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MAGNETIC SYSTEM OF THE TEVATRON ELECTRON LENS

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Introduction

In the framework of collaboration between IHEP and FNAL, a magnetic system of the Tevatron Electron Lens (TEL) has been designed and built. The TEL magnetic system will be set in the superconducting ring of the Tevatron proton-antiproton collider. The system provides solenoidal field to focus an electron beam, which affects on antiproton beam and, thus, compensates beam-beam effects in the Tevatron [1].

1. General description of magnetic system

The longitudinal cross-section of the TEL magnetic system is shown in **Figure 1**.

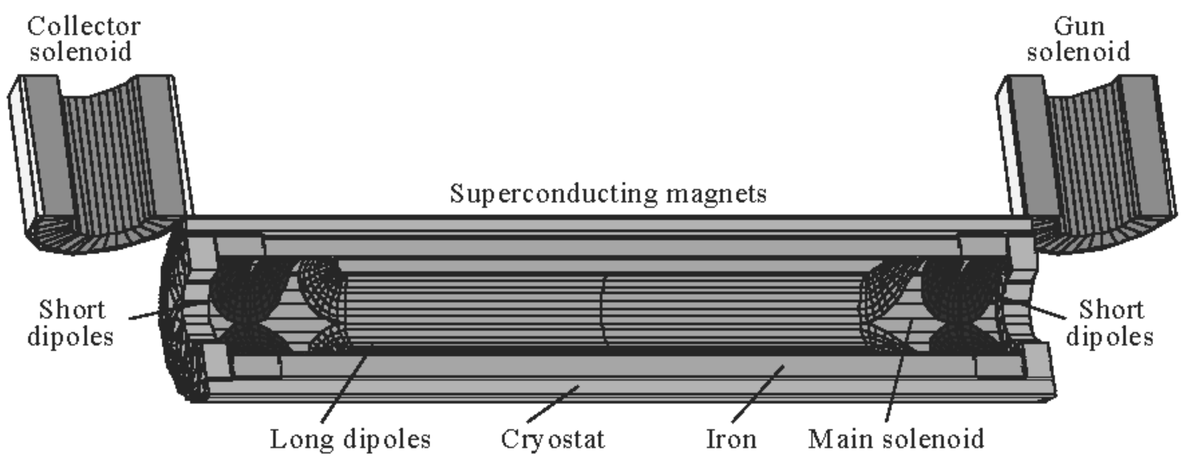


Figure 1. Longitudinal cross-section of TEL magnetic system.

The system consists of seven superconducting (SC) magnets (solenoid and six steering dipoles) and two conventional solenoid magnets each equipped with corrector coils. An electron gun is supposed to be placed in center of the first conventional solenoid and an electron beam collector in the second. The electron beam will be born on the electron gun cathode, transported through the interaction region in a 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.

2. SC magnets

The solenoid coil is made of a flat transposed cable consisting of 10 SC wires (NbTi filaments in copper matrix) each 0.85 mm diameter. The wire has 550 A critical current at 4.2 K and 5 T and Cu/SC ratio of 1.38. Dimensions of bare cable are 1.44×4.64 mm ^{2}.The cable is wrapped by polyimide film of 0.03 mm thickness with 1/3 overlap. The main SC coil is wound on stainless steel tube of 151.4 mm diameter and 4 mm thickness. The frame insulation is three layers of polyimide film of 0.1 mm thickness.

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-meter long coils are placed in the central region of the SC solenoid. All these dipoles are for correction of the electron beam trajectory inside the magnetic system. The steering dipoles are wound of cable transposed from 8 wires of 0.3 mm diameter. The wire has 50 A critical current at 4.2 K and 5 T and Cu/SC ratio of 1.5. Dimensions of bare cable are 0.45×1.48 mm^2. The cable is wrapped by polyimide film of 0.03mm thickness with 1/3 overlap. In lateral dipoles, all wires in cable are superconducting. Current in central dipoles is small, and the cable has three SC wires and five Cu wires. The central dipoles have one layer, lateral dipoles consist of two layers and inter-layer spacer of 0.2 mm thickness.

Magnetic field calculations of the magnetic system were carried out using the MULTIC code [2]. The main parameters of the TEL SC magnets are presented in Table.

