Quench Protection Considerations for CESR Superconducting IR Quadrupoles

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I. INTRODUCTION

The following note presents some considerations on quench development and quench protection for the CESR superconducting IR quadrupoles.

II. QUENCH RESISTANCE GROWTH, CURRENT DECAY, AND INTERNAL VOLTAGE

Following Wilson[1], the growth of the quench resistance with time is described by the following equation:

$$R_Q(t) = \begin{cases} \dfrac{3Lt^5}{t_Q^6} \quad for \;\; 0 \le t < t_a \\ \dfrac{L\left(30t_a^3t^3 - 30t_a^3t^2 + 6t_a^5\right)}{2t_Q^6} \; for \;\; t \ge t_a \end{cases} \tag{1}$$

in which

$$t_Q = \sqrt[6]{\frac{90LF_1^2A^2}{4\pi J_{op}^4\rho_1 v_r^2 v_z}} \tag{2}$$

and

$$t_a = Max\left(t_{ar},\; t_{al}\right); \quad t_{ar} = \frac{a_2 - a_1}{2v_r}; \quad t_{al} = \frac{l}{2v_z} \tag{3}$$

In these equations, L is the magnet's inductance, J_{op} is the overall current density in the coil before the quench, A is the wire area, v_r is the radial quench velocity, v_z is the longitudinal quench velocity, l is the length of the magnet, and a_1 (a_2) is the inner (outer) coil radius. Relations for the quench velocities are given in ref. [2].

The energy deposited in the coil is related to the resulting coil temperature θ by the following phenomenological relation, which defines F_1:

$$\frac{\int I^2dt}{A^2} = F_1\sqrt{\frac{\theta}{\theta_1}} \tag{4}$$

In this note, we use $F_1=2.1\text{x}10^{16}$ A^2-sec/m^2 [1], for θ_1 = 100 °K.

The resistivity of the copper in the coil is taken to have the following temperature dependence, which defines ρ_1:

$$\rho(\theta) = \rho_1 \frac{\theta}{\theta_1} \tag{5}$$

We use ρ_1=3x10^{-9} Ω-m, for the resistivity of copper at θ_1=100 ^{o}K.

The time t_{ar} (t_{al}) in Eq. (3) corresponds to when the propagating quench hits the radial (azimuthal) coil boundary. The expression (1) corresponds to a simplified model of the quench development, in which the quench propagates in three dimensions (axially, radially and azimuthally) until the time t_a, after which it propagates in only one dimension (azimuthally) until the current decays to zero. We neglect the brief period of two dimensional quench propagation between t_{ar} and t_{al}. Details are discussed in [1].

A simple circuit model of the quenching magnet is indicated in Fig. 1:

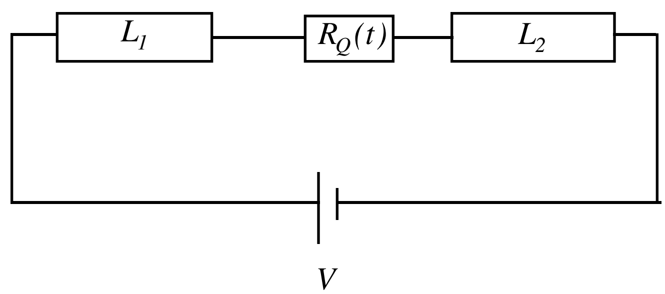

Fig. 1:
Circuit model for quenching magnet

The developing quench resistance R_Q(t) splits the magnet into two pieces, of inductance L_1 and L_2. Neglecting the mutual inductance between the two pieces, we have

$$V + L_1 \frac{dI}{dt} - IR_Q(t) + L_2 \frac{dI}{dt} = 0 \tag{6}$$

The power supply voltage V is very small compared to the other terms in this equation, so

$$L\frac{dI}{dt} = IR_Q(t) \tag{7}$$

and so the current decay is given by

$$I(t) = I_0 \, exp\left[-\frac{\int_0^t R_Q(t)dt}{L}\right] \tag{8}$$

The voltage across the normal zone ("internal voltage") is just $V_{int}(t) = I(t)R_Q(t)$.

