Fermi National Accelerator Laboratory

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Gradient and Harmonic Field Measurements of the 4Q120 Quadrupole

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GRADIENT AND HARMONIC FIELD MEASUREMENTS OF THE 4Q120 QUADRUPOLE

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Abstract

The magnetic field gradients as well as the harmonics of two 4Q120 quadrupoles were measured utilizing a rotating coil system at Fermilab's MTF. One magnet was from the 1975 Series, and another from the TeV II Series. For excitation currents where the remnant field is a small fraction of the total, values of the absolute gradient for the latter magnets are typically 2% lower. Among the harmonics, the skew sextupole component has the highest value for both magnets. The harmonic measurements show small differences between the "power" and "return" ends of the magnet.

Gradient Measurements

Magnetic field measurements were taken on two 4Q120 quadrupoles. See Figure 1a. The first magnet (FRD10751 in the Research Division Numbering System) is one of a series fabricated by Industrial Coils Inc. of Middleton, Massachusetts in 1975. It's label reads "4Q120/1550, serial number 1011, 4/28/75". The second magnet (FRD11436) was manufactured as part of the TeV II upgrade in 1985, and carries a Fermilab Technical Support label reading "Tev II 4Q120, TV2-018, 5/16/85". Typically the two series of magnets are taken to be equivalent, and are used interchangeably. The laminations are identical and the length of steel for each of them is 120 inches. The copper coils and the amount of insulation are slightly different.[1] The two different types can be distinguished physically in that the TeV II magnet has an additional 3/8 inch thick steel plate on all four sides of the outside case which serve in

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[1]See Technical Services drawings 2221-MD-27384, 2221-ME-27703, 2221-MD-27483, and 2221-ME-27472.

place of the fillet weld. The 1975 series uses butt welds to hold the case together. In addition, there are other physical differences in appearance. The 1975 series are painted dark orange, but some are brown, and they have tan coil packs having indentations separating the four quadrants. The TeV II series are painted light orange, they have white coil packs and the indentations between quadrants is filled in.

The measurements were taken at the Fermilab Magnet Test Facility (MTF) using a rotating Morgan coil.[2] The coil had the capability to measure the following Poles--2P, 4P, 6P, 8P, 10P, 12P, and 20P. All of these separate coils were mounted on a glass-epoxy (G10) cylinder with the wires at a radius of 34.5 mm. The active length for the coils is approximately 94 $^3/_8$ inches (the various separate harmonic coils differ only by several wire diameters which altogether is less than 1/8 inch).

Since the 4Q120 magnet is longer than the Morgan coil, the procedure for obtaining $\int G\,dl$ was to combine two sets of measurements, one from each end of the magnet to cover the whole length. Figure 1b and 1c illustrate the principle.

On one end, the probe is connected to a motor drive which rotates the coil through the magnetic flux. This end has the capability to be moved in the X-Y plane so the probe can be centered. The other end of the probe is held in place by an aluminum support block that fits into the bore tube of the 4Q120. The support block holds a bearing, and also contains a series of set screws to assure the probe is geometrically centered. Measurements from the 2P pickup showed that the probe was aligned. The amount the probe extended inside the magnet was determined by measuring the length remaining outside the steel and subtracting that length from 94 $^3/_8$ inches.

For quadrupole measurements the information came from the coil known as "q1", the fourth wire from the inside of the probe. See Figure 1b or 1c. Measurements of the current came from a transducer monitoring the power supply which has an absolute calibration better than 0.1%. After setting the current, a complete set of measurements were taken at the power end with the probe setup in configuration 1b. To take the return end measurements, the magnet was not rotated 180°, rather the probe was changed into that shown in Figure 1c. An extension rod is added to the motor end, and the aluminum support block changes ends. The end that was supported by the aluminum block now protrudes outside the other end of the magnet where it is connected to a support having X-Y adjustments.

