TEST RESULTS OF THE MAGNETIC SYSTEM FOR THE TEVATRON ELECTRON LENS

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Abstract. The magnetic system of the Tevatron Electron Lens (TEL) was manufactured by IHEP and successfully tested in Fermilab. The system consists of seven superconducting and four conventional magnets and provides solenoidal field to focus an electron beam, which collides with antiproton beam and, thus, compensates beam-beam effects in the Tevatron [1]. Description of the system as well as basic calculated characteristics of the magnets are presented. Test results of the magnets including magnetic field measurements are reported.

1 MAGNETIC SYSTEM DESCRIPTION

The longitudinal cross-section of the TEL magnetic system [2,3] is shown in Fig. 1:

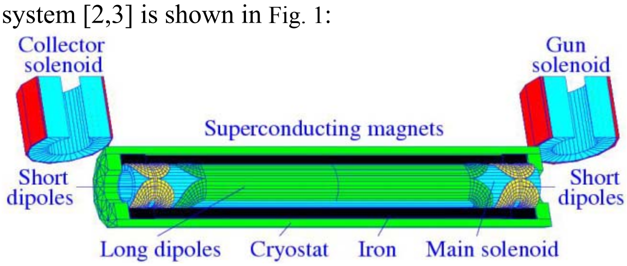

Fig. 1. Longitudinal cross-section of the magnetic system.

The system consists of seven superconducting (SC) magnets (one large solenoid plus six steering dipoles) and two conventional solenoid magnets each equipped with corrector coils. An electron gun is placed in center of the first conventional solenoid and an electron beam collector in the second one. The electron beam is born on the electron gun cathode, transported through the interaction region in the strong solenoidal field of the SC solenoid and absorbed in the collector. The requirement of the field quality is that the magnetic field lines in the main SC solenoid are straight within 0.2 mm in both vertical and horizontal planes along 2 m length of the long dipoles.

The coil of the main solenoid is constructed of a flat transposed cable consisting of 10 NbTi SC wires. Six steering dipoles are placed on the outer surface of SC solenoid coil. Four pairs of 250 mm long coils form (short) lateral vertical and horizontal dipoles at each end of the solenoid. Two pairs of 2 meters long coils are placed in the central region of the SC solenoid. All these dipoles are for correcting the electron beam trajectory.

Magnetic field calculations of the magnetic system were carried out using the MULTIC code [4]. SC solenoid coil together with steering dipoles is enclosed in a magnetic shield made of low-carbon steel. The yoke reduces currents in steering coils, improves homogeneity of magnetic field inside solenoid aperture, compresses magnetic field lines at the ends of the coil block, and reduces stray fields. The winding of solenoid with preliminary tension and compression of SC coil by bandage of the stainless steel half-shells allows one to reduce degradation and training of the SC coil. The main parameters of the TEL SC magnets are presented in Table 1. Computer calculations of the solenoid coil stress have been performed for all stages of winding and showed that cable tension during coil winding have to be 200 N and preload higher than 1 MPa between coil and iron.

Table 1. Main parameters of the SC magnets.

	Solenoid	Lateral dipoles		Central dipoles	
Field direction		Hor.	Ver.	Hor.	Ver.
Inner coil radius, mm	76.00	100.0	103.7	100.0	103.7
Outer coil radius, mm	98.68	103.5	107.1	103.5	107.1
Coil length, mm	2500	270	270	1960	1960
Number of layers	14	2	2	1	1
Total turn number	7289	640	664	640	664
Operating current, A	1800	200	200	100	100
Central field, T	6.5	0.79	0.82	0.20	0.20
Maximal field, T	6.5	2.2	2.2	0.5	0.5
Stored energy, kJ	950	1.2	1.3	0.9	1.1
Inductance, H	0.6	0.057	0.066	0.18	0.21
Critical current (B_{max}, 4.6 K), A	3000	640	640	540	540
Critical temperature (B_{max}, I), K	5.3	7.1	7.1	8	8

During the change of current through the SC solenoid dynamic heat release occurs in the coil and other metal parts. Some heat is due to hysteresis in magnetization of the superconductor and the steel of the yoke. Heat is also provoked by eddy currents generated in inner stainless pipe, into the copper matrix of SC wires and in the yoke.