SC magnets	**Solenoid**	**Lateral dipoles**		**Central dipoles**	
Magnetic field orientation		Horizontal	Vertical	Horizontal	Vertical
Inner coil radius, mm	76.0	100	103.7	100	103.7
Outer coil radius, mm	98.68	103.5	107.1	103.5	107.1
Coil length, mm	2500	270	270	1960	1960
Total current, kA	12963	64	66.4	16	16.6
Layer number	14	2	2	1	1
Turn number/layer	521	320	328	320	328
Total turn number	7289	640	664	640	664
Operating current I, A	1800	200	200	100	100
Central field, T	6.5	0.79	0.82	0.20	0.20
Max field in coil B_m, 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_m, 4.6 K), A	3000	640	640	540	540
Critical temperature (B_m, I), K	5.3	7.1	7.1	8	8

SC solenoid coil together with steering dipoles are enclosed in magnetic shield made of low-carbon steel. The shield is 48.5 mm thick over the length of 270 mm and 38.5 mm thick in the central part over 1960 mm length. 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 outer surface of the iron has 16 grooves of 15 mm width and 2 mm depth. The grooves are need for passage of helium flow and they are also used for laying of cables for central and lateral dipoles. The yoke is produced of four non-laminar equal ring sector cylinders of 2500 mm lengths. The yoke was tightened by two 5 mm thick stainless steel half-shells and then the shells were welded. 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 solenoid coil stress calculations during all stages of manufacture and operation were executed with help of computer code. The calculation shows that cable tension during coil winding have to be equal to 200 N and preload higher than 1 MPa between coil and iron. Azimuth clearance of 0.5 mm between the ring sector parts of iron yoke during assembling is done.

All SC coils together with the magnetic shield are enclosed in a helium vessel. The vessel has 142.4 mm diameter and 4 mm thick inner tube; outer shell diameter is 324 mm diameter and 5 mm thick and 2590 mm long. There is a box in the front of the helium vessel, which contains current leads, helium pipes and pipes going to a relief valve. Thermal shield made of 2 mm thick copper sheet surrounds the helium vessel. The outer surface of the shield is covered with superinsulation and cooled by liquid nitrogen. Small radial gap between the inner tubes of the vacuum vessel and the nitrogen shield does not allow one to place superinsulation between them and this part of the nitrogen shield is cooled by means of thermal conductivity only.

The vacuum vessel has 114 mm diameter and 2.1 mm thick inner tube, 480 mm diameter and 5 mm thick outer shell and 2690 mm length. There are two boxes attached in the head part of the vacuum vessel. A bigger box contains current leads, pipes for helium input—output and relief, connectors of potential wires. Smaller box has pipes for nitrogen input-output. The cold part of the magnetic system with mass of about 1350 kg is hung up to the vacuum vessel in two cross-sections with help of two vertical suspensions and two horizontal tension members in each of cross-sections. The tension members are made of titanium alloy and have diameter of 10 mm. The axial direction the cold mass is fixed by help of longitudinal titanium tension members and anchor fixed on vacuum vessel.

The current leads of the main solenoid are designed for the maximum current of 1800 A. Each current lead is a braid of 3500 copper wires of 0.13 mm diameter placed in stainless steel tube of 14 mm inner diameter. Glass-cloth-base laminate tube of 1 mm thickness is placed between cooper wires and stainless steel tube for electrical insulation. The current leads are cooled by 0.125 g/s of helium flow. The length of the cooled part is about 750 mm. Heat leak through both 1800 A current leads to helium is equal to 4 W. The current leads of the dipole magnets are designed for 200 A current. The current carrying element is 8 mm diameter copper tube. Glass-cloth-base laminate washers connect six tubes in an assembly. The washers are pulled onto the tubes and are glued between them. The assembly is placed in 38 mm inner diameter stainless steel tube. The washers have grooves for 0.067 g/s cooling helium gas flow. Heat leak to liquid helium through the current leads for all SC dipoles is 2x1.4=2.8 W.

Total static heat load onto the helium vessel is 12 W and 25 W onto the nitrogen thermal shield of the cryostat. TEL cryostat is a part of the Tevatron magnet string cooling system. So, 24 g/s of liquid helium pass through the channels in the yoke and ring gap between inner tubes of helium vessel and SC solenoid and besides 20 % of the liquid helium flows through the ring gap.

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. To estimate the heat release, we used results of early made measurements of properties of structural materials and the superconductor [3, 4]. Calculated power of the heat release in the main components of SC solenoid design is 1.5 W at the current ramp rate of 5 A/s and 8.5 W at 18 A/s. 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. In that case, the estimated temperature rise of inner layer of the SC solenoid (at maximum magnetic field) and helium flow in the cryostat are 0.01 and 0.1 K, respectively. Critical temperature of SC solenoid is 5.3 K at 1800 A and 6.5 T (see Table) and its temperature margin equals 0.6 K at helium temperature of 4.6 K. For the dipole magnets critical temperature is 7.1 K and the temperature margin is bigger than in the SC solenoid.

3. Quench and protection of SC magnets

Our studies of the quench processes show that the SC solenoid coil is not self-protected against resistive transition and some protective precautions namely, 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 provoked at the end of the coil inner layer at the maximum current of 1800 A, the quench detector threshold 1 V, time delay 50 ms, energy discharges on dump resistor 0.56 Ohm and maximum voltage across the dump resistor less than 1000 V. Quench process continues 2 s approximately, 90 % of stored energy dissipates in the dump resistor and 10% inside the cryostat, and the maximum temperature of coil hot spot is about 270 K.