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[2]G. H. Morgan, "Stationary coil for measuring the harmonics in pulsed transport magnets." In <u>Fourth International Conference on Magnet Technology</u>, held at Brookhaven 1974, page 787.

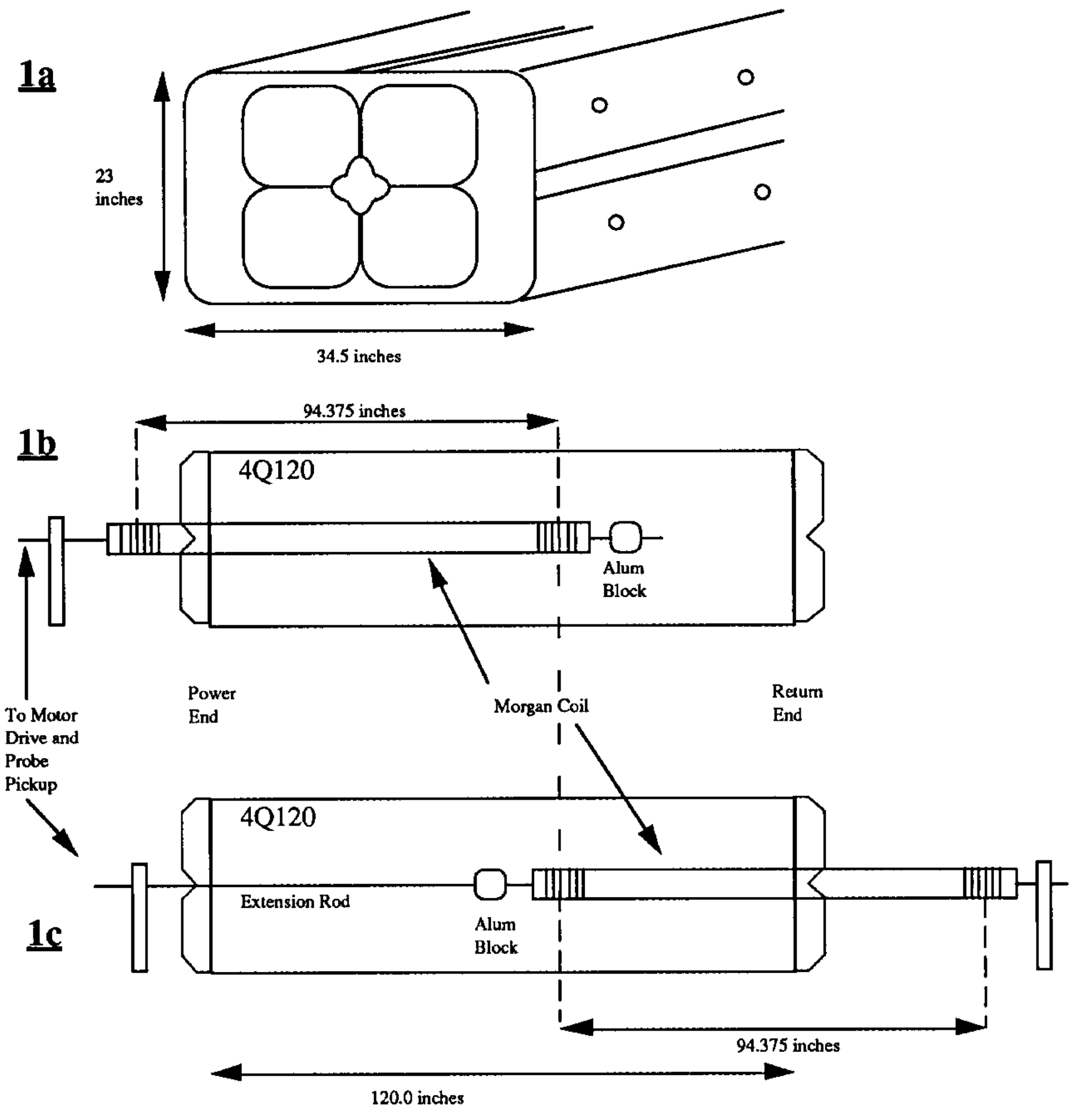
1a
23
inches
34.5 inches
94.375 inches
1b
4Q120
Alum
Block
Power
End
Morgan Coil
Return
End
To Motor
Drive and
Probe
Pickup
4Q120
Extension Rod
Alum
Block
1c
94.375 inches
120.0 inches