Current ramp rate less than l0 A/s is taken as a guideline value for the magnet excitation in order to limit the total heat load to liquid helium at 15 W. The SC solenoid coil is not self-protected against resistive transition and fast quench detection and removal of stored energy to the external dump resistor must be taken. Simulation of quench spread through the coil was made for the case when quench was initiated at the end of the coil at the maximum current of 1.8 kA. The quenching lasts ~2 s, 90% of stored energy (~1 MJ at 6.5 T) dissipates in the dump resistor and 10 % inside the cryostat, and the maximum temperature at the coil hot spot is 270 K.

The energy stored in SC dipoles is much smaller - about 1.3 kJ – and one can allow all the energy to be dissipated in the coil during the quench. In that case hot spot temperature will not exceed 120 K. But to lower risk of spreading the quench to the main solenoid, the scheme of quench protection with an external dump (as for the main solenoid) is used. The hot spot temperature does not exceed 43 K for lateral and 29 K for central dipoles.

The gun and collector solenoids have almost identical design. The solenoid has 0.4 T nominal magnetic field, 0.19 Ω electrical resistance and 18 mH inductance. The coil has 250-mm inner diameter, 474 mm outer diameter and 300 mm length. The solenoid coil consists of 17 pancakes (total number of turns 391), which are assembled on a common pipe of a 240 mm inner diameter. Water temperature rise in the coil is 300 C at 0.7 MPa pressure drop and nominal current of 340 A.

Electron beam shape and position correctors are set inside each of the conventional solenoids. The corrector consists of four coils, which can be commutated either as a quadrupole or as two dipoles (vertical and horizontal). Each coil has layer shape geometry with 0.74° inner and 40.04° outer angles, 112.5 mm inner radius and 8.6 mm thickness. The length of coil is 298 mm. The dipole and quadrupole fields are equal to 1.9 mT/A and 60 mT/m/A.

2 MEASUREMENT EQUIPMENT

The block diagram of the 3D Hall probe system is illustrated in Fig. 2. A movable rod supports the Hall probe, which can be translated 240 mm horizontally and 70 mm vertically. Additional rods can be interchanged to offer 1500 mm full range along the z-axis. The spatial resolution of any point is 10 mm in each direction. Power drivers operate three stepping motors moving the probe, and position sensors provide feedback to the controller mechanism. The direct-control module translates this information into command signals for the motor drivers.

The analog signals from the 3D Hall probe go to the three-channel Hall device and then to an analogue digital converter (ADC). The digital modules communicate via the data bus to the RS-232 port of a computer. The computer code is able to measure field data at a point, along a straight or magnetic lines and throughout a preset area or volume in the Cartesian or cylindrical coordinate systems.

Fig. 3 shows a schematic of how the field lines of the SC solenoid were measured by the second method. A small trolley holds a freely rotating magnetic rod, and this trolley is moved inside the solenoid by means of a long track. A mirror is glued to the rod and, therefore, also rotates as the rod aligns itself with the local magnetic field. Beyond one end of the solenoid is a small laser aligned along the axis of the trolley's motion. The output beam hits the mirror and reflects back onto a position-sensitive device (PSD). Everything is adjusted so that, at the center of the solenoid, the laser beam is centered on the PSD. As the trolley is moved along the length of the solenoid, small deviations in the magnetic field appear as changes in the location of the reflected laser beam, which are detected by the PSD. The PSD produces signals that are easily converted back to horizontal and vertical displacement of the beam. Through geometry, the angle of the field is deduced, which is integrated to find the transverse displacement of the field along the length of the solenoid. Another LabVIEW program automates the data collection and analysis process. The estimated errors of the spatial resolution are 10 μm vertically and horizontally and 2 mm along the z-axis.

