# Magnetic Performance Of New Fermilab High Gradient Quadrupoles

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*Abstract*

For the Fermilab Tevatron low beta insertions installed in 1990-1991 as part of a luminosity upgrade there were built approximately 35 superconducting cold iron quadrupoles utilizing a two layer cos $2\theta$ coil geometry with 76 mm diameter aperature. The field harmonics and strengths of these magnets obtained by measurement at cryogenic conditions are presented. Evidence for a longitudinal periodic structure in the remnant field is shown.

## I. INTRODUCTION

The low-beta insertions installed in the Fermilab Tevatron in 1990-1991 at the B0 (CDF) and D0 interaction regions include several devices containing new high gradient quadrupoles of the so-called "717" design cross section [1]. Table 1 enumerates the devices containing "717" quadrupoles; it can be seen that only four different magnetic lengths are involved. The Q1 and Q5 magnets were made so as to be interchangeable in the accelerator. The TSK and TSJ devices are spool pieces similar to the conventional Tevatron spools, but one nested weak corrector package is replaced with a strong "717" trim quadrupole.

Table 1

Low Beta Insertion Components Containing "717" Cross Section Design Quadrupoles

| Lattice Designation | Nominal Magnetic Length (m) | Number of Magnets Built | Number of Magnets Tested | Excitation Current at 1 TeV (A) |
|---|---|---|---|---|
| TSJ | 0.61 | 3 | 3 | 4832 |
| TSK | 0.61 | 4 | 3 | 4832 |
| Q1/Q5 | 1.40 | 12 | 11 | 2011/2821 |
| Q2 | 3.35 | 5 | 4 | 4811 |
| Q4 | 3.35 | 5 | 5 | 4811 |
| Q3 | 5.89 | 5 | 5 | 4746 |

This quadrupole is a cold iron two shell magnet in an SSC dipole-like cryostat. Each pole has 19 inner and 28 outer layer turns of 36 strand Rutherford style superconducting NbTi cable. The nominal copper to superconductor ratio is 1.5:1. The strand insulation is copper oxide. The cable twist pitch is 72 mm (except for 81 mm in a few reels at the end of the cabling run). The nominal gradient is 29.1 T/m/kA. At 4.6 K operating temperature these quadrupoles quench around 5200 A [2].

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## II. FIELD HARMONICS

### A. Notation and Conventions

It is conventional to report field harmonics in a two dimensional transverse representatiion with the implicit understanding that except for the ends there is no significant longitudinal variation. The representation used here is

$$B_x - iB_y = Q \sum_{n=o} (a_n - ib_n)(z/R)^n \qquad (1)$$

where $z = x + iy$, R is a normalization radius conventionally taken as 25.4 mm for Tevatron components, Q is the quadrupole strength in tesla, and $a_n$ ($b_n$) are the skew (normal) harmonic coefficients. In this representation the $a_n$ and $b_n$ are dimensionless but their numeric values depend on the choice of R. It is conventional to suppress a factor of $10^{-4}$, which results in the harmonic coefficients being reported in "units". The coordinate system origin is such that $a_0 = b_0 = 0$, i.e., there is no dipole. The coordinate system orientation is such that $a_1 = 0$ and $b_1 = 1$. In a perfectly symmetric quadrupole the "allowed" harmonic coefficients $b_n$, n=1,5,9,... may have non-zero values determined by details of the design; all other harmonic coefficients would be zero. To the extent that the "non-allowed" harmonics arise from geometric imperfections in the as-built magnets, they are usually independent of excitation current, but symmetry may also be violated by differences in the properties of the superconductor in the constituent sub-coils. The allowed harmonics show behavior (hysteresis and time dependence) depending on the excitation history.

### B. Harmonics Measurement System

The field harmonics were measured cold using the system previously employed for the Tevatron arc quadrupoles and the initial low beta insertion quadrupoles at B0 (CDF) [3]. A loosely fitting flexible double-walled vacuum insulated warm bore was threaded through the magnet beam tube to enable the 2.388 m long harmonic probe to operate

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at room temperature. The length of the Q2, Q4 (Q3) magnets required measuring in 2 (3) end-to-end longitudinal positions and combining the data to obtain the average harmonics for the magnet. The transverse position of the warm bore (and therefore of the harmonic probe) relative to the magnet coil was not mechanically well controlled. It was assumed that the probe rotated with its axis parallel to but displaced from the magnet coil axis; the dipole signal measured by the probe was used to infer the displacement, and the measured harmonics were "shifted" to a coordinate system transversely centered on the magnet. The mechanics of the setup suggested that this method should indicate the probe axis lay below the magnet axis by 1.0 to 2.5 mm.

