in the bucking coil: both bucking coils are at about the same potential.

**Because making circuit in accordance with Fig. 7 results in higher voltages in all the elements, it is recommended to use Fig. 1 for making connections during testing.**

**Also, it is desirable to use dump resistance in the range 0.5 – 1.3 Ohm and connect the outer layer of the main coil with the dump resistance.**

## References:

1. I. Terechkine. “Analysis of Quench in a Focusing Solenoid of the CH Section of the HINS Linac” , TD-06-067, Fermilab, TD, Dec. 2006.
2. S. Obraztsov, I. Terechkine, “A tool for Modeling Quench Propagation and Related Protection Issues”, TD-06-063, Fermilab, TD, Dec. 2006