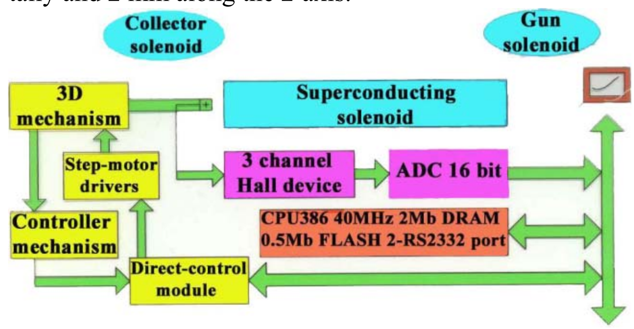

Fig. 2. Block diagram of the 3D Hall measurement system.

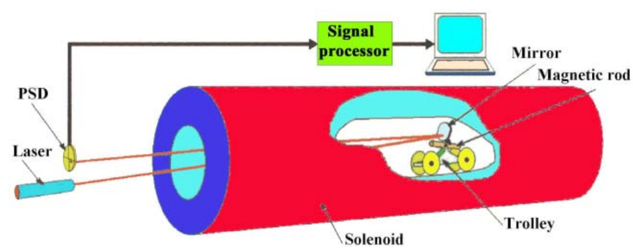

Fig. 3. Schematic drawing of the process to trace the magnetic field lines in the main solenoid. The actual trolley supports a small rod-mirror assembly in a compound gimbal.

3 TESTS OF MAGNETS

The ellipticity of the magnetic field in the solenoids was measured be less than ±0.2%, the accuracy of the measurement system. A corrector coil built into each solenoid can be configured as two dipoles (horizontal and vertical). The corrector magnetic length was calculated to be 248 mm, making the integrated dipole field equal to 0.4712 mT×m/A and the integrated quadrupole field equal to 14.88 mT/A. This last value allows one to adjust the ellipticity by at the maximum operating field of 0.4 T. The dipole correctors can rotate the field lines about ±1.3° at the maximum field, which provides ±10-mm displacement of the field lines at the edges of the solenoid. The on-axis residual field along the magnetic axis is approximately 0.6 mT near the iron cover and decreases linearly to about 0.2 mT near the stainless steel cover.

In the first high current test of the SC solenoid, 6.6 T was reached at the current ramp rate of 3 A/s and after that the solenoid could not be quenched up to 6.7 T at 10, 20, and 30 A/s. The magnet quenches very quietly and does not consume much helium at the quench.

The longitudinal distribution of the normalized field

B/B_{max} is shown in Fig. 4 for the SC magnets, where B_{max} is equal to 6.5 T in the solenoid, 0.8 T in the short dipoles, and 0.2 T in the long dipoles.

Fig. 5 shows the magnetic lines going out of the SC solenoids (0, ±5 mm) to the beginning of the collector solenoid. The left vertical line marks the edge of the SC coil; the right vertical line shows the axis of the collector solenoid. The solid magnetic lines are without short dipole field. The dotted lines present the magnetic lines with 100 A current in the short steering dipole, which corresponds to 0.4 T dipole field. The main fields are 6.5 T in the SC solenoid and 0.4 T in the collector solenoid. The initial position of the calculated line (the lower solid line) has a little shift (5.1 mm instead 5.0 mm).

The deviations of the magnetic axis from a straight line of the SC solenoid are shown in **Fig. 6** and Fig. 7. At full power, the vertical deviations are spanning –25 to 25 mm of the axis and the horizontal deviations are from –100 to 75 mm; these values are less than the required 0.2 mm tolerance. The left side depicts how the field lines change from 3 T to 6 T, while the right side illustrates how five field lines distributed horizontally differ from each other. The deviations are small enough (about 8 mm maximum, and the horizontal displacement shows similar uniformity) that unintentional lensing effects will be minimal.