The peak temperature in the coil is obtained from Eq. (4):

$$\theta = \theta_1 \left[\frac{\int_0^{\infty} I^2(t)dt}{A^2 F_1} \right]^2 \tag{9}$$

with I(t) given by Eq. (8). The stored energy is

$$W_{stored} = \frac{1}{2} L I_0^2 \tag{10}$$

The quench parameters appearing in Equations (1-10), for the CESR IR quadrupoles, and for the LEP-200 quadrupoles, are shown in Table I.

Quench parameter	**CESR IR main quadrupole**	**CESR IR skew quadrupole**	**CESR IR dipole**	**LEP-200 quadrupoles**
I_0 (A)	1225	325	40	1900
Turns	364	216	710	200
L (H)	0.303	0.136	0.725	0.297
l (m)	0.65	0.65	0.65	2
v_z (m/sec)	9.485	13.59	7.88	11
v_r (m/sec)	0.294	0.421	0.244	0.341
W_{store} (kJ)	228	7.2	0.58	535
A (mm^2)	6.33	0.94	0.168	
J_{op} (A/mm^2)	194	346	239	327
t_Q (sec)	0.47	0.12	0.15	0.30
t_a (sec)	0.067	0.024	0.041	0.09
V_{max} (volts)	640	340	200	2200
θ_{max} (^oK)	158	86	24	290

Table I: Quench parameters

Fig. 2 shows the internal voltage $V_{int}(t)$, at the beginning of a quench, for the CESR IR main quads; Fig. 3 shows the voltage during the whole quench. Fig. 4 shows the decay of the current, from Eq. (8).

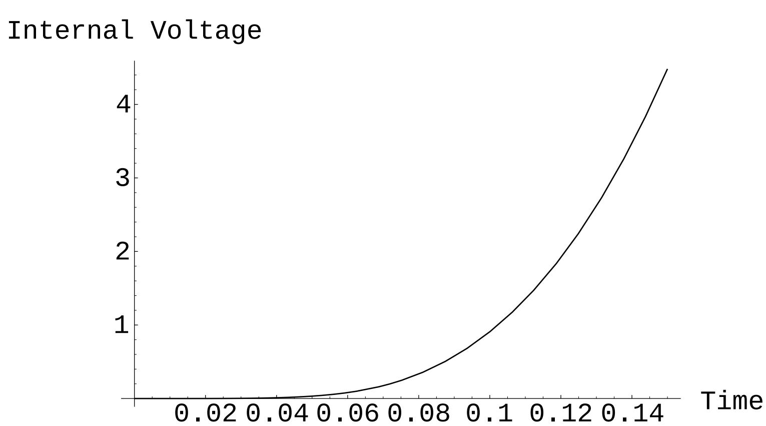

Fig. 2
Internal resistive voltage $V_{int}(t)$ (volts) vs. t (sec), at start of quench; for CESR IR main quads

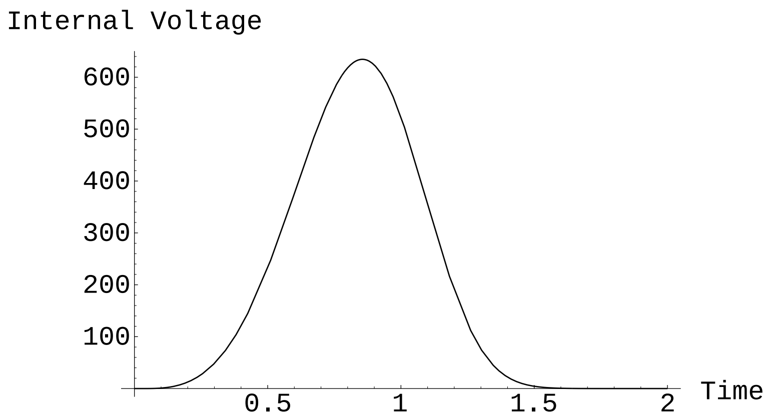

Fig. 3
Internal resistive voltage $V_{int}(t)$ (volts) vs. t (sec);
for CESR IR main quads

