# A Permanent Magnet Dipole Correction Element for the Tevatron

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*Abstract*

We have constructed four Halbach-type[1] permanent magnets for use as correction dipoles in the Tevatron. Each magnet consists of 16 trapezoidal prisms of Ferrite, arranged in a cylindrical shell. The magnets may be rotated freely about the beamline by a stepper motor, and are used in pairs to provide any field integral between 0 and 0.6 T–m, in any plane. The correctors buck the dipole component of the static magnetic field caused by the various toroids of the D0 detector, and thus prevent a closed orbit distortion in the Tevatron. The tight space constraints (6" square by 12" long for each pair) and difficulty of getting utilities beyond a dc control cable to the location led us to choose a permanent magnet rather than a Copper-Iron one. We describe briefly the principle of their design and operation. Next the mechanical design, motion control system and field quality are discussed. We conclude with a summary of our operating experience.

## INTRODUCTION

Static magnetic fields capable of perturbing the Tevatron beam at 150 GeV are generated by the EF, CF, and SAMUS toroid components of the D0 detector. At the time the magnets were designed, the integrated field in the D0 detector was anticipated to be as large as 0.4 T–m.[2] This field is expected because the main toroid does not have symmetrically placed excitation coils. Since this is equivalent to a 66 μrad bending of the proton beam at 150 GeV (the Tevatron injection energy), or about 15% of the strength of a Tevatron correction dipole, it was decided to correct the field locally with one magnet at each end of the detector. Because of the tight space constraints at the desired location (6" x 6" x 12"), and because an engineering analysis showed that a properly sized electromagnet would be difficult to design, a permanent magnet of the Halbach design was chosen.[1] The magnets were designed and built by Permag Corp., a division of Dexter Magnetics.[3]

A total of four units, dubbed Permanent Dipole Correctors (PDCs) were constructed. See Fig. 1 for an end on view of one magnet. Two PDCs were installed at each end of the D0 detector. A pair of magnets, both having the same strength $B$, can create any net field from 0 to $2B$ by rotating the field direction of each member in a scissors like motion. In addition, the plane of the net field can be chosen by an overall roation of both members. In practice, one chooses the horizontal and vertical field components desired independently and selects orientations that satisfy both planes simultaneously. Provided $B_x{}^2 + B_y{}^2 < B^2$, the request can be satisfied.

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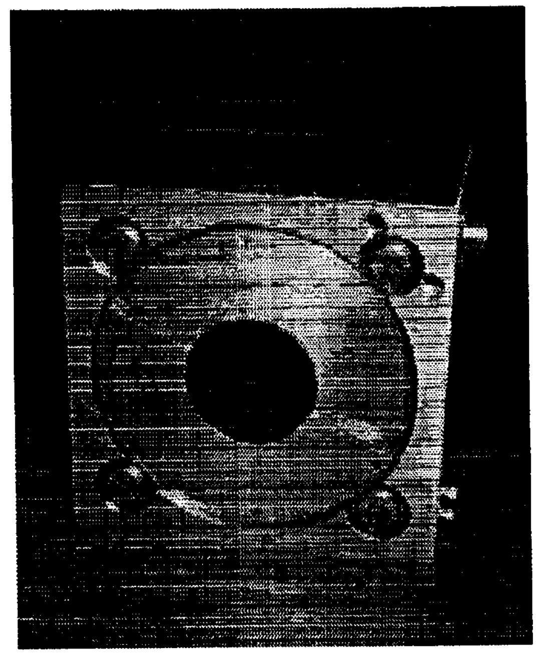

Fig. 1. The Permanent Magnet Dipole Corrector (PDC) consists of a cylindrical shell filled with ferrite. The magnet is rotated by a stepper motor to any position about the beam axis. The field is normal to the parting plane of the two half shells.

## DESIGN

The design of the PDCs is an approximation to a cylindrical shell of magnetic material with a continuously varying direction of magnetization **M**. Such a configuration gives a perfect multipole $n$ provided that $\theta$, the direction of **M**, varies as twice the azimuth angle $\varphi$ : $\theta = 2\,n\,\varphi$. For a dipole, $n = 1$ and so $\theta = 2\,\varphi$. In Ref. 1 and references cited therein, Halbach has shown that using piecewise constant approximation to a continuously varying **M** gives a reasonably good multipole. We used 16 trapezoidal prisms, each having a constant and properly oriented **M** direction, to build up a cylinder.

