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A Radiation-Hardened Pulsed Magnet for the Tevatron-I Target Station

P. Hurh, M. Gormley, J. Hangst*, and S. O'Day
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
and J. Howell
Argonne National Laboratory, Argonne, Illinois 60139

Abstract

The pulsed dipole magnet, used at the Antiproton Source target station to bend the path of 8 GeV secondary antiprotons from the residual primary proton beam, has had a history of failure due to the intensely radioactive environment in which it must operate. A new radiation-hardened pulsed magnet has been designed to replace this magnet. This unique water cooled single turn dipole utilizes radiation resistant materials while exhibiting uniform field characteristics of 1.573 T over 1 m.

I. INTRODUCTION

The Fermilab Antiproton Source utilizes a target station to produce, collect and deliver antiprotons to the Antiproton Source's Debuncher and Accumulator rings. Antiproton production is accomplished by bombarding a metal target (typically 7-8 cm of copper) with a single Booster proton batch that has been accelerated to 120 GeV in the Main Ring accelerator and extracted for delivery to the target station. The diverging antiprotons produced by the bombardment are gathered by an antiproton collection lens (a 2 cm diameter lithium lens with a design gradient of 1000 T/m). The collected 8 GeV antiproton secondaries are then bent away from the non-interacting primary proton beam by 3 degrees using a pulsed dipole magnet. Thus the primary proton beam is delivered to a water cooled beam dump while the secondaries are transferred to a beamline for injection into the Debuncher ring.

The major operational problems of the target station are a direct result of the extremely high radiation environment in which the components are required to operate To provide adequate shielding, the target station components are embedded in a vault of steel and concrete. Recent measurements have indicated that, during normal operation, the dose levels at the surface of the pulsed magnet are well in excess of 100 R/hr. The pulsed dipole which has been used during the last two collider runs was not specifically designed for this target station application. Figure 1 shows the relevant components of this conventional multi-turn magnet which was originally used as a beam line trim magnet. The upper and lower copper coils (100 turns each) are insulated by vacuum impregnated epoxy and separated from each other by G-10 composite spacer blocks. These organic materials are highly susceptible to radiation and thermal degradation and are suspected to be the prime culprits in the seven catastrophic failures which have occurred during the last two collider runs.

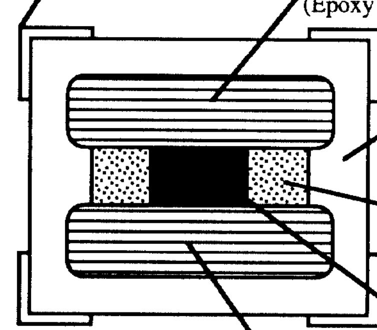

Figure 1. Schematic end view of 200 turn dipole.

The failures exhibited were varied (turn to turn shorts, coil to ground shorts, cracked laminations, etc.). Although complete autopsies could not be performed on these dipoles because of the high residual radioactivity, visual inspections of the failed magnets strongly indicated the causes of their failures. Observations have shown that the epoxy used to insulate the coils had been degraded sufficiently (thermally and/or radioactively) to cause abundant oxidation and in some cases apparent flow of the insulating epoxy. Note that the thermal heating is not joule heating due to the excitation current but rather beam heating due to the shower of target produced secondaries depositing energy in the magnet core. A thermocouple mounted on the exterior of the magnet core reaches temperatures in excess of 150°C during antiproton production. Also the G-10 spacer blocks were observed to be completely blackened by the secondary radiation and, in some of the failed dipoles, decomposed and crumbled into small granular pieces.

To eliminate these problems, a new dipole has been constructed with design characteristics that were chosen to ensure survival in the severe environment of the target station. Efforts have been made to utilize radiation resistant materials (minimize use of organic materials), strengthen the support structure of the laminated core, and reduce core and coil heating. The incorporation of these characteristics should greatly improve the operational performance of the target station.

* Currently on leave at Institute of Physics, Aarhus University, Denmark

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II. Magnet Design and Construction

In order to accommodate the design characteristics described in the previous section, the dipole is designed as a robust, water cooled, laminated core with a single turn copper coil. Insulation between the coil and core is achieved by utilizing a radiation resistant poly(amide-imide) material. Figure 2 shows a cross section view of the single turn pulsed magnet.