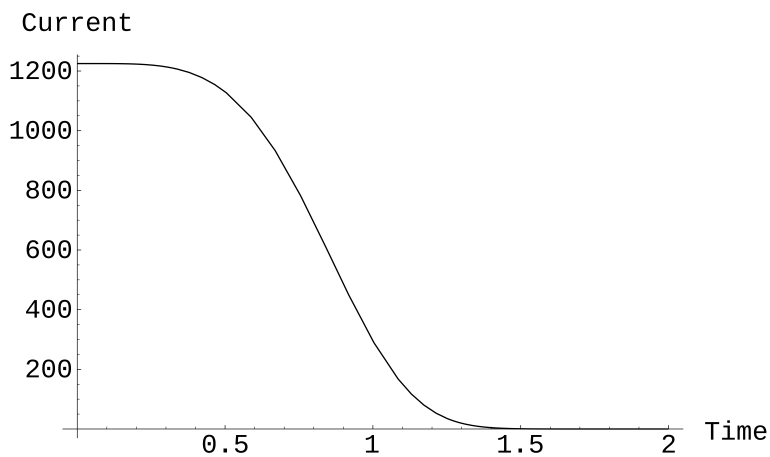

Fig. 4
Current I(t) (amps) vs. t (sec), after a quench;
for CESR IR main quads

III. QUENCH DETECTION

During the quench the voltage across the magnet leads remains very close to zero, with the internal resistive voltage balanced by $L\frac{dI}{dt}$. To sense the start of a quench, an internal voltage tap (say halfway down the magnet) may be used. The voltage difference between this tap and the leads of the magnet provides a direct measure of the internal voltage. This, however, requires that a voltage tap monitoring wire be built into the magnet. Alternatively, the current in the magnet may be monitored, and its derivative combined with the measured inductance L of the magnet to obtain $L\frac{dI}{dt}$. Then, from Eq. (6),

$$V_{int}(t) = V_L + L\frac{dI}{dt} \tag{11}$$

in which V_L is the (small) voltage across the leads. Detection of a quench occurs when $V_{int}(t)$ crosses a preset threshold. The value of the threshold will depend on the noise and accuracy in the measurements of L, $\frac{dI}{dt}$, and V_L. For example, if the overall error in determining $V_{int}(t)$ were on the order of 100 mv, then one could safely set a 1 volt threshold for quench detection. From Fig. 2, for the CESR IR main quadrupoles, this occurs at about 0.1 sec after the quench. We will call the time at which the internal voltage reaches 1 volt, the quench detection time, t_s. Table II gives the calculated quench detection times for the three CESR IR magnet coils.

Quench parameter	**CESR IR main quadrupole**	**CESR IR skew quadrupole**	**CESR IR dipole**
Quench detection time (sec)	0.1	0.03	0.043

Table II: Quench detection times

IV. QUENCH ENERGY EXTRACTION

The circuit in Fig. 5 allows some of the stored energy in the magnet to be extracted after the detection of the quench.

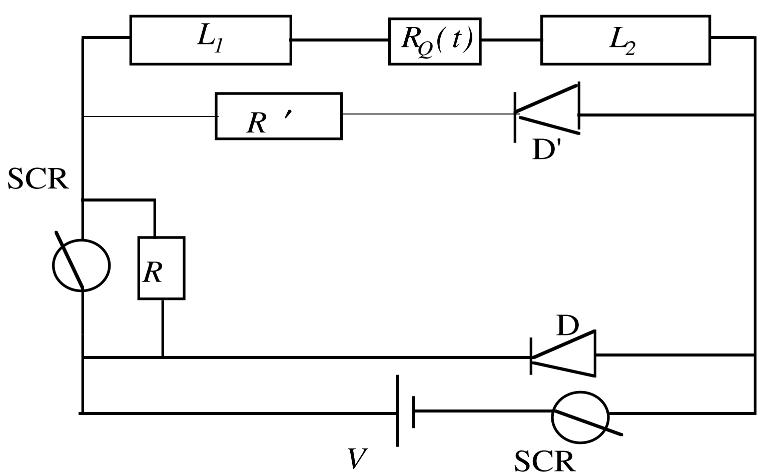

Fig. 5
Quench energy extraction circuit

When a quench is detected, as discussed in section III above, the SCR switches are opened, disconnecting the power supply and switching in the resistor R to the circuit. The current bypasses the power supply through the diode D. Some of the stored energy in the magnet is dissipated in R, which reduces the peak temperature rise in the magnet, the total LHe boiloff, and the internal voltage. However, the voltage developed across the resistor R appears between the leads of the magnet, which must be designed to accommodate this.

