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Warm Magnetic Measurements in Insertion Quads QRI103 - QRI110

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1. Introduction:

As of December, 1993, eight production insertion quadrupole magnets with 13cm inner diameter coils have been built. These production magnets are numbered QRI103 through QRI110. The magnets QRI001 and QRI002 were prototype magnets in this series. The cross section for the QRI103-QRI110 magnets was designed based on the measured harmonics in QRI001 and QRI002. Apart from the cross-section, the lead configuration was also changed to reduce the rather large dodecapole terms contributed by the lead end. The design details can be found in a relevant magnet division note [1].

The first two production magnets (QRI103 and QRI104) have been built to finish, including the ends. These two magnets have also undergone thorough warm and cold tests. The remaining magnets in the series (QRI105 through QRI110) have been collared but not completely assembled. In particular, the end connections have not been completed. This will be done at a later date. However, in order to assess the field quality and to monitor the manufacturing process, warm magnetic measurements have been carried out on all of these magnets. This note describes the techniques used for warm measurements of the body and the integral harmonics. The results of warm measurements for this first batch of production Q1 magnets are summarized. The magnets to be built after QRI110 are expected to have a change in b_5 and b_9 due to a change in the pole shim and the midplane gap sizes.

2. Construction Features Specific to QRI103-QRI110:

The magnets QRI103 through QRI110 in the series of Q1 magnets had pole spacers which were ground to get the correct pole position. However, an inspection of some pole spacers revealed that both the pole position as well as the pole width were out of specification after grinding. Therefore, this fact must be taken into account while comparing calculations with the measurements. The midplane half-gap was 0.010" at 0 and 180 degrees, and was 0.006" at 90 and 270 degrees. These asymmetric midplane shims were used to reduce the rather large unallowed octupole terms seen in the prototype magnets QRI001 and QRI002. All production insertion quadrupoles will have magnetic tuning shims installed to trim the unwanted harmonics. *These tuning shims were not installed for these warm measurements, except in the case of QRI104, where we studied the influence of nominal size tuning shims.*

3. Experimental Details:

Except for QRI103 and QRI104, the four coils of the magnets were not soldered together in series. Instead, the eight leads were connected in the appropriate configuration with the help of clamps. Since the leads tend to run parallel to the length of the magnet, they could contribute significantly to the integral harmonics. The connections, therefore, were made as

close to the magnet as possible such that the extra lengths of the leads did not carry any current. The integral harmonics were obtained with a 2.78m long, 8.15cm diameter measuring coil (Coil-75). The magnetic length of these magnets is 1.44 meter. The measuring coil was placed axially centered into the magnet for the integral measurements. No particular attempt was made to center the measuring coil radially into the magnet. Typical radial offsets of the measuring coil were about 3-4 mm. The measured harmonics were, however, corrected for the radial offsets by making the dipole terms zero.

3(a) Measurement of Body Harmonics:

Since the ends in most of the magnets tested were not as they would be in the final magnets, it was felt that a measurement of the body harmonics in these magnets is essential. This would have required a short measuring coil (similar to the 9" long measuring coil for 8cm magnets, Coil-37) of an appropriate radius. Unfortunately, no such coil has been built. The signal strength with coil-37 is not adequate to get even the lower order harmonics with reasonable accuracy in the warm measurements. As a result, it was decided to use the integral coil-75 at several carefully chosen axial locations in the magnet and then obtain the body harmonics by a suitable subtraction technique, as described in the following.

Fig.1 shows the four different configurations of the integral coil-75 used for measurements of body harmonics in the magnets. For the positions numbered 1 and 2, the measuring coil was inserted into the magnet from the non-lead end in order to avoid the lead end with clamps etc.. Position 2 gives the integral field from the non-lead end and about half of the straight section of the magnet. Position 1 integrates the field over another 16" of the magnet straight section. These additional 16" are on the lead end side of the magnet center. Thus, a difference between integral fields measured at positions 1 and 2 gives the fields for the 16" long straight section on the *lead end side* of the magnet center. It should be noted that the harmonics are generally measured with the measuring coil inserted from the lead end. The harmonics obtained for positions 1 and 2 were corrected for the fact that the coil was inserted from the non-lead end.

