IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

THE TEVATRON BO LOW BETA SYSTEM

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Abstract

A low beta insertion has been installed at the BO straight section of the Tevatron, the location of the Collider Detector Facility. The focus is achieved with four superconducting quadrupole doublets. The engineering design and performance of this system exclusive of beam behavior will be described including the magnets and their power supply, quench protection and cryogenic subsystems.

Introduction

The BO low beta insertion consists of four nested high field superconducting quadrupole doublets that bracket the BO straight section. The outermost doublet (Q1 circuit) replaced the quadrupoles located at A48 and B12 of the normal magnet lattice. The other doublet quadrupoles - circuits Q2, Q3 and Q4 - were inserted at the start and end of the BO straight section. In addition to the low beta quadrupoles, 8 correction dipoles, 16 beam position detectors, 6 flying wire detectors and 9 cryogenic vessels were added to the tunnel.

The low beta doublets are powered with separate power supplies. The Q1 circuit operates at approximately half the ramp current during beam acceleration and is programmed thru a ±6 kA range during a low beta squeeze. The other doublets are powered after the particle beams have reached their peak energies and as the low beta squeeze starts. During a low beta squeeze cycle, the existing quadrupole, skew quadrupole and sextupole correction magnets in the Tevatron are reprogrammed to maintain stable circulating beams. Small orbit distortions (±.040") caused by low beta quadrupole misalignments are corrected with additional dipole correctors and the local dipole correction magnets close to the BO straight section. Each of the Q2, Q3, Q4 quadrupoles has motor driven mounts which can be adjusted to correct for larger orbit distortions. A more detailed description of the low beta lattice and the required low beta controls are given in accompanying papers at this conference.[1,2]

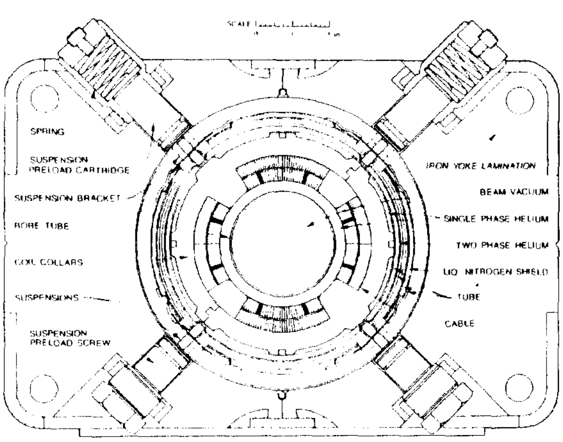

Fig. 1. Low Beta Quadrupole Cross-section

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

Low Beta Quadrupoles

A cross section of the low beta quadrupoles is shown in Fig. 1. Except for changes in their cryostats and overall lengths, the quadrupoles are mechanically identical to the Tevatron quadrupoles.[3] The cable copper to superconductor ratio has been changed from 1.8/1 to 1.3/1 to allow these magnets to operate at currents in excess of 6 kA. At 6 kA, the quadrupoles have a gradient of 26 kG/in. The maximum required gradient to achieve a β^* of 1 m at a beam energy of 1 Tev is 25.4 kG/in. All of the quadrupoles were cold tested for maximum operating current and field quality prior to their installation in the tunnel and all achieved their design fields with minimum training. Additional quadrupole parameters are given in Table 1.

Table 1 Low Beta Quadrupole Parameters

Cable Cross Section (in)	.044 x .055 x .307
Strand Diameter (in)	.0268
No. Strands/Cable	23
Filaments (μm)	20
Copper/Supercond. (nom.)	1.3/1 by volume
Cable Short Sample	6290 A, 5.79 T, 4.6 K

	Inner coil	Outer Coil
Inner Radius (in)	1.750	2.088
Outer Radius (in)	2.067	2.405
Key Angle (deg)	30.1194	30.7839
No. Turns	14	20