An additional resistor R' and diode D' may be placed across the magnet. In this case, the magnet discharges through the parallel combination of R and R'. The SCR switch and R are still required, however, since the diode D' will not conduct without the voltage drop provided by R.

With the resistor R switched into the circuit at the time t_s, and with R'=0, the resistance in the circuit is

$$R_{tot}(t) = \begin{Bmatrix} R_Q(t) \ \ for \ \ 0 \le t < t_s \\ R + R_Q(t) for \ \ t \ge t_s \end{Bmatrix} \tag{12}$$

and the current is given by Eq. (8), with $R_{tot}(t)$ in place of $R_Q(t)$. The internal voltage and current are shown in Fig. 6 and 7, respectively, for R=0.27 Ω and t_s =0.1 sec. (The reason for choosing this value of R is discussed below). The voltage which appears across the magnet leads is just I(t)R; its maximum is about 330 volts in this case.

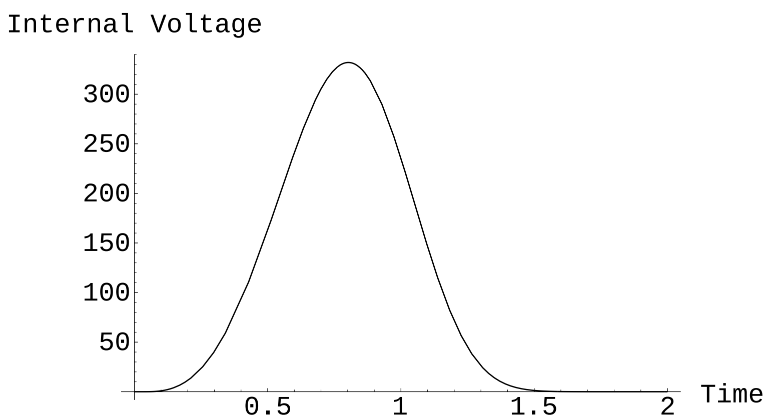

Fig. 6

Internal resistive voltage $V_{int}(t)$ (volts) vs. t (sec), with 0.27 Ω dump resistor in the circuit; quench detection at t_s=0.1 sec; for CESR IR main quads

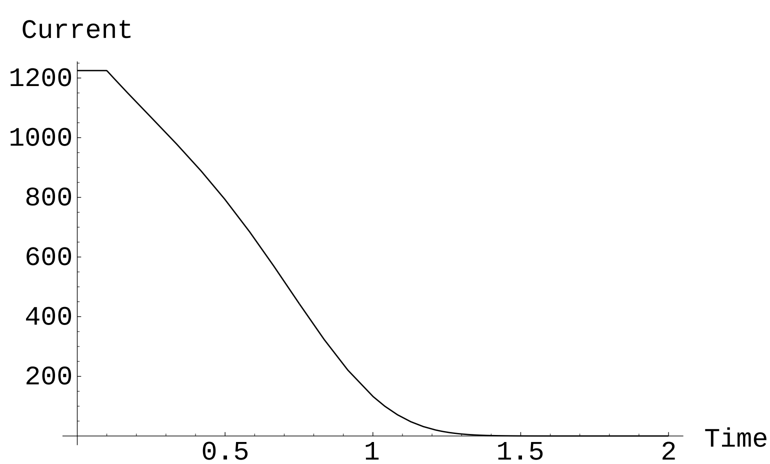

Fig. 7

Current I(t) (amps) vs. t (sec), after a quench, with 0.27 Ω dump resistor in the circuit; quench detection at t_s=0.1 sec; for CESR IR main quads

There is a rapid drop in current at t_s, when the resistor R is switched in, because generally R >>$R_Q(t_s)$. The rapid drop in current may cause other parts of the magnet to quench through eddy current heating. (This is sometime referred to as "quench back").

