THE DO LOW β POWER AND QUENCH PROTECTION SYSTEM

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Abstract

A new low β insertion has been designed for the BO and DO straight sections of the Tevatron Collider. Each low β insertion consists of 18 superconducting quadrupoles which are powered independently of the Tevatron accelerator magnets to focus the beams at the interaction region. This paper describes the quench behavior of the low β quadrupoles, their power circuits, and their quench protection systems.

Introduction

The low β insertion presently installed at the BO straight section of the Tevatron Collider uses 8 quadrupoles to focus counter-rotating beams at the interaction point of the Colliding Beam Facility [1]. The new low β insertion uses 18 quadrupoles per insertion to simultaneously focus the beams and match the insertion in beta and dispersion to the contiguous accelerator lattices [2]. The insertions are matched primarily to allow two or more low β insertions to operate simultaneously within one accelerator with minimal coupling. Initially, the insertions will be installed at BO and DO of the Tevatron Collider; a third location is also under consideration.

Each insertion has 11 independent power circuits that can be programmed to independently adjust β^* of either interaction region through a 0.25 m to 1.7 m range. The insertions are physically identical and use two superconducting quadrupole magnet types especially designed for the low β insertions. The two-shell quadrupoles need a high current circuit with quench heaters and a microprocessor-based quench protection system. The single-shell quadrupoles appear self-protecting and only require a rudimentary quench protection system. The cryostats of the low β quadrupoles are connected directly to the Tevatron magnet lattice. This eliminates the need for separate LHe and vacuum systems. However, each low β quadrupole has a pair of LHe cooled power leads which need to be monitored for overheating.

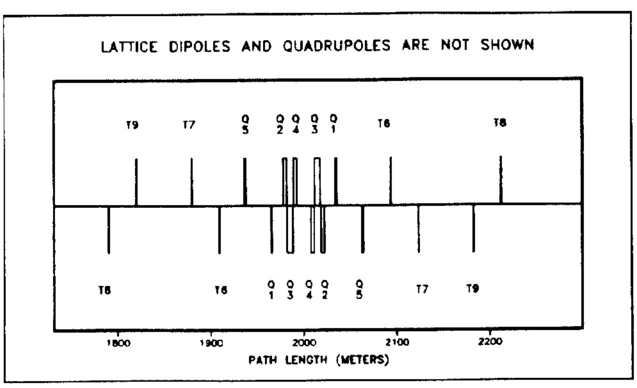

Figure 1. Elements of the low β lattice.

The geometry of a low β insertion is shown in Figure 1. Each insertion consists of 12 two-shell quadrupoles and 6 one-shell quadrupoles. The smaller one-shell quadrupoles were developed to reduce the required number of high current circuits per insertion. The inner 10 two-shell quadrupoles (doublets Q1 through Q5) are individual magnets. They are symmetrically placed around the geometric center of the straight section and are powered with equal currents as focussing-defocussing pairs. The remaining two-shell doublet (T6) and the one-shell quadrupoles (doublets T7 through T9) replace weaker correction quadrupoles normally located in correction packages (spool pieces) adjacent to regular Tevatron lattice quadrupoles. These quadrupoles are only approximately centered on the straight section and therefore have unequal currents in the upstream and downstream quadrupoles of a doublet.

*Operated by Universities Research Association, Inc., under contract with the U.S. Department of Energy.

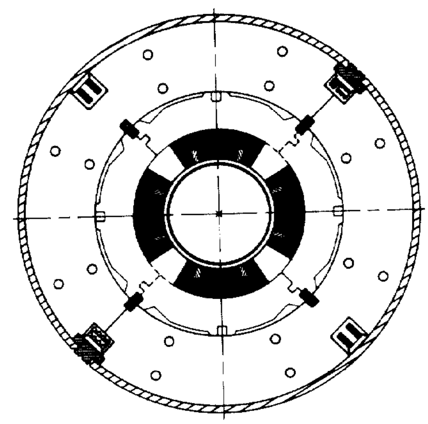

Figure 2. Cross-section of the two-shell quadrupole.

Quench Behavior of Two-shell Quadrupole

The cross-section of the two-shell low β quadrupole is shown in Figure 2. This magnet was designed to reach a gradient of 1.4 T/cm at a current of 4.8 kA and temperature of 4.8 K. The inner and outer coils are fabricated out of the same superconducting cable. The magnet parameters that control the quench behavior of this magnet are listed in Table 1.