The geometry of the cylinder is fixed at the inner diameter by the beampipe. The outer diameter is set to acheive the desired field quality and to satisfy geometric constraints. Fortunately, it proved possible to acheive our desired field quality of multipoles not in excess of 1% of the dipole field at 1/2" and to still stay within the 6" square alotted, while using ferrite instead of the more expensive SmCo. The overall parameters of the magnet are given in Table 1.



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## MAGNET CONSTRUCTION

The trapezoidal segments were constructed by cutting and grinding trangular prisms having their easy magnetic axis properly orientated. Trianglar prisms were then paired to form trapezoidal prisms. The prisms were next epoxied together inside a form consisting of an aluminum half-shell and a thin alumninum coverplate. (The coverplate protects the magnetic surface from ferromagnetic debris that might inhibit free rotation about the beampipe).

The magnetic field was mapped using a standard rotating coil magent mapper at the Fermilab Magnet Test Facility. The results are presented in Table 2. The integrated dipole field proved to be consistent to the 1% level. The mulitpoles were within tolerance for this undemanding application. The most important constraint is how well the dipole fields for each pair can be matched, since this sets the minimum net field in the off (antiparallel) configuration. The mapping results show that by pairing magnets a residual field of 2 Gauss-m is obtainable.

TABLE 1. Parameters of the Permanent Dipole Correctors

| | |
|---|---|
| Number of units | 4 |
| Trapezoidal elements per unit | 16 |
| OD of magnetic material | 5.600" max. |
| ID of magnetic material | 2.600" min. |
| PDC unit ID | 2.560" min. |
| Beampipe OD | 2.5" nominal |
| Magnetic Length | 5.875" max. |
| Min. Integrated Field | 12000 Gauss-in |

TABLE 2. Field Quality of the PDCs. The PDCs were mapped at the Fermilab Magnet Test Facility using a standard rotating coil magnet mapper. The multipoles higher than dipole are given in Fermilab standard units as a fraction of the dipole field at a 1" radius. 2–pole means quadrupole, 3–pole means sextupole, etc. The magnets are listed in the order installed, proceding from North to South.

| Multipole | UP1 | UP2 | DN1 | DN2 |
|---|---|---|---|---|
| Dipole (T–m) | 0.0349 | 0.0347 | 0.0353 | 0.0352 |
| Normal 2–pole | –0.002 | –0.012 | 0.003 | –0.003 |
| Skew 2–pole | 0.0004 | 0.002 | 0.003 | –0.001 |
| Normal 3–pole | –0.010 | –0.013 | –0.007 | –0.008 |
| Skew 3–pole | 0.005 | 0.013 | –0.0004 | 0.001 |
| Normal 4–pole | –0.0005 | –0.003 | –0.0002 | –0.001 |
| Skew 4–pole | –0.002 | –0.003 | –0.0003 | 0.001 |
| Normal 5–pole | 0.001 | 0.005 | –0.008 | –0.007 |
| Skew 5–pole | 0.008 | 0.005 | 0.004 | 0.003 |
| Normal 6–pole | –0.003 | 0.001 | –0.0005 | 0.0005 |
| Skew 6–pole | 0.003 | 0.001 | 0.0002 | 0.0001 |
| Serial No. | 003 | 001 | 002 | 004 |

## MOTION CONTROL SYSTEM

A stepper motor is used to rotate the PDCs via a pinion and a 7:1 reduction gear cut into the outside surface of the magnet cylinder. The 3-phase stepper motor makes steps of 360 degrees, but internal gearing includes a 60:1 reduction. Thus, with the external gear, it takes 1260 steps to make one rotation, so the magnets can be positioned to a precision of ±0.3 degrees. The magnets' rotation is monitored by a potentiometer that is geared similarly to the stepper motor. In addition, for redundancy there is a microswitch that senses a machined flat on the cylinder surface. There are thus two methods for controlling the angular position—dead reckoning from the microswitch position and reading the potentiometer position. In practice both are used because although the potentiometer gives a more reliable reading than counting steps there is a dead space of a few degrees when the potentiometer "turns over."

The PDCs are controlled by a Fermilab C057 CAMAC card. This card was developed for stepper motors used to control collimators, and thus provides a standard interface to the accelerator control system. Since the present application involves rotary motion, several control signals had to be re-interpreted. In addition, because of size restrictions, a special stepper motor was used. An interface card was designed to translate from the C057 to the commercial stepper motor driver.