This is generally advantageous, as all poles of the magnet quench rapidly and the peak temperatures and voltages are reduced. This effect has not been included in the numerical calculations given in this note.

The total energy extracted from the magnet (dissipated in R) is

$$W_{ext} = R\int_{t_s}^{\infty} I^2(t)dt \tag{13}$$

Fig. 8 shows the fraction of the total energy extracted (W_{ext}/W_{stored}) vs. the value of the dump resistor R, in Ω. Fig. 9 shows the peak coil temperature vs. the value of the dump resistor, from Eq. (9). Fig. 10 shows the peak internal voltage, and the peak lead voltage, vs. R. These figures have been calculated for the main CESR quadrupole, with a quench detection time of $t_s = 0.1$ sec.

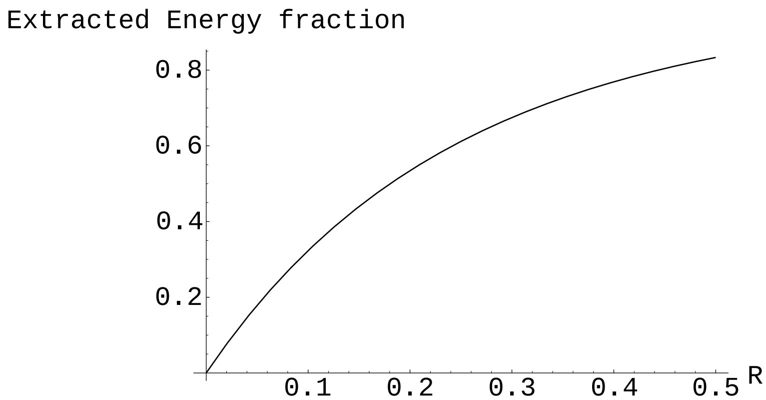

Fig. 8

Extracted energy fraction W_{ext}/W_{stored} vs. R (Ω); quench detection at t_s=0.1 sec; for CESR IR main quads

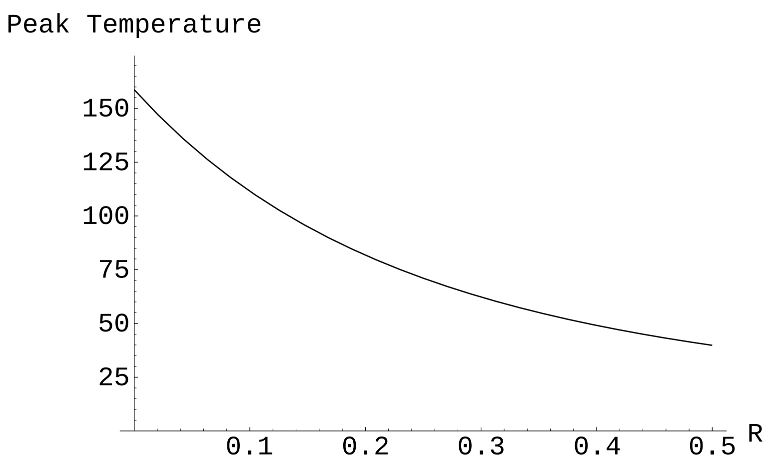

Fig. 9

Peak coil temperature θ(°K) vs. R (Ω); quench detection at t_s=0.1 sec; for CESR IR main quads