Figure 1

For magnet FRD10751, the following individual measurements of ∫G dl were made:

Measurement (1)--probe reaching 60.5" into the steel at the "power" end.
Measurement (2)--probe reaching 59.5" into the steel at the "return" end.
Measurement (3)--probe reaching 80.0" into the steel at the "power" end.
Measurement (4)--probe reaching 40.0" into the steel at the "return" end.
Measurement (5)--probe reaching 10.0" into the steel at the "return" end.

For magnet FRD11436, the individual measurements of ∫G dl were:

Measurement (6)--probe reaching 60.0" into the steel at the "power" end.
Measurement (7)--probe reaching 60.0" into the steel at the "return" end.

The measurement dates for (59.5"+60.5"), (80.0"+40.0"), and (60.0"+60.0") were 5/2/90, 5/9/90, and 5/16/90 respectively. TABLE 1 lists the individual measurements 1 thru 5 for FRD10751. ∫G1 dl & ∫G2 dl columns give the sum of the corresponding "power" plus "return" ends yielding ∫G dl for the entire quadrupole. The integrated (59.5"+60.5") measurement compares favorably with the (80.0"+40.0") measurement. Except at very low currents, there is less than 0.1% difference between the two measurements over the full range of excitation currents.

TABLE 2 lists the measurements for FRD11436. It has a greater remnant field and also a smaller slope in the linear region than FRD10751. In addition, at high currents where the remnant contributes very little to the total gradient, the same amount of current gives less ∫G1 dl than FRD10751, being uniformly lower by as much as 2%. All data were taken sequentially both on the up-ramp 0-1900 amps and the down-ramp 1900-0 amps, without going back to zero between the individual measurements. One should keep in mind that even though there are measurements as high as 1900 amps, the magnet was not designed to operate routinely at these values because the cooling is inadequate. The magnet was designed to run at 50 kwatts DC at about 1200 amps.

Taking the length of a 4Q120 as 120.0 inches, the data can be put into a form that is most commonly used by beamline physicists--gradient (kg/inch) vs. current. Figure 3 shows this graphically. Saturation begins in the 800 to 900 amp region and becomes most pronounced at the highest current of 1900 amps. The linear region is well described by :

FRD10751 (Early Series)	I(amps) = -9.8 + 193.4 *G(kg/inch)
FRD11436 (TeV II Series)	I(amps) = -37.8 + 197.0 *G(kg/inch)
	4Q120 length ≡ 120.0 inches

Fringe Field

In actuality the magnetic length of the 4Q120 changes with current. Measurements on the "return" end previously listed as (2), (4), and (5), can be used to separate out the effective length into a length inside the steel and an average length in the air due to the fringe field.

l(effective) = l(steel) + l(fringe)

Taking all the measurements at the same end of the magnet so systematics are not an issue, the ∫G dl values at 10", 40.", and 59.5" can be used to separate the individual measurements into the so-called body gradient (G0) times l(effective). For each current, a straight line fit is made using the lengths 10.", 40.", and 59.5" as one axis and ∫G dl = R(10."), ∫G dl = R(40."), and ∫G dl = R(59.5") as the other axis.

R(l) = ml + b

For example, at the nominal 800 amps R(l) = 24.714 = 0.41057*l + 0.2776, l = 59.5. The slope of this line, m , is the body gradient G0. Both m and b vary with the current--m(i) and b(i). Substituting the various m values gives l(fringe) as a function of current.