Table 1. Two-shell Magnet Parameter

Cable Mid-Thickness (in.)	0.0353 +/- .0006
Cable Width (in.)	0.385 +/- .0005
Number of Cable Strands	36
Strand Diameter(in.)	.0208 +.0002/-.0000
Copper-to-Supercond. ratio	1.5:1 by Volume
Cable Insulation (in.)	Three Helical layers of B-stage coated .001 x .375 Kapton
J_c at 4.2 K 5 T (A/mm^2)	3000
Inner/Outer Turns per Pole	19/28
Magnet Inductance (mH/in.)	.199
Q1,Q5 Magnet Length (in.)	54.07
Q2,Q4 Magnet Length (in.)	132.0
Q3 Magnet Length (in.)	232.0
T6 Magnet Length (in.)	23.875

The magnet cable parameters have been used to calculate the peak quench temperature - assuming adiabatic ohmic heating - as a function of quench Miits (Figure 3). Quench Miits equal the square of the cable current integrated over the quench duration in units of $10^6 A^2 s$. Ohmic heating is approximately adiabatic for a two-shell quadrupole operating at its peak current of 4.8 kA. At this current, the quench Miits must be 5.18 or less in order to limit the peak cable quench temperature to 500 K.

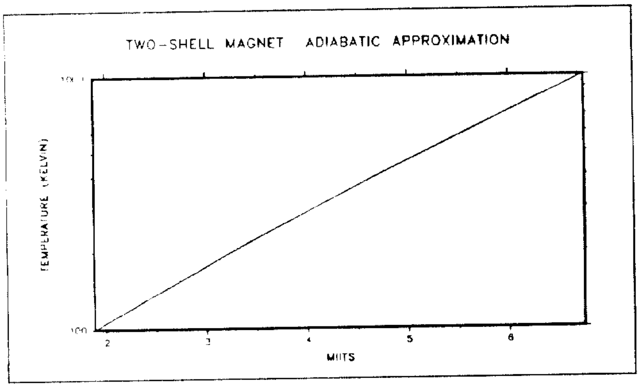

Figure 3. Quench temperature vs. quench Miits

The quench Miits accumulated by a magnet in a series connected circuit are the sum of the Miitage accumulated during quench detection and the Miitage accumulated during the time required to reduce the circuit current to zero. The Miitage accumulated during quench detection is a function of the quench resistance growth and the quench voltage threshold. The Miitage during current decay depends on quench resistance growth - in this case mostly due to the quench heaters - and the power circuit impedance.

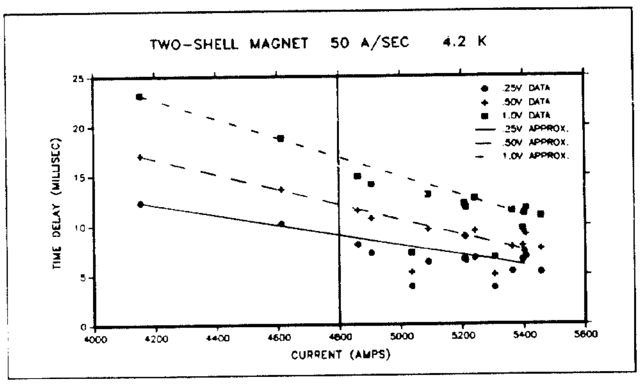

Figure 4. Spontaneous quench voltage growth.

The spontaneous quench resistance growth of the first production magnet (test serial number LQ1P01) has been measured during its initial training quenches in a dewar operating at 4.2 K. The delays to reach three quench voltages are plotted in Figure 4 as a function of quench current. The erratic nature of the data reflects the variation of released mechanical energy during training or different quench origins in the magnet. The straight lines drawn through the data represent an eye-ball estimate of the expected maximum quench delay. A spontaneous quench at a magnet current of 4.8 kA takes 9 ms, 12 ms and 17 ms to reach a quench voltage of 0.25 V, 0.5 V and 1.0 V respectively. If we use a 0.25 V, three 60 Hz line cycle averaged quench detection threshold, the quench detection delay will lie between 23 ms and 40 ms. At the 4.6 K cryostat temperature of the tunnel refrigeration system, these times will be shorter as the quench velocity increases.