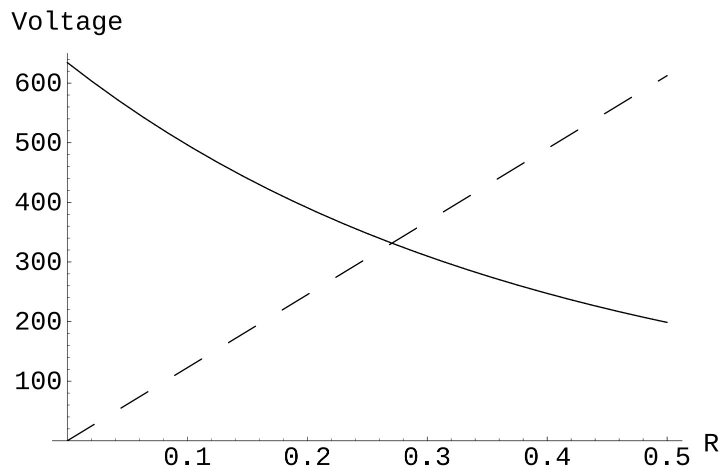

Fig. 10
Maximum internal resistive voltage $V_{int}(t_{max})$ (in volts) (solid line), and maximum voltage across the magnet leads (dashed line), vs. R (in Ω); quench detection at t_s=0.1 sec; for CESR IR main quads

As is evident in Fig. 10, larger R gives more energy extracted and lower internal voltages, but larger lead voltages. As the "optimum" value of R, we choose that value for which the peak internal lead voltage and the peak lead voltage are equal. Table III then gives the calculated "optimum" R values, the peak internal=lead voltages, and the corresponding extracted energy fraction and peak coil temperatures, for the three CESR IR magnet coils.

Quench parameter	**CESR IR main quadrupole**	**CESR IR skew quadrupole**	**CESR IR dipole**
Dump R (optimum) (Ω)	.27	.54	2.7
Maximum $V_{int}=V_{leads}$ (volts)	330	175	108
W_{ext}(kJ)	146	4.5	.36
W_{ext}/W_{stored} (%)	64	63	62
θ_{max} (^{o}K)	67	39	11.5

Table III: Quench energy extraction parameters

For comparison with measurements[3] made on the LEP-200 quadrupoles, the parameters given in Table I were used to calculate the quench development, in this simple model. From [3], quench detection occurred at t_s=0.05 sec. At this time, the calculated internal resistive voltage is 0.75 volts.

Fig. 11 shows the total calculated energy extracted, vs. dump resistor, for these quadrupoles, using the same model, and the parameters of Table I.

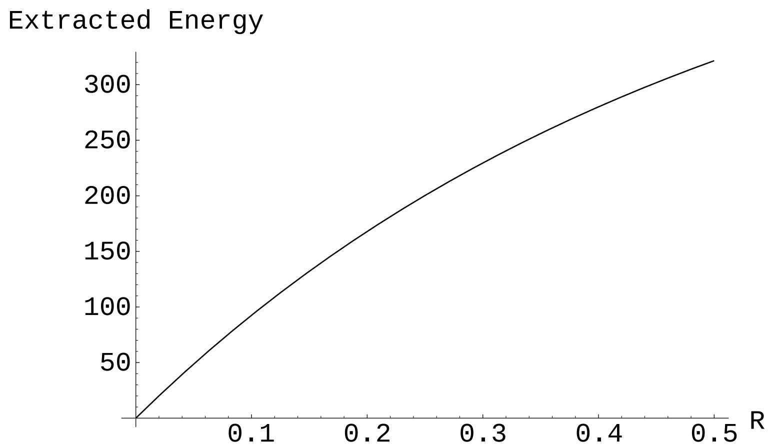

Fig. 11

Energy extracted (kJ) vs. R (Ω), for LEP-200 quadrupole; quench detection at t_s=0.05 sec.

From [3], the resistor was switched in at t_s=0.05 sec, and 145 kJ was extracted with a 167 mΩ dump resistor. This agrees reasonably well with the prediction in Fig. 11.

For R=0.167 Ω, the calculated maximum lead voltage is 320 volts, the calculated maximum internal voltage is about 1800 volts, and the calculated peak coil temperature is 220^{o}K. The measured[3] internal resistive coil voltages were in the range of 100-200 volts, and the coil temperature (calculated from the measured Mitt's) is 100-150 ^{o}K. The large discrepancy between the calculated and measured internal voltages is hard to understand.

V. REFERENCES

[1]. Wilson, "Superconducting Magnets", p 211

[2]. G. Dugan, "Observations on proposed CESR Phase III Interaction Region Quads", CBN 95-14

[3] A. Ijspeert, T. M. Taylor, M. Begg, "Construction and Test of Superconducting Quadrupoles for the LEP2 Low-Beta Insertions", p 2277