R(steel) = G0*[l(effective)] = m*[l(steel)+l(fringe)]
l(fringe) = {[R(steel)]/m} -l(steel)

Of the three measurements at each current, the one having the smallest percentage error is at R(59.5"), because it has the largest absolute value. However, since R(59.5") was not measured at the nominal 900 amps, to include it on the plot, it was calculated by the average straight line ratio between the nominal 800 and 1000 amps, and then relating R(59.5") and P(60.5").

$$R(59.5'') = (27.830)\left[\left(\frac{24.714}{25.136} + \frac{29.546}{30.064}\right)\Big/2.\right] = 27.357 \qquad \text{@ 900 amps.}$$

Excitation current is then plotted versus l(fringe).

l(fringe) = {R(59.5")/m(i)} – 59.5"

A graph of l(fringe) at each end of the magnet as a function of current is shown in Figure 2. Thus at low currents the effective length is about 121.6 inches. This gives a quantitative feel for how far the field effectively extends outside the magnet, keeping a constant gradient. The decrease in effective length as a function of excitation current can be understood as a saturation phenomena. When the steel is unsaturated, almost all the field lines in the air just beyond the magnet are generally parallel to the steel, and thus have a significant component in the same direction as the body of the magnet. In saturation, the lines "bulge" out further and further into the air, giving a longer path length and also having both parallel and perpendicular components with respect to the body. As a result, when the probe measures the field integral, the amount adding in the same direction as the body of the magnet is reduced compared to when the lines have a short path and are essentially parallel to the face.

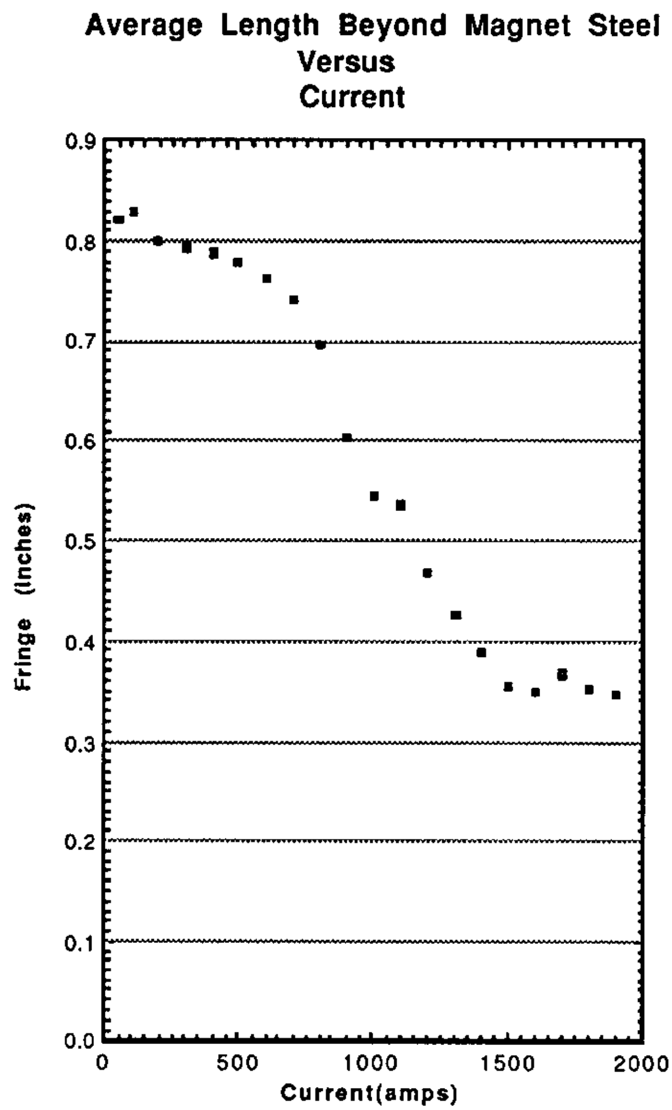

Figure 2

This should not be confused with the previous section where fits were done defining l(effective) to be 120.0 inches. It is common practice to take l(effective) constant as the length of the steel and include the varying part along with the gradient.

