Analysis of Quench Properties of the Q3 Magnets with and without Open Circuit Heater Elements

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INTRODUCTION

The Q3 magnets have 2 independent heater elements that are energized by the quench protection system. One heater element in the Q3 magnet at A4 became an open circuit after the initial cooldown. Recently the second element became an open circuit. The Q3 magnet at A4 is powered in series with a Q3 magnet at B1. The heaters in the magnet at B1 are still intact.

The purpose of this study is to determine if the magnet circuit can be operated without undue risk of damage to the magnets. The risk of damage to the magnet at A4 is less of a concern since repairing the heaters is expected to be a major effort in any event. There is one spare Q3 magnet.

SIGNIFICANCE OF THE MIITS

An element of a superconducting magnet may be destroyed if subjected to high temperature as the result of a quench. The temperature rise (ΔT) caused by the addition of an infinitesimal amount of energy per unit mass (ΔQ) is:

$$\Delta T = \frac{\Delta Q}{c_v} \quad [1]$$

where c_v is the specific heat capacity per unit mass. The amount of energy deposited is equal to the electrical energy dissipated minus the amount of energy transported to cooler portions of the conductor.

Neglecting the cooling effect (the "adiabatic" approximation) the temperature rise can be written as:

$$\Delta T = \frac{\rho I(t)^2 \Delta t}{A^2 \sigma c_v} \quad [2]$$

where ρ is wire density, σ is the electrical conductivity, A is the cross-sectional area of the wire, and Δt is the time the current is applied. For larger time intervals, one can integrate Eqn. [2] to obtain:

$$\int_{T_i}^{T_f} \frac{A^2}{\rho} \sigma(T) c_v(T) dT = \int_0^{\infty} I(t)^2 dt \quad [3]$$

Eqn. [3] shows that the temperature rise for a given cable depends only on the integral of the current squared: a quantity that is easily measured experimentally. The integral on the right-hand side of Eqn. [3] is conventionally expressed in units of $\text{kA}^2\text{-sec}$. These units are also known as MIITs (pronounced as "mites"). The abbreviation is derived from M=Mega= 10^6 , II=current times current, and integrated over T=time. The abbreviation MIITS is also used - at least colloquially - to refer value of the integral as well as its units.

The low beta magnets and quench protection system were designed to limit the maximum temperature to 800°K . According to calculations¹ 6.2 MIITs are required to yield a temperature rise of 800°K .

MEASUREMENT OF THE MIITS

The Q3 low beta magnet systems were quenched manually using the circuits that measure the voltage across the magnet coil. When the current is constant, this voltage is normally zero (because the magnet is superconducting). The heaters are energized if the QPM detects a voltage in excess of 0.25 V. A quench was introduced artificially by adding 0.5V to the actual voltage for one cell. The remainder of the QPM system operated normally. Quenches were induced at B0 and also at D0 for comparison. Table I summarizes the quenches that were induced by this technique.

¹Karl Koepke, "B0/D0 Low Beta Quench Behavior," June 22, 1990, unpublished.

Table I. Measured MIITs versus excitation current

Current (Amps)	B0 MIITs	D0 MIITs
3000	3.38	
3500	3.77	3.61
3900	3.96	
4300	4.26	4.23

The energy deposited (MIITs) depends critically on the time origin that is chosen. The time origin chosen is the time that the QPM system "detected" the quench. However, in this test the magnets do not actually quench until the heaters are fired. The current versus time for the test quench at D0 is shown in Fig. 1a. The current does not noticeably decay until about 100 msec after "detection." A typical beam induced quench is shown in Fig. 1b. In this quench the delay is more like 50 msec (presumably the quench begins to reduce the current before the heaters have a chance to warm the magnet). However, a real quench is subjected to the full magnet current for about 50 msec before the quench is detected (see Ref. 1). This latent period before detection is not included in the calculation of the MIITs. These two biases in our measurements approximately cancel, and it is believed that values in Table I are approximately the same as would be seen in real quenches.

Fig. 1a. Current versus time for a test quench at 4300 A.

Fig. 1b Current versus time for a beam induced quench at 4300 A.