Each two-shell magnet is fitted with two independent heater circuits for redundancy. Each heater consists of two .001 in. thick, 0.5 in. wide stainless steel strips that can be energized in series or in parallel depending on their end connections. The heaters are imbedded within the center of the .02 in. thick Kapton layer that electrically insulates the coils from their aluminum containment collar. Each heater power supply consists of a 6.6 mF capacitor bank that can be charged up to 450 V. The effectiveness of the quench heaters was measured by energizing the heater(s) with the test magnet effectively shorted by the bypass diodes of the magnet circuit power supply. Each heater power supply was adjusted to obtain an initial heater current of 40 A in the heater strips. The heater resistance - 54 in. long magnet with series connected heater strips - and the heater power supply load resistance were 4.8 Ω and 5.3 Ω respectively.

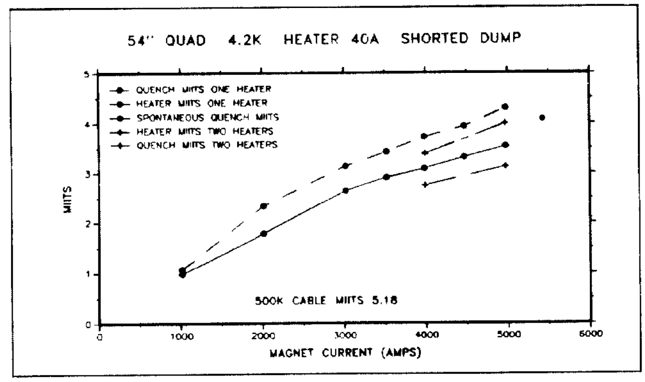

Figure 5. Quench protection-heater induced Miits.

The measured heater-induced quench Miitage is shown in Figure 5. Quenches were initiated with one heater or with both heaters energized simultaneously. The single heater quench data represents a heater failure mode as both heaters will be used in the tunnel. For heater-induced quenches, the Miitage integration was done twice; starting at the instant that the heater power supply was triggered and starting at the instant when the quench voltage is barely visible within the 10 mV noise of the detection channel. The difference in the two integrations shows the Miitage penalty due to heater quench delay. The isolated data point represents a single spontaneous quench. A single heater was energized after the spontaneous quench voltage reached 1.5 V; the Miitage integration started when the quench voltage became visible within the 10 mV noise of the detection circuit.

The worst case tunnel scenario considered is a quench within a coil at 4.8 kA with one of the heaters inoperative. The maximum Miitage that a quenching magnet will experience is 5.08 Miits which according to Figure 3 represents a peak temperature of 470 K. The assumed quench detection delay of 40 ms accounts for .92 Miits. The remaining 4.16 Miits are obtained from the one-heater curve in Figure 5. Under normal circumstances with both heaters operative, the quench temperature at 4.8 kA is 420 K. This quench temperature analysis neglects the spontaneous quench resistance, the magnet circuit impedance, and the higher operating temperature of the tunnel. They all tend to reduce the quench temperature even further. The analysis applies only to coil quenches. Lead quenches will be eliminated through complete stabilization with copper or made safe by doubling the superconducting cable to quadruple the Miitage capacity of the connection.

Quench Behavior of One-shell Quadrupole

The one-shell quadrupole is described in another paper of this conference [3]. The quadrupole has a gradient of 0.5825 T/cm/kA, an inductance of .505 mH/in., and the tunnel geometry constrains these magnets to a total length not to exceed 30 in. The maximum operating current required for the low β insertion is 1.0 kA. The magnet's coils are wound with of 5-in-1 conductor; 5 individually insulated monolithic strands are electrically connected in series to reduce the required magnet current by afactor of 5. The production magnet strands will be fabricated from the same superconducting material as used in the two-shell magnets but will be drawn to a rectangular cross section of .0430 in. x .0694 in.

A test magnet, dimensionally identical to the production magnets but composed of cable with a 1.8:1 copper-to-superconductor ratio, has been tested in a dewar. This magnet had no integral voltage taps or quench heaters. Quench detection was performed by a total magnet voltage minus magnet inductive voltage subtraction with the quench detection level set at 1.0 V. The magnet was quenched at currents lower than the first training quench by mounting a 15 Ω resistor on each magnet lead at the point were they entered the magnet cold mass. Quenches that originate in the magnet leads can be considered as worst-case quenches as the quench resistances originating at these locations grow slowly due to low magnetic field, good helium contact, and the quench propagation is limited longitudinally to the wire.