TABLE 1

Current(amps) and Individual Measurements for FRD10751; R=Return End; P=Power End; $\int G1\,dl = R(59.5") + P(60.5")$; $\int G2\,dl = R(40.") + P(80.")$. Unit for $\int G\,dl$ is Tesla-meter/meter; $\int G\,dl/I$ is kg/inch.

Amps	R(59.5")	P(60.5")	P(80.")	R(40.")	R(10.")	∫G1 dl	∫G2 dl	∫G2 dl/I
.0	.051	.056	.071	.036	.010	.107	.107	0.009
52.4	1.609	1.634	2.166	1.097	.290	3.242	3.263	0.272
103.2	3.173	3.226	4.261	2.155	.570	6.399	6.416	0.535
203.2	6.281	6.368	8.409	4.250	1.125	12.649	12.659	1.055
303.1	9.384	9.516	12.557	6.345	1.679	18.900	18.902	1.575
406.3	12.459	12.659	16.683	8.423	2.229	25.118	25.106	2.092
501.5	15.530	15.782	20.802	10.498	2.776	31.312	31.300	2.608
601.3	18.575	18.890	24.881	12.557	3.316	37.465	37.438	3.120
704.7	21.742	22.109	29.122	14.690	3.875	43.851	43.812	3.651
804.7	24.714	25.136	33.120	16.688	4.388	49.850	49.808	4.151
903.0		27.830	36.679	18.451	4.822		55.130	4.594
1003.0	29.546	30.064	39.668	19.917	5.184	59.610	59.585	4.965
1102.7	31.300	31.843	42.026	21.086	5.487	63.143	63.112	5.259
1201.4	32.763	33.340	44.008	22.064	5.713	66.103	66.072	5.506
1307.3	34.063	34.670	45.770	22.936	5.920	68.733	68.706	5.726
1406.1	35.082	35.695	47.125	23.595	6.077	70.777	70.720	5.893
1504.5	35.846	36.475	48.166	24.101	6.192	72.321	72.267	6.022
1604.5	36.379	37.023	48.897	24.450	6.281	73.402	73.347	6.112
1703.9	36.804	37.454	49.461	24.735	6.362	74.258	74.196	6.183
1801.3	37.159	37.807	49.929	24.972	6.416	74.966	74.901	6.242
1901.5	37.491	38.176	50.399	25.213	6.473	75.667	75.612	6.301
1704.3	36.797	37.447	49.439	24.737	6.351	74.244	74.176	6.181
1504.5	35.851	36.478	48.164	24.110	6.199	72.329	72.274	6.023
1306.2	34.121	34.720	45.813	22.962	5.932	68.841	68.775	5.731
1103.0	31.412	31.957	42.164	21.156	5.495	63.369	63.320	5.277
903.0	27.532	28.021	36.944	18.576	4.862	55.553	55.520	4.627
704.7	21.875	22.239	29.313	14.804	3.903	44.114	44.117	3.676
501.5	15.634	15.892	20.974	10.570	2.796	31.526	31.544	2.629
303.2	9.476	9.617	12.680	6.408	1.696	19.094	19.088	1.591
103.2	3.264	3.309	4.371	2.209	.583	6.573	6.581	0.548

TABLE 2

Current(amps) and Individual Measurements for FRD11436; R=Return End; P=Power End; $\int G\,dl$=R(60.")+P(60."). Unit for $\int G\,dl$ is Tesla-meter/meter, $\int G\,dl/I$ is kg/inch.