Yoke Inner Radius (in)	4.000
Yoke Dimensions (in)	9.75 x 15.478

	Q1	Q2	Q3A,B	Q4
Coil Length Actual (in)	69.	182.9	146.9	146.9
Magnetic (in)	66.1	180.	144.	144.
Yoke Length (in)	63.	176.9	140.9	140.9
Slot Length (in)	129.	195.	159.	159.
Ind./mag.(mH)	7.1	19.3	15.5	15.5

The low beta doublets are assembled out of 10 quadrupoles. The Q3 doublet magnets (288" magnetic length) were split into separate 144" magnets to facilitate fabrication and handling. The Q1 magnet assembly is the most complicated. Its length was set by the available space (128.972") at the B12 lattice location. In addition to the 66.1" quadrupole, this assembly contains 40" concentric wound horizontal and vertical correction dipoles, two 6 kA and four 50 A power leads, a vertical beam detector, cold bypass buses to allow the accelerator magnet bus to bridge the gap at this location, relief valves for the single phase LHe, two phase LHe and LN, carbon resistor thermometers and voltage taps for quench detection. The A48 magnet is identical to reduce the number of spare magnets required. Field polarities are adjusted by reversing the magnet current polarities. The other quadrupoles are simpler, containing single phase LHe relief valves because of their relatively long lengths and voltage taps for quench protection. The Q2, Q3, Q4 magnet strings are mechanically symmetric in rotation around the center of the BO straight section except for the cryogenic connection points to the original magnet lattice. This simplified the mechanical layout while again reducing the required number of replacement parts.

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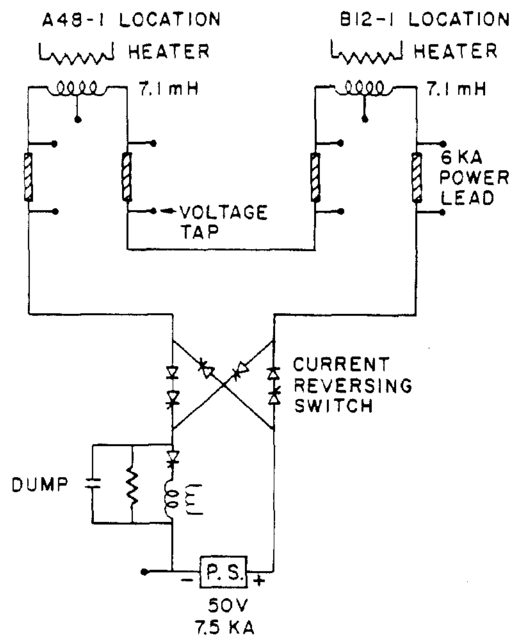

Fig. 2. Power Circuit for the Q1 Doublet

Power Circuit

The low beta circuits operate on separate power supplies which are programmed with microprocessor controlled waveform generators[4]. The power circuit for the Q1 doublet is shown in Fig. 2. The power circuits for the other doublets are similar. The Q1 circuit contains a thyristor current reversing switch.[5] This allows the use of identical power supplies for all the circuits. The Q3 circuit contains two dump circuits - one next to the power supply, the other centered in the inductive load - to reduce the voltage-to-ground during a dump by a factor of 2. All of the power supplies and dumps are located in the B0 service building. Warm electrical connections are made with 2" square, 1.125" inner diameter, water-cooled bus. The helium cooled power leads are rated at a constant 6 kA.

The power supplies installed at present are temporary units initially intended for beam line magnets. They are 12 pulse, 150 kW dc, current programmable supplies which are capable of a continuous 5 kA at 30 V and have a current regulation tolerance of .05%. The low beta supplies on order have a regulation tolerance of .001% and a continuous output current of 7.5 kA at 50 V. The temporary supplies limit low beta operation to a beam energy of 800 GeV.

None of the power supplies are voltage inverting. The required current regulation with negative current rates is possible due to the voltage drop across the resistive elements in series with the superconducting magnets. The Q1 circuit has additional diodes in the current reversing switch which allows -300 A/s current rates down to zero output current. The superconductiong magnets quench at current rates in excess of 300 A/s. Therefore, a minimum of approximately one minute is required to squeeze the beam size to a β^* of 1 m.