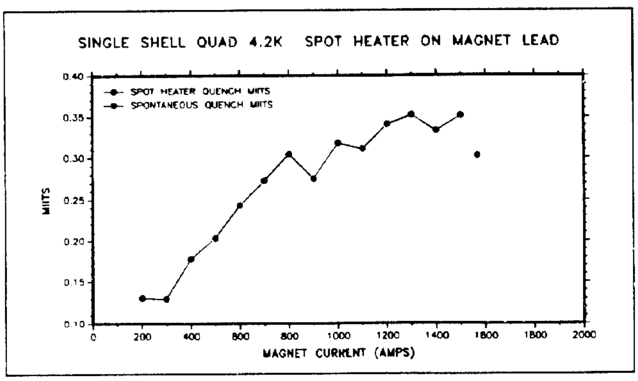

Figure 6. Spot heater induced Miits.

The magnet was quenched in 100 A magnet current increments until the first spontaneous training quench occurred. The quench Miits, integrated from the time when the quench was barely visible in the detection circuit, are plotted in Figure 6. At the instant of quench detection, the magnet power supply was switched to bypass. There was no series resistive dump in the circuit. At the lower and higher magnet currents, it was difficult to accurately determine the time of quench start. This accounts for the nonsmoothness of the Miitage curve. Notice that the Miitage of the first training quench, which originated within the magnet, lies below the Miitage of heater-induced quenches. This magnet is self-protecting, i.e., the magnet does not require quench heaters or an external dump resistor to remove the magnet transport current before the normal quench zone overheats and causes irreversible damage.

An adiabatic calculation of the expected peak quench temperature versus quench Miits for single-shell magnets fabricated with 1.5:1 or 1.8:1 copper-to-superconductor ratio cable is plotted in Figure 7. The quench Miitage has to be less than .335 and .362 for the 1.5 and 1.8 ratio cables respectively to limit the peak quench temperature to 500 K. The Miitage during a quench of a production magnet will closely approximate the Miitage measured for the test magnet as the effects of lowering the copper content in the cable, a lower quench velocity and a higher cable resistance per unit length, to a large extent cancel. This cancellation and the higher operating temperature of the magnet in the tunnel should make the 1.5:1 copper-to-superconductor magnet self-protecting over the current range required for the low β insertion.

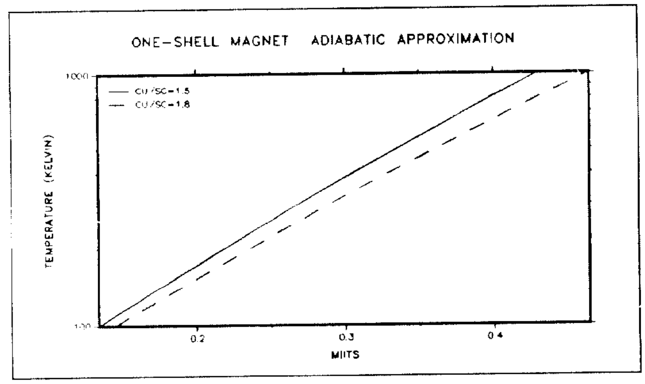

Figure 7. Quench temperature vs. quench Miits.

Power Circuits and Quench Protection Circuits

An active quench protection system, i. e., quench heaters, are used to protect the two-shell magnets against quench damage. Quenches are detected via voltage taps on the magnets by a microprocessor Quench Protection Monitor (QPM). At the instant of quench detection, two quench heaters per quadrupole are energized and the circuit power supply is shut off. A resistive dump circuit is not used; quench protection redundancy is obtained through the use of two heaters.

The two-shell circuits will reuse the 50 V, 7500 A, 12 pulse power supplies presently used to power the low β insertion at the BO straight section. These supplies have a regulation tolerance of 10^{-5}. The supplies are connected to the magnets via water-cooled 2 in. square copper bus. The T6 circuit also requires a 500 A shunt power supply across one of its load magnets to permit the load magnets to operate at different currents. The QPM will be a second generation version of the units used to protect the Tevatron superconducting magnets [4]. The new QPM uses a 68020 microprocessor; is programmed in C; and is compatible with the accelerator's newly installed Token Ring communications link. The quench protection function of all five circuits will reside in one microprocessor. The QPM and its associated electronics are designed to be failsafe.

The design of the one-shell power circuits assumes that these magnets will be self-protecting and that these magnets do not require a QPM or quench heaters. Each one-shell magnet is connected to its dedicated power supply via doubled 500 MCM cable. The circuit power supplies will be 10 V, 1 kA, 6 pulse supplies with a regulation tolerance of 10^{-4}. Quench detection will be performed by an analogue subtraction of the total and inductive voltages of a magnet. Quench detection is necessary to turn off the circuit power supplies and as an input into the beam abort system. The power supply over-voltage trip setting will serve as a redundant quench detection circuit.

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