When tested at 100 Hz, the motion control system performed satisfactorily but the drive train exhibited excessive vibration. Since the PDCs are designed to be moved infrequently, the step rate was lowered to 10 Hz and no further problems were encountered.

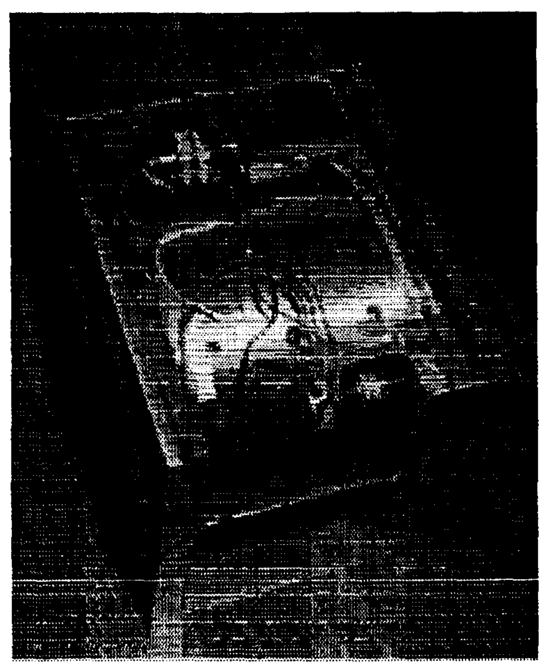

Fig. 2 The PDC with cover removed to show the stepper motor (rear) and potentiometer (front). The stepper motor drives a 7:1 gear cut into the surface of the magnet cylinder via a small pinion. The potentiometer is geared similarly.

## OPERATING EXPERIENCE

The PDCs have been tested, although they are not used operationally, since it has been found that the D0 toroids in fact have a very small effect on the Tevatron beam, about 0.1

mm rms distortion of the beam. The PDC units are capable of producing a 0.7 mm RMS distortion with a cusp at D0 when they are turned to the parallel configuration. The horizontal and vertical planes are sufficiently decoupled that only a 0.1 mm distortion is observed in the orthogonal plane (See Fig.. 3). The magnets may find operational use in a planned upgrade of the D0 detector to include a solenoid.

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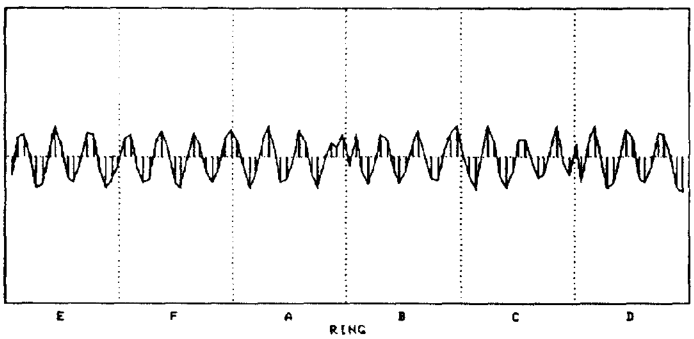


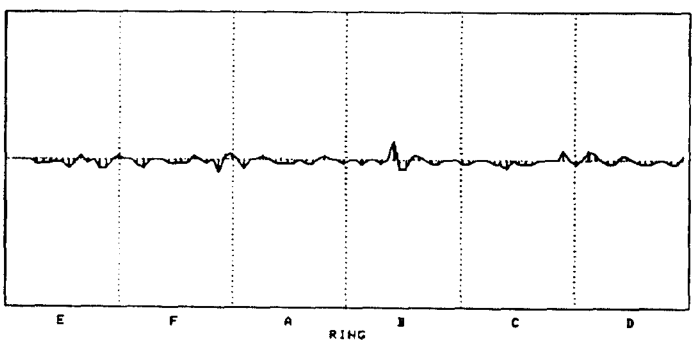


Fig. 3 The upper trace shows horizontal orbit with two PDC magnets parallel, fields vertical. A total orbit distortion of 0.7 mm RMS is observed. In the vertical plane (lower trace) there is hardly any effect. Both orbits are subtracted from the normal closed orbit of the Tevatron. In both cases the scale is ±5 mm.

## REFERENCES

[1] K. Halbach, Nucl. Instr. and Meth. 169, 1 (1980)..
[2] H. Jostlein, "Stray Fields from the D0 Muon Toroids: Shielding and Correction Magnets," unpublished memo, April 1989.
[3] 1050 Morse Ave., Elk Grove Village, IL 60007.