The regulation requirements can be separated into three segments: the beam acceleration cycle during which only the Q1 circuit is powered; the programmed segment during which the beam β function changes; and the final segment at low beta and constant current. The most stringent regulation condition occurs during the final constant current mode during which the machine tune shift tolerance is estimated to be .0003. This tune shift implies that the low beta circuits must be current regulated (drift and ripple) to approximately .001%. No additional filters are required except for a passive filter in the Q1 circuit whose inductance of 14 mH is insufficient to guarantee uniform slow spill during fixed target operation.

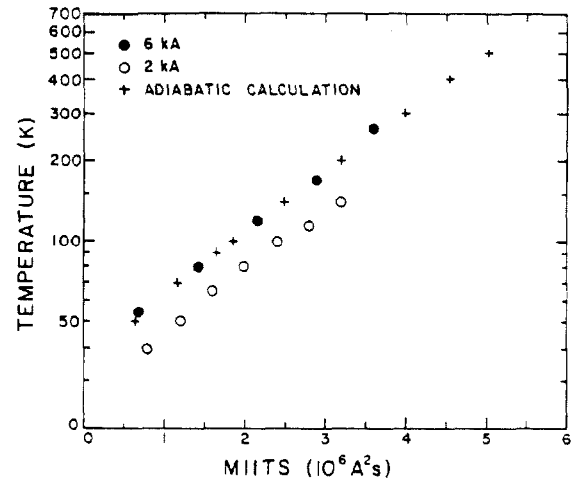

Fig. 3. Cable Temperature versus Miits

Quench Protection

The reduced copper content and high operating current of the low beta superconducting cable relative to Tevatron cable[6] makes quench protection somewhat more difficult. The measured low beta cable temperature as a function of the integral $\int I^2 dt$ (10^6 A^2s equal Miits) is shown in Fig. 3. Fig. 4 shows a measurement of Miits versus quench current for a Q1 magnet with its terminals shorted during the quench.

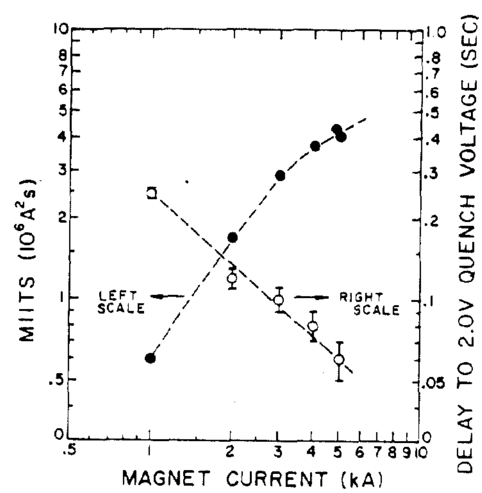

Fig. 4. Miits and quench delay versus magnet current for heater initiated quenches.

The primary quench protection for the low beta magnets are the resistive dumps. Table 2 shows the dump resistances that, for magnet currents up to 6 kA and a quench detection level of .25 V, limit the peak conductor temperatures to 500 K. The advantage of external dumps is that they absorb most of the magnet's energy, thereby minimizing the refrigerator disturbance and the likelihood of a secondary quench in an adjacent Tevatron magnet.

Table 2 Dump Circuit Parameters

Circuit		Dump	
Number	Inductance (mH)	Resistance (mΩ)	Voltage at 6kA (V)
Q1	14.2	71	426
Q2	38.6	193	1158
Q3	62.	* 310	* 1860
Q4	31.	155	930

* Total for two dump circuits

Redundancy in quench protection is obtained with quench heaters as the dc contactors used in the Tevatron dumps[7] are too slow in this application. The quench heaters are energized simultaneously with the dump(s). Below a magnet current of 1 kA, the quench heaters become increasingly unreliable in starting a quench. In this case, the series resistance of the circuit is sufficient to protect the magnets as long as the power supply shuts off.