The energy stored in dipoles is about 1.3 kJ. The results of simulation of quench process in the coils show that after the quench detection and switching off the current supply, one can allow all the energy to be dissipated in the coil. In this case temperature of coil hot spot will be about 120 K at lateral dipoles and 50 K at central dipoles. But to lower this temperature in order to reduce the possibility of spreading the quench to the main solenoid, the scheme of quench protection with external dump (as for the main solenoid) is used. Simulations of quench processes in lateral and central dipoles show that the maximum voltage across the dump resistor is 400 V (the value of resistance is 2 Ohm for lateral and 8 Ohm for central dipoles); the maximum resistor's temperature rise is 80 K. In this case the hot spot temperature does not exceed 43 K for lateral and 29 K for central dipoles.

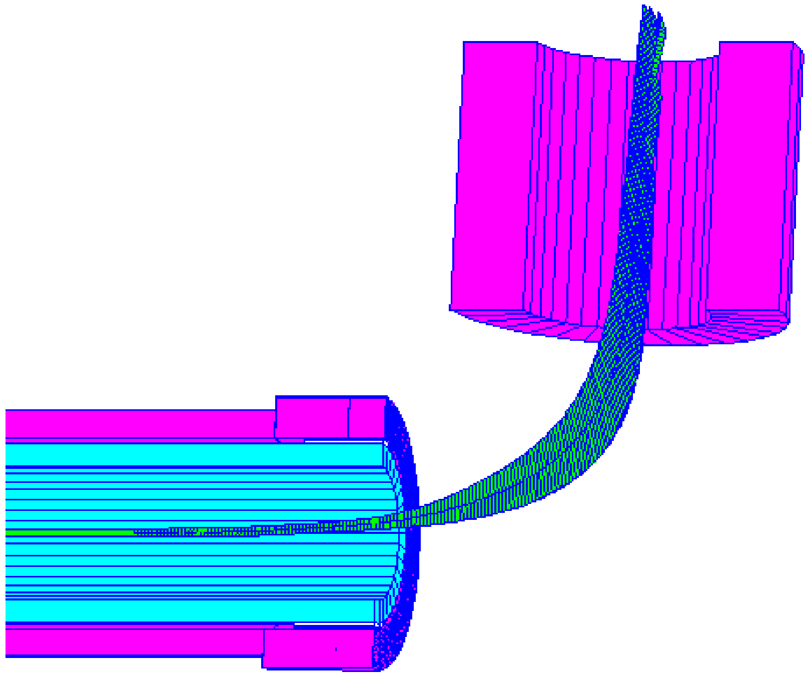
4. Conventional magnets

Gun and collector solenoids have practically the same design. The solenoids are wound of 8.25×8.25 mm^2 copper conductor with water hole of 5.5 mm diameter. The conductor is wrapped by 0.2 mm thickness of glass tape with 50% overlap. The solenoid has 0.4 T nominal magnetic field, 0.19 Ohm 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 common pipe of 240 mm inner diameter. The pancakes are sorted in six sections, which have serial electrical current connection, while cooling water is supplied in parallel. Heating of the water in the coil is 30 ^{0}C at 0.7 MPa pressure drop and nominal current.

The solenoids have a stainless steel flange at the end closer to the SC solenoid and an iron (low carbon steel) flange at the other end. The thickness of the iron flange is 12 mm for the gun solenoid and 37 mm for the collector solenoid. To reduce stray fields, both solenoids have low carbon shields around the coil, which has average thickness of 12 and 20 mm for the gun and the collector solenoids, respectively. Because of that difference in shielding, the field of 4kG requires different nominal currents of 340 and 320 A for gun and collector solenoids, respectively.

Magnetic forces acting either on the electron gun or on the collector solenoids while they installed in the TEL near the SC solenoid are 1.9 kN in perpendicular direction to the axis of SC solenoid and 8.5 kN in parallel direction. The total force equals to 8.7 kN. The magnetic field tube with initial radius of 5 mm and starting from the main SC solenoid to the collector solenoid is shown in **Figure 2**. It needs about 100 A operating current in the short steering superconducting dipole in order to get the electron beam hits in the center of the warm solenoid.

There are correctors 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 equal to 298 mm. The coils were wound by 1 mm diameter cooper wire and have 620 turns each. The dipole field is equal to 19 G/A; the quadrupole field is equal to 6 G/A/cm. These coils allow correction the electron beam



cross-section shape and/or to adjust transverse position of an electron beam relative to the solenoid axis.

Figure 2. Magnetic force tube from the SC solenoid to the collector solenoid

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 SC cable tension and preload of SC coils are calculated to make sure the necessary mechanical stiffness and strength of the block of the coils. The chosen cable design and cooling of the SC magnets ensure sufficient temperature margin for operating of SC magnets and their safety during quench. 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 one to carry out correction of the electron beam motion.

References

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