Amps	P(60.0")	R(60.0")	$\int G\,dl$	$\int G\,dl/I$
.0	.148	.136	.283	0.024
52.4	1.645	1.643	3.288	0.274
103.2	3.183	3.183	6.366	0.531
203.2	6.257	6.264	12.521	1.043
303.1	9.347	9.351	18.697	1.558
406.3	12.432	12.415	24.847	2.071
501.5	15.496	15.492	30.988	2.582
601.3	18.515	18.512	37.027	3.086
704.7	21.640	21.631	43.271	3.606
804.7	24.332	24.496	48.828	4.069
903.0	27.018	27.038	54.056	4.505
1003.0	29.203	29.189	58.392	4.866
1102.7	30.922	30.933	61.855	5.155
1201.4	32.495	32.438	64.933	5.411
1307.3	33.827	33.755	67.582	5.632
1406.1	34.858	34.787	69.645	5.804
1504.5	35.624	35.572	71.196	5.933
1604.5	36.173	36.102	72.275	6.023
1703.9	36.592	36.530	73.122	6.094
1801.3	36.940	36.884	73.824	6.152
1901.5	37.279	37.214	74.493	6.208
1704.3	36.597	36.578	73.175	6.098
1504.5	35.648	35.617	71.265	5.939
1306.2	33.920	33.868	67.788	5.649
1103.0	31.179	31.128	62.307	5.192
903.0	27.404	27.359	54.763	4.564
704.7	21.938	21.923	43.861	3.655
501.5	15.727	15.721	31.448	2.621
303.2	9.570	9.565	19.135	1.595
103.2	3.357	3.351	6.708	0.559