The run-to-run reproducibility of the low order harmonics of interest was consistently better than 0.1 units. Uncertainties associated with the as-built probe geometry and the validity of the assumptions in the shifting procedure suggest the low order harmonics have an absolute accuracy nearer to ±0.5 units.

The data were taken as follows. A standard excitation "pre-ramp" was done followed by ramping at 25 A/s to the first target current. The current was held constant and the measurement started about 60 seconds later. This delay was not well regulated, and to some extent the meaning of the values of the allowed harmonics was degraded by the time dependence effect in these magnets [4]. Upon completion of the measurement at a given current the magnet was ramped at 25 A/s to the next target current and the procedure repeated.

### *C. Harmonic Data*

Table 2 shows selected harmonic coefficients obtained at a nominal 4250 A excitation on the up-ramp together with corresponding data from the original Tevatron arc quadrupoles [5].

Table 2

Selected Harmonic Coefficients of 31 Low Beta and ~200 Tevatron Arc Quadrupoles

| Harmonic coefficient | Low beta Mean (units) | Low beta Standard deviation (units) | Tevatron arc Mean (units) | Tevatron arc Standard deviation (units) |
|---|---|---|---|---|
| $b_2$ | 0.62 | 1.88 | 1.98 | 3.69 |
| $a_2$ | -0.43 | 3.11 | 2.83 | 3.41 |
| $b_3$ | 0.13 | 0.76 | 1.25 | 0.93 |
| $a_3$ | -0.30 | 0.99 | -0.45 | 1.97 |
| $b_4$ | 0.15 | 0.48 | -0.26 | 0.74 |
| $a_4$ | -0.25 | 0.65 | -0.72 | 0.80 |
| $b_5$ | -3.38 | 1.62 | -1.91 | 1.70 |
| $a_5$ | 0.04 | 0.61 | 0.21 | 0.44 |
| $b_6$ | 0.05 | 0.30 | 0.05 | 0.28 |
| $a_6$ | 0.11 | 0.37 | 0.18 | 0.29 |

### *D. Discussion of Data*

Coil dimensional data obtained during fabrication showed the new quadrupoles have more uniform sub-coils than the Tevatron quadrupoles had. So the means of distributions of their non-allowed coefficients were expected to be nearer zero and the distribution widths smaller. Table 2 entries show this has occured. The unexpectedly large width of the $a_2$ distribution, which has contributions from all four cold masses, is not understood.

The normal 12-pole data are shown in detail in Figure 1. Although the accelerator can tolerate several units of normal 12-pole, an effort was made to keep it small. Unlike the Tevatron arc quadrupoles, where the ends were compactly wound and the body field designed to have sufficient positive $b_5$ to compensate for the negative $b_5$ in the ends, these new quadrupoles were designed to have nearly zero $b_5$ in both the ends and body field separately. A copper wedge was used in the body inner shell, and spacers and different length shells were used in the ends.

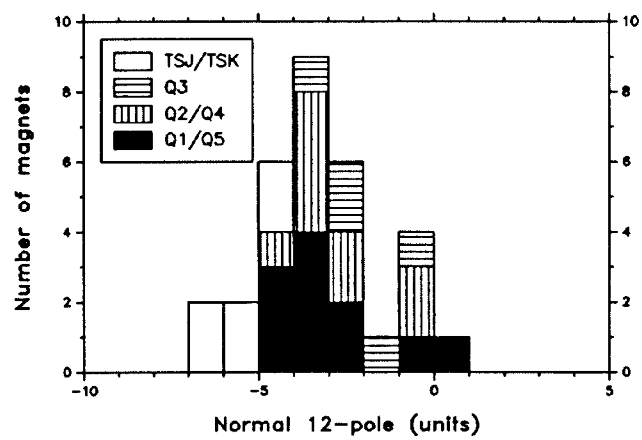


Figure 1. Normal 12-pole data at 4250 A

Data from the Q3's indicate that the average body field $b_5$ = -1.8 units. The ends have sufficient negative $b_5$ to produce in Q3's an average total $b_5$ = -2.2 units. In the short TSJ/TSK spools the negative $b_5$ from the ends depresses the average total $b_5$ to -5.6 units. The large width of the $b_5$ distribution in Table 2 comes in part from combining all four cold mass lengths.