The main point, however, is that the energy deposited in the Q3 magnets at B0 (where the heaters are missing from the Q3 at A4) is very nearly the same as the energy deposited in the Q3 magnets at D0 (where the heaters are intact). Evidently, a combination of the increased quench rate in the good Q3 magnet at B1 and a dI/dt induced quench at the broken Q3 magnet at A4 result in the overall quench energy at B0. This conjecture is examined in more detail in the section (below) on the time dependence of the magnet resistance.

VOLTAGE TO GROUND

The voltage to ground can be described fairly accurately by considering only the inductance and resistance in the magnets and the distributed ground circuit in the power supply. The approximate equivalent circuit is shown in Fig. 2.

Fig. 2. Existing magnet and power supply equivalent circuit during a quench.

During a quench the power supply is approximately a short circuit (solid line at the bottom of the circuit). The voltage divider to ground places the ground halfway between the two terminals of the power supply. Since the power supply is essentially a short circuit, both of the power supply terminals must be at approximately ground potential. The total voltage around the loop must be zero, so the voltage drop across A4Q3 (+ ΔV) must be equal and opposite to the voltage drop across B1Q3 ($-\Delta V$). The potential to ground at various points in the circuit is shown in the circles. The capacitor is present to reduce the high-frequency common-mode voltage. It has no effect during quenches since the voltage across the capacitor is (almost) zero.

The source of the voltage to ground is caused by an imbalance in the impedances of A4Q3 and B1Q3. The magnets are assumed to have equal inductances that remain constant during the quench. The time dependence of the resistance, however, depends on the properties of the quench. If the resistances of the two magnets are equal throughout the quench, then the impedances of the two magnets are equal. The voltage drops across the two magnets are equal and therefore must be zero (since their sum must be zero). If the resistances are unequal, however, there will be a voltage to ground. Extreme voltages to ground can result in magnet failure.

Because of the missing heater in the A4Q3 magnet, the resistance in the B1Q3 is expected to be greater. This effect results in a positive voltage to ground at the center-tap between the magnets. The voltage to ground for a quench at 3500 A is shown in Fig. 3.

Fig. 3. Voltage to ground for a quench at 3500 A using the original distributed ground. The nearly flat curve is the voltage at the power supply terminals, and the sharply peaked curve is the voltage measured at the center tap between the magnets.

A new grounding scheme was invented and implemented as shown in Fig. 4. The new circuit (neglecting the effect of the capacitor) places the ground approximately halfway between the potential at the two ends of the A4Q3 magnet. The voltages to ground (again neglecting the capacitor) are shown in the circles.

Fig. 4. Improved power supply and magnet grounding system.

The voltage to ground for a quench using the new circuit is shown in Fig. 5. Except for the change in ground circuit, the quench is identical to the one shown in Fig. 3. While the new circuit splits the voltage drop across the A4Q3 magnet for dc pulses, the capacitor affects the ac response. If the voltage across the magnet is suddenly changed, the capacitor voltage will not be at its steady state value of $\Delta V/2$ and there will be a difference in the voltage to ground at the two ends of the magnet. The capacitor will acquire charge through the 5 KΩ resistor and the combined impedance of the remainder of the circuit. The capacitor charging time is determined mainly by the values of the capacitor and the 5 KΩ resistor ($R \times C$). In the presence of a time-varying magnet voltage, a short time constant minimizes the difference between the capacitor voltage and its steady state value. It has been determined that resistor can be replaced by a short circuit with no adverse consequences, so we plan to make that change at a convenient opportunity.

The measured peak voltages to ground during the quench tests are given in Table II. The lower current quenches were made with the original distributed ground, and they have been divided by 2 to provide a rough comparison.

Fig. 5 Voltage to ground for a quench at 3500 A using the new distributed ground. The negatively peaked curve is the voltage at the power supply terminals, and the positively peaked curve is the voltage measured at the center tap between the magnets.