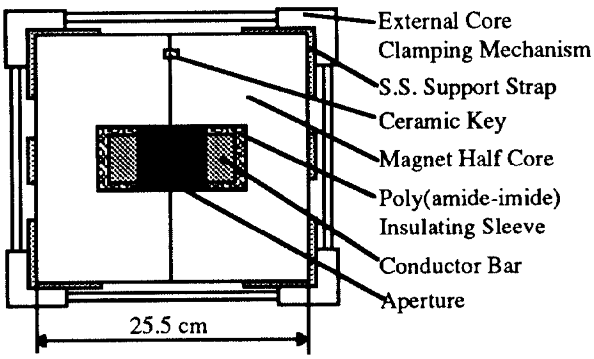

Figure 2. Schematic cross section view of Single Turn dipole (water cooling and coil tie rod details omitted for clarity)

A. The Coil

The single turn coil is constructed of two rectangular copper (OFHC) bars with a cross section of 1.52 cm x 2.86 cm. Electrical potential from the power supply is applied across the conductor bars at the upstream end of the magnet and current is carried by one of the bars to the downstream end. At the down stream end, a copper crossover plate transfers the current to the end of the second conductor bar which carries the current back to the upstream end. All copper coil parts are silver plated to resist corrosion, increase the current carrying capabilities on the surface of the conductors, and to aid in making connections between coil parts. All connections to the ends of the conductor bars are bolted interference fits to ensure smooth transitions for the excitation current.

B. The Core

The core consists of 0.356 mm thick laminations (stamped from AISI type M-19 steel with AISI C-5 surface insulation) constrained by several welded stainless steel support straps and two stainless steel end plates (2.5 cm thick). The overall length is 106 cm. The core is constructed in two halves to ease the installation of the conductor rods. The two halves are aligned to each other via ceramic keys and clamped together by external tie rods. The core assembly is structurally robust and can easily resist the 2,500 pounds (approximate) of electromagnetic force which develops between the conductor rods. This force, created by the opposing directions of current in the rods, attempts to repulse the conductor bars away from each other and must be resisted by the surrounding core.

C. The Coil to Core Assembly

A secure coil to core connection must be achieved to combat the effects of the electromagnetic force described above. The pulsed nature of the force (the magnet is pulsed in synchronism with the beam pulse) can result in fatigue failures of the coil parts unless the conductor bars are securely pre-loaded against the inner surface of the core. This connection is achieved by bolting the conductor rod to the core with titanium (6Al-4V alloy) tie rods. Figure 3 shows a cross section view of a typical coil to core connection. The conductor bar is insulated from the core by a sleeve of poly(amide-imide), and the titanium tie rod is insulated from both the core and the conductor by a poly(amide-imide) bushing. The conductor bars are bolted in this fashion every 5 cm along the length of the magnet resulting in 20 holes in both the conductor rods and the half cores.

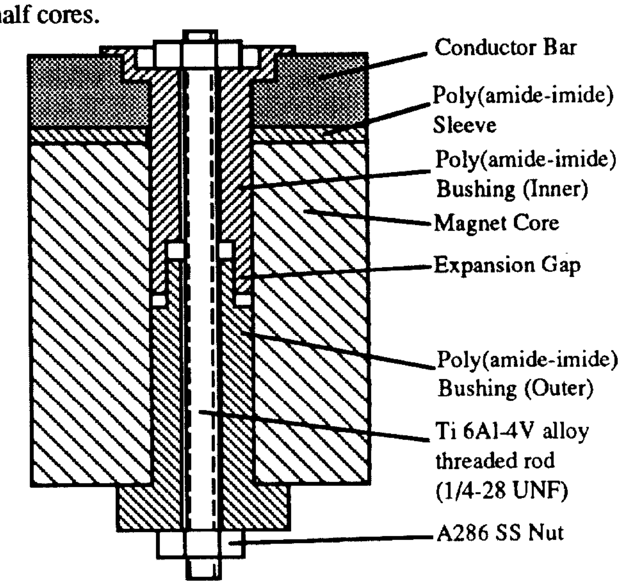

Figure 3. Cross section view of typical coil to core assembly

D. The Water Cooling System

The primary mode of heating in the target station magnet is caused by deposition of energy into the steel core from secondary particles. Thus, the water cooling system is designed to cool the steel laminations rather than the coil as in conventional magnet cooling systems. Figure 4 shows the cooling system mounted on the magnet. The system consists of four copper cooling blocks which are clamped to the lamination edges. Each cooling block has two rectangular copper tubes (1 cm x 0.6 cm cross section) brazed into it. Water flowing in the tubes (0.047 liters/sec per tube) removes heat from the block which in turn removes heat from the laminations.

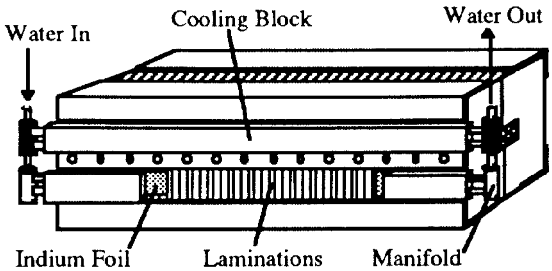

Figure 4. Schematic view of water cooling system (some details omitted for clarity).