## III. PERIODIC REMNANT FIELD

Recently at DESY it was observed that in HERA dipoles there is a longitudinal periodicity in the normal sextupole and dipole at 300 A excitation [6]. The dipole oscillation amplitude is of order 0.05 mT out of .23 T and the wavelength corresponds to the twist pitch of the cable and no other longitudinal dimension of the magnet. It is an effect from the superconductor. The effect was subsequently seen in SSC dipoles in the remnant field. There have been conjectures that it is due to stand-to-strand variation, possibly arising from coldwelds in some strands made during the cabling process.

A hall probe detector was used to study the remnant field of the Q1/Q5 magnet designated as N5401F; it has no known coldwelds. A holder was designed to place two hall probes near the x-axis at x = ±15 mm to sense the total y-component of the field; the actual probe positions are known only to ±1 mm due to the mechanics of the warm bore system.

Figure 2 shows typical data. The remnant field configuration had been prepared by quenching the magnet, ramping it to a 4800 A flattop for 1200 seconds, and then ramping down to zero current at 200 A/s. The data were taken at longitudinal intervals of 0.635 mm (0.25 inch); taking one datum required 10 seconds, and an entire scan shown required approximately 900 seconds. The upper trace was initiated 3250 seconds after the return to zero current. The pronounced longitudinal oscillation has wavelength of 72.0±0.7 mm, which is close to the cable twist pitch for this magnet. The fall off on the right is due to the probe exiting the end of the magnet. The lower trace was initiated 340 seconds after the return to zero current. It is evident that the amplitude of the oscillation decreased with time while the lower trace was being taken left to right, and it decreased further between scans principally by the minima filling. Data taken 2.0, 4.5 and 17.6 hours after return to zero current showed the minima contining to fill but at an ever slower rate.

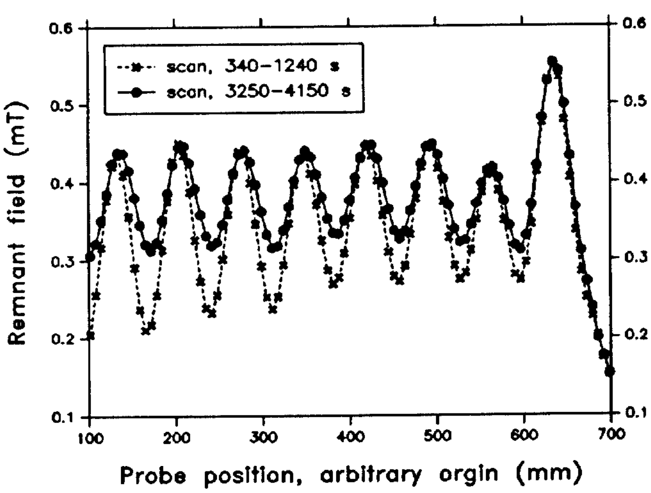


Figure 2. Example of periodic field

Other preparations of the remnant - shorter flattop duration and lower flattop current - result in smaller amplitude oscillations and different time dependences. Note that longitudinal scans made at other places in the two dimensional cross section also show oscillatory behavior with the same wave length, but with different amplitudes and varying time dependences. And it is not universally true that the amplitude decreases principally by the minima filling.

## IV. INTEGRATED FIELD DATA

The integrated gradient was measured cold using the same stretched wire probe system used for Tevatron arc quadrupoles [3]. The vagaries of magnet repair enabled N5401F to be measured on four separate occasions. The results suggest a run-to-run reproducibility of ±0.05%. Systematic errors are thought to be considerably larger - of the order ±0.2%.

Table 3

Integrated Field Data at 4000 A

| Lattice Designation | Integrated Gradient (Tesla/kA) Lowest | Mean | Highest |
|---|---|---|---|
| TSJ/TSK | 17.45 | 17.49 | 17.53 |
| Q1/Q5 | 40.50 | 40.60 | 40.69 |
| Q2/Q4 | 97.33 | 97.48 | 97.62 |
| Q3 | 172.04 | 172.27 | 172.44 |

For the shorter two cold mass lengths the difference between weakest and strongest device is about 0.46%. For the 200 original Tevatron 1.68 m long arc quadrupoles production control of the strength was ±0.2% [5]. As expected, in a percentage sense the longer quadrupoles have less strength variations.

## V. REFERENCES


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