4Q120 Quadrupole Field vs. Current

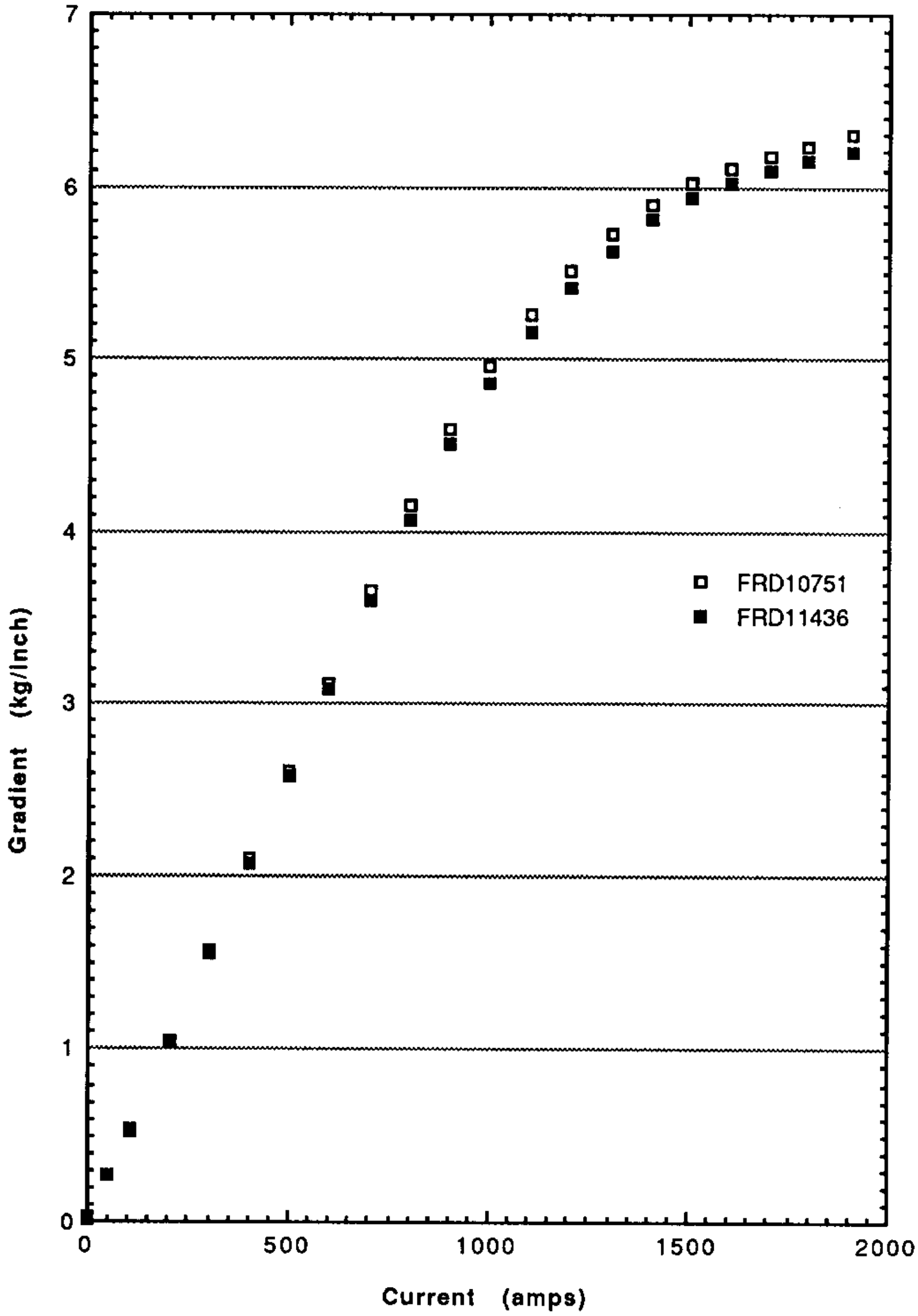

Figure 3

Harmonic Measurements

In addition to measuring the quadrupole field as a function of current, harmonic measurements were made on both magnets at 600, 1200, and 1600 amps.

The harmonic measurements were taken on both the power and return ends for each of the quadrupoles at their = 60 inch probe values. This was done at three different currents--600, 1200, and 1600 amps. The measurements were analyzed in terms of a two-dimensional harmonic representation

$$B = B_y + iB_x = \sum_{J=1}^{\infty}\left(C_N a^{N-1}\right)\left(\frac{r}{a}\right)^{(J-1)} c_J \, e^{i((J-1)\theta+\chi_J)}$$

in which B_y and B_x are components of the magnetic field, C_N is the harmonic field of the dominant field component (N=2 for quadrupoles), and a is the reference radius. Characterizing the shape imperfections of the field by comparing them to the dominant harmonic components leads to a definition of the normalized harmonic coefficient c_J

$$c_J = \frac{C_J a^{J-1}}{C_N a^{N-1}} = \frac{C_J a^{J-N}}{C_N} \qquad c_J e^{i(\chi_J)} = \left(\mathrm{b}_J + i\,\mathrm{a}_J\right)$$

Some symmetry properties are most easily seen by separating the normalized coefficient into ("normal"≡b_J), and ("skew"≡a_J) terms.

$$\mathrm{b}_J = c_J{}^{*}\cos\chi_J \qquad \mathrm{a}_J = c_J{}^{*}\sin\chi_J$$

c_J, χ_J are the normalized harmonic coefficient and its phase. b_J and a_J are the corresponding normal and skew normalized harmonic coefficients. r and θ are the cylindrical position coordinates and a is the reference radius at which the harmonic coefficients are normalized. The quadrupole field is the angular reference and is assumed it has no skew quadrupole (χ=0). Since the measurements were made with a coil having a radius of 34.5 mm and it is customary to give the results at a reference radius of 1.0 inch, the calculated b_J and a_J were converted from the measured c_J by,

$$c_J^a = c_J^A \left(\frac{a}{A} \right)^{J-N}$$

Substituting N=2, A=34.5, & *a*=25.4 for a quadrupole, the harmonic coefficients at a radius of 1.0 inch for each magnet are given below in units * (1.0E4):