4 OPERATIONAL EXPERIENCE

The TEL has been installed in the Tevatron in February 2001, and been in operation since March and there were no quenches in the TEL at the typical operational field of 3.5 T in the main solenoid. The magnetic system worked reliably providing the control of the electron beam size and trajectory that allowed the first successful demonstration of the betatron tune shift of 980 GeV protons in the Tevatron. It was found experimentally that the electron beam can be steered to pass through the main solenoid if the gun solenoid field is in the range of B_{Gun}=0.19-0.42 T for B_m=3.5 T (outside the range, the beam touches parts of the vacuum system in the bend sections of the TEL). Currently, we study possible modifications of the bending sections, which can allow clean beam passage over even wider range of magnetic field ratios B_m / B_{Gun}. As it was mentioned above, that will make possible wider variation of the electron beam size in the main solenoid magnet.

5 CONCLUSION

The Tevatron Electron Lens magnetic system consisting of seven SC and four conventional magnets has been developed and fabricated in IHEP for increase of luminosity in Tevatron. The system of conventional and SC solenoids create necessary trajectory of magnetic field lines for the TEL electron beam motion. SC dipoles and warm correctors permit to carry out correction of the electron beam motion.

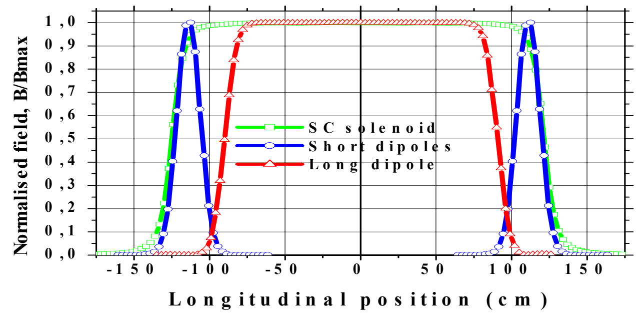

Fig. 4. Longitudinal distribution of the normalized fields of the SC magnets.

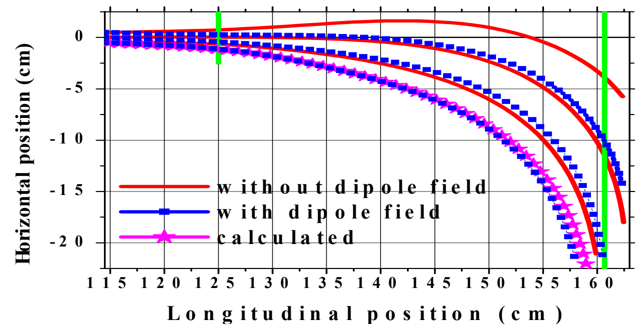

Fig. 5. Magnetic lines from the SC solenoid to the collector one.

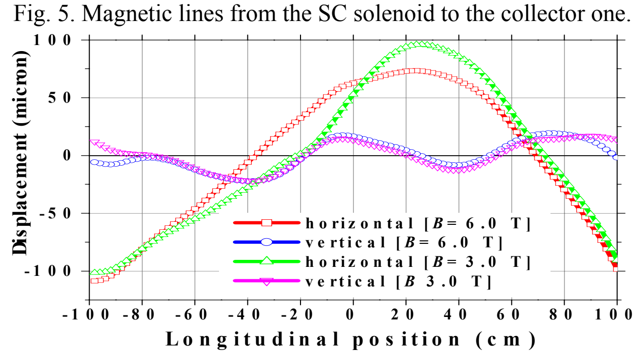

Fig. 6. Transverse displacement of various field lines along the length of the main solenoid at different field strengths.

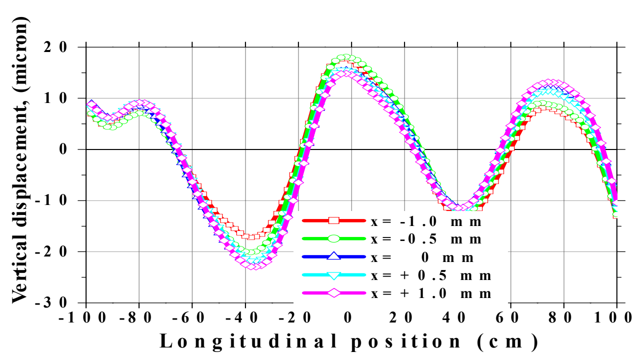

Fig. 7. Transverse displacement of various field lines along the length of the main solenoid at different horizontal positions.

6 REFERENCES

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