A standard Tevatron Quench Protection Monitor (QPM)[7] with modified software is used to monitor the magnets for quenches and the power leads for overheating. The QPM compares four coil voltages to determine the presence of a quench. The quench detection level is 0.25 V. Noise or electronic drift related false quenches have not been a problem. In the case where only two magnets are in the circuit, the voltages are obtained with magnet center taps. The dump circuits, heater power supplies, voltage to frequency converters, etc., are either standard Tevatron components or sufficiently similar to simplify operation and maintenance.

Cryogenics

Although electrically independent, the low beta quadrupoles are cryogenically in series with the Tevatron magnets. This eliminates the need for separate refrigeration systems but increases the 4.6 K heat load for the A4 and B1 refrigerators by as much as 115 W each. In addition, each refrigerator has to supply LHe cooling for eight 6 kA power leads (16.8 l/hr per lead at 6 kA dc).

The Q1 magnet assemblies replace smaller magnets in the Tevatron magnet lattice. The Tevatron power bus now bypasses this location inside a 4.6 K transfer line. The remaining low beta magnets are attached to the Tevatron magnet cryogenic system at the points were the cryogenic system ended at the start and end of the B0 straight section. The modified cryogenic arrangement - upstream and downstream are identical - is shown in Fig. 5. The original cryogenic turn-around boxes were replaced with a power feedcan for the Q2 magnet, followed by the Q2 magnet, a spacer piece which also contains two beam position monitors, the Q3A and Q3B magnets, a modified turn-around box and finally, the Q4 magnet.

The two Q3 magnets closest to the beam interaction point and both Q4 magnets had to be mounted on support beams which project into the B0 Collision Hall. The solid angle coverage for high energy physics relative to the beam collision point was enhanced by minimizing the size of the original cryogenic turn-around box and by moving it inward between magnets Q3B and Q4. The Q4 magnets are therefore only cooled with direct return subcooled LHe. A return path for the LN was provided by adding a second concentric shield to this magnet's cryostat. An inherent cool-down time increase of a factor of two was accepted for this magnet.

In addition to the Joule-Thomson valve which separates the single phase and two phase LHe, each modified turn-around box also contains the He cool-down line, cryogenic relief valves, cryogenic instrumentation, two beam position detectors and the electrical connections for the Q3 and Q4 magnets. The power leads for these magnets are 30 ft back inside the tunnel. A transfer line, cooled only by the power lead LHe flow, transports the superconducting leads from the power leads to the turn-around box.

Acknowledgements

Many people have contributed to the Low Beta effort. In particular, we want to acknowledge the substantial contributions of our colleagues: D.Augustine, H.Barber, J.Carson, R.Ducar, H.Edwards, J.Edwards, R.Ferry, J. Fritz, H.Fulton, T.Groves, D.Johnson, R.Johnson, H.Jostlein, F.Krzich, S.Lackey, F.Lange, E.Larson, G.Lee, J.Lockwood, W.Marsh, D.Mizicko, C.Moore, A.Oleck, S.Reeves, C.Rode, G.Tool, F.Walters, F.Willeke, D .Wolff.

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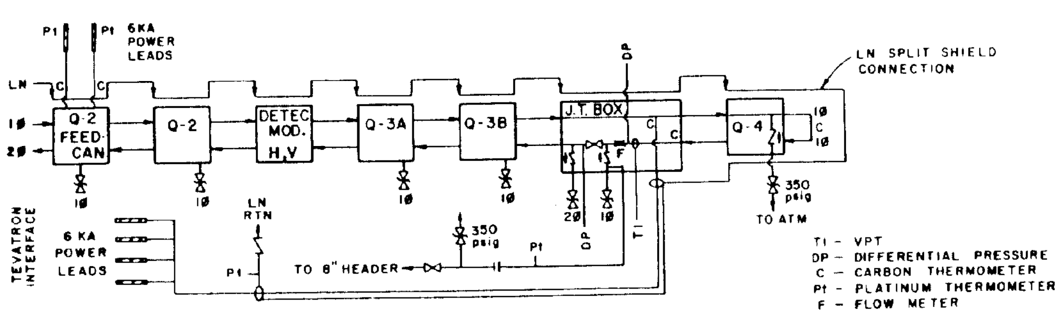

Fig. 5. Low Beta Cryogenic Arrangement