FRD10751

		Return End		Power End	
Amps	Pole	Normal	Skew	Normal	Skew
600.0	6P	-0.49	1.44	0.14	1.70
600.0	8P	1.35	0.82	2.70	0.07
600.0	10P	0.35	-0.59	0.21	-0.58
600.0	12P	-1.93	-0.11	-1.78	0.01
600.0	20P	0.11	0.01	0.11	0.00
1200.0	6P	-2.35	6.61	0.10	6.70
1200.0	8P	1.62	0.62	2.92	0.01
1200.0	10P	0.20	-0.65	0.13	-0.63
1200.0	12P	-1.75	-0.10	-1.62	0.02
1200.0	20P	0.10	0.01	0.10	0.00
1600.0	6P	-4.22	6.71	-0.53	5.93
1600.0	8P	1.70	0.59	2.93	0.00
1600.0	10P	0.11	-0.64	0.11	-0.58
1600.0	12P	-1.89	-0.16	-1.78	0.01
1600.0	20P	0.09	0.00	0.09	0.01

FRD11436

		Return End		Power End	
Amps	Pole	Normal	Skew	Normal	Skew
600.0	6P	2.27	2.30	0.18	1.68
600.0	8P	-6.32	-0.30	-9.19	-0.26
600.0	10P	0.16	-0.15	0.07	-0.29
600.0	12P	-1.74	-0.02	-1.82	-0.03
600.0	20P	0.10	0.00	0.10	0.00
1200.0	6P	5.09	8.69	-0.12	8.78
1200.0	8P	-6.24	-0.30	-8.99	-0.15
1200.0	10P	0.30	-0.30	0.10	-0.47
1200.0	12P	-1.64	-0.10	-1.71	-0.03
1200.0	20P	0.09	0.01	0.09	0.00
1600.0	6P	3.08	9.12	-4.28	11.29
1600.0	8P	-6.24	-0.24	-8.95	-0.16
1600.0	10P	0.23	-0.34	-0.01	-0.55
1600.0	12P	-1.75	-0.04	-1.81	-0.03
1600.0	20P	0.09	0.01	0.09	0.00

Summary

Magnetic field measurements have been made on the "Early" Series and the "TeV II" Series 4Q120 quadrupoles. The technique of combining separate measurements when the physical probe is shorter than the magnet works well. Errors can come from (1) the accuracy of positioning the probe, (2) the current measurement, and (3) the electronics measuring the induced EMF. In our particular situation, the largest error came from the first item. The probe was positioned in Z to $\pm$ 1/16 inch, which was easy to accomplish. This translates into a maximum error of 0.125"/120." $\approx$ 0.1%, and in fact for the same magnet the (59.5"+60.5") measurement came out within 0.1% of the (80.0"+40.0") measurement.

Beam optics requiring high precision should be careful not to connect the two different quadrupole types in series to the same power supply. Treating the two Series interchangeably could lead to as much as a 2% error. The linear regions for the two Series are well described by,

FRD10751 (Early Series) $I(\text{amps}) = -9.8 + 193.4 * G(\text{kg/inch})$
FRD11436 (TeV II Series) $I(\text{amps}) = -37.8 + 197.0 * G(\text{kg/inch})$

I $\leq$ 800 amps; Length $\equiv$ 120. inches

Beyond 800 amps, for interpolation purposes, taking the same length, $L \equiv 120.0$ inches, Table 1 and Table 2 can be converted into practical units by dividing the $\int G\,dl$ columns by 12. This then gives current(amps) in the first column and the gradient (kg/inch) in the last column, the same units as are used in Figure 3.

The contribution from the fringe field to $\int G\,dl$ is small. The effective length varies from 121.6 inches at low currents to 120.7 inches at high currents. Considering the 4Q120 has a maximum full aperture over 4 inches, such small distances beyond the steel length of 120. inches are quite good.

Over all the harmonics, both the "normal" and "skew" sextupole components are largest for both magnets. Of the "normal" and "skew" components, the "skew" is uniformly larger. The "TeV II" Series also has a large normal octupole component compared to the "Early" Series.

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