Table II. Measured MIITs versus excitation current

Current (Amps)	B0 Voltage to Ground (peak V)	D0 Voltage to Ground (peak V)
687	7†	
1500	37†	
2000	219†	
3500	312	72
3900	386	
4300	460	23

†These measurements were made with the original distributed ground system. The number quoted reduced by the ratio of voltage to ground measured at 3500 A with the old and new distributed ground systems..

As can be seen the voltage to ground is considerably higher at B0 (with the new distributed ground) than it is at D0 (with the original circuit). The acceptable voltage to ground during a quench has been chosen to be 750 V. The observed B0 voltages are within this range.

The arbitrary limit of 750 V to ground is based on a rather uneducated guess as to what ought to be a conservative rating for the magnets. However, there is reason to believe that it may be

reasonable. The magnets have been successfully subjected to 1 kV during hi-pot tests. The magnets have also been subjected to larger voltages to ground during normal operation than is indicated by Table II. Typical quenches results in low voltages to ground, but the voltage to ground can be much larger than that given in Table II (where both magnets were quenched simultaneously) if one magnet quenches before the other. An example is shown in Fig. 6, where the voltage to ground at B0 rose to 530 V. It is expected that the voltage to ground values shown in Table II actually represent the worst case at B0. Quenches induced in A4Q3 should increase the resistance of that magnet and therefore *reduce* the voltage to ground.

Fig. 6. Largest voltage to ground at B0 found in a search of the achieved circular buffers (from November 1993 to July 1995)

TIME DEPENDENCE OF THE RESISTANCE

The resistance of the magnets can be inferred from the rate of decay of the current and the voltage to ground. The inductance of the magnets is assumed to be fixed at 46 mH per magnet. The total resistance of the circuit is

$$R_t = \frac{L}{I} \frac{dI}{dt} \quad [4]$$

where L is the inductance of the two magnets in series and $I(t)$ is the measured current. The voltage drop across the upstream magnet is proportional to the difference in resistance of two magnets

$$\Delta V = I \frac{R_u - R_d}{2} \quad [5]$$

and of course the total resistance is the sum of the resistances of the two magnets:

$$R_t = R_u + R_d$$

The current is recorded directly by the QPM system and the voltage drop across the magnet can be determined from the voltage to ground measurements. An analysis of the time development of the resistance of the D0 quench at 3500 A is shown in Fig. 7. A similar quench at B0 is shown in Fig. 8.

Fig. 7. Time dependence of a 3500 A quench at D0.

Fig. 8. Time dependence of a 3500 A quench at B0.

The resistances at D0 are approximately equal for both magnets (as expected). However, at B0 the resistance comes almost entirely from the B1Q3 (the magnet with the heaters. The total resistances in the circuits at B0 and D0 is nearly the same, however. The same analysis was applied to a quench at B0 when the magnets were excited with 4300 A of current. In this case, there is a small, but definite resistance in the A1Q3 magnet just before the magnet is subjected to the peak rate of change in current (see Fig. 9).

Fig. 9. Time dependence of a quench at 4300 A at B0.

EFFECT OF THE TRIM POWER SUPPLY

If the development of the quench is dominated by the energy supplied by the heater circuits, the effect of the missing heater on the A4Q3 magnet on a typical quench is to make a positive voltage drop across the B1Q3 magnet (the resistive voltage exceeds the inductive voltage). Under these circumstances the trim power supply protection diodes are reverse biased and have no effect on the development of the quench. In the case that beam losses dominate the development of the quench, A4Q3 could have a higher resistance than B1Q3. In this case, the diodes will become forward biased and will shunt some current around the B1Q3 magnet. Should this occur, the effect will be not be harmful. The high resistance in A4Q3 (the magnet without any heaters) will cause the current to decay more rapidly compared to the case when A4Q3 has lower resistance. The action of diodes will reduce the decay rate of the current over what it would be in their absence, but they will also reduce the voltage to ground.

If the trim supply were moved to the upstream quad, a low resistance in A4Q3 would cause the diodes to be forward biased. These diodes would shunt current around the B1Q3 magnet and would leave the A4Q3 unprotected. Thus, we conclude that it is unsafe to change the current configuration of the trim power supply until the A4Q3 magnet heaters are repaired.

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