Due to the rough lamination edges, the transfer of heat is limited by thermal contact resistance. Therefore a strip of 0.127 mm thick indium foil is clamped between the cooling blocks and the laminations to fill any small gaps and thus provide more surface area for cooling.

The water system was tested by outfitting the magnet core with several thermocouples and monitoring their outputs as heat was applied externally via heater tapes. 4800 watts of heat into the magnet core resulted in a peak core temperature of 140°C without water cooling. With water cooling and with maintaining the heat input at a continuous 4800 watts, the peak temperature of the core was reduced to 55°C in 2.5 hours.

III Magnetic Field Measurement

The new dipole must provide a magnetic field of 1.55 Tesla over an effective length of 1 m to steer the secondary antiprotons into the Debuncher injection beam line. This field, synchronized with the beam pulse (0.5 Hz), should be uniform to within a few percent over an aperture of 3.5 cm x 4.0 cm. In order to ensure that these requirements are met by the design, the characteristic field distributions, excitation curve, and inductance of the pulsed magnet were measured and compared with a two dimensional model calculation (POISSON computer code).

A magnetic field probe (wire loop type) was used in conjunction with integrating electronics to measure the magnetic field integrals $\int B_y dz$ versus z and $\int B_y dz$ versus x in the median plane. An integrating amplifier was connected to the coil and provided an output voltage which related the magnetic field integral to the induced voltage in the coil. The magnet excitation current was measured with a precision Pearson current transformer.

An examination of the field integral for increasing excitation currents revealed no indications of saturation at currents less than or equal to the design current.

Figure 5(a) shows the measured variation of the field integral $\int B_y dz$ versus x in the median plane. The variation of the field integral across the aperture of the dipole is shown to be less than 0.8% +/-0.2%. Also shown in figure 5(a) is the prediction of the computer model. The variations in the field integral are significantly smaller near the coils than the model prediction. This difference is suspected to result from the exclusion of the conductor rod bolt holes in the model.

Figure 5(b) shows the measured field integral $\int B_y dz$ versus z. From the linearity shown, a mean field of 1.573 T may be extracted (at an excitation current of 43.8 kA). The model calculation predicts a field 5% lower at this current. It is unclear whether this discrepancy reflects a systematic error in the measurements or an inaccuracy in the permeability of the steel core used in the model calculations.

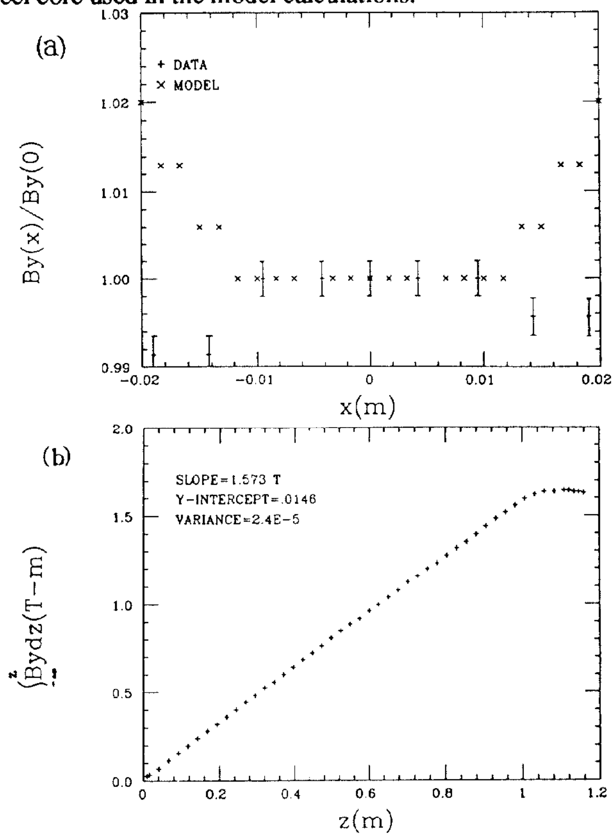

Figure 5. (a) Field integral versus x, (b) Field integral versus z.

An examination of the magnetic probe signal without integrating electronics allows the calculation of the inductance and resistance of the magnet. With the observed pulse half period of 355 μsec and assuming a value of 5000 μF for the power supply capacitance, the measured inductance is 2.539 μH and the resistance is 3.387mΩ.

IV. Conclusion

Work is presently underway to design a second single turn pulsed magnet. This magnet will include glass reinforced poly(amide-imide) and/or ceramic insulation materials to reduce a slight creep problem encountered with the unreinforced insulation during thermal testing. Some features will also be redesigned to facilitate ease of assembly.

The single turn pulse magnet will be ready for installation in the target station vault during the forthcoming fixed target run. Future antiproton production at the target station will greatly benefit from the increased reliability this magnet offers. Target station downtime due to pulsed magnet failures should be eliminated by the addition of this single turn pulsed magnet.