It has been the experience with the cold body measurements of the prototype quadrupoles that the unallowed harmonics tend to vary along the length of the magnet. Therefore it is not sufficient to measure the body harmonics in only one section of the magnet. To obtain the body harmonics on the non-lead end side of the magnet, positions 3 and 4 of coil-75 were used where the coil was inserted from the lead end (see Fig.1). From the four measured field harmonics at the four positions, it is possible to estimate the body harmonics separately in the two halves of the magnet and also the two end harmonics. The formalism to obtain these four quantities is presented in the next section.

4. Formalism for Obtaining the Body Harmonics:

The model assumed is illustrated in Fig.2. The variation of a given harmonic along the length of the magnet is shown schematically. The n-th harmonic from the lead end is represented by a delta-function of integrated area B_n unit.meter for the normal and A_n unit.meter for the skew component. The non-lead end is similarly represented by the primed

quantities. The straight section extends for a length of L_{eff}, and is divided into two halves. The lead end half is assumed to have body harmonics of b_n and a_n units while the primed quantities denote values on the non-lead end side.

Let $\mathfrak{b}_n(i)$ and $\mathfrak{a}_n(i)$ denote the harmonics measured *in units* at the i-th position. These harmonics are normalized to the integral quadrupole field, as measured at the i-th position. If L_i is the straight section length probed by the i-th position, then we have,

$$L_i = \frac{\text{Measured Transfer Function at the } i \text{ th Position}}{\text{Total Integral Transfer Function of the Magnet}} \times L_{eff}\,; \qquad L_{eff} \approx 1.44\,\text{m} \quad (1)$$

The total integral transfer function of the magnet is obtained from the fifth position of the measuring coil, where it is placed axially centered into the magnet. In terms of the previously described quantities, we may write the following four equations for the normal harmonics:

$$B'_n + b'_n L_{eff}\ /\ 2 + b_n (L_1 - L_{eff}\ /\ 2) = \mathfrak{b}_n(1).\, L_1 \quad (2)$$

$$B'_n + b'_n L_2 = \mathfrak{b}_n(2).\, L_2 \quad (3)$$

$$B_n + b_n L_{eff}\ /\ 2 + b'_n (L_3 - L_{eff}\ /\ 2) = \mathfrak{b}_n(3).\, L_3 \quad (4)$$

$$B_n + b_n L_4 = \mathfrak{b}_n(4).\, L_4 \quad (5)$$

$$b_n^{body} = (b_n + b'_n)\ /\ 2 \quad (6)$$

In writing equations (3) and (5), it is assumed that the lengths L_2 and L_4 are nearly equal to $L_{eff}/2$. From the above four equations, the normal body harmonics in the two halves of the magnet and the integrated end harmonics in the two ends can be determined. A similar set of equations can be written for the skew components to obtain the skew harmonics. It should be noted that the above equations make use of an unknown quantity, L_{eff}. However, it has been the experience with the prototype magnets that the effective length is quite constant at 1.44 meters for these magnets. Furthermore, when one solves for the *body harmonics*, the results are insensitive to the actual value of L_{eff} since all the lengths in the above equations are proportional to L_{eff} (see Eq.1). Finally, the body harmonics averaged over the entire magnet are assumed to be the averages of the body harmonics measured in the two halves of the magnet (Eq.6).

5. Results:

The results of the measurements are summarized in Tables I through V. Table I shows the results of integral measurements. The integral transfer function shows a remarkable consistency between magnet to magnet. The variation of about 0.03% in the transfer function is well within the measurement noise. The other allowed harmonics also have small magnet to

magnet variation. The integral b_5 term in QRI105 and QRI106 is about 1 unit higher than in the subsequent magnets. It is likely that in the integral measurements of these two magnets, the eight leads were not clamped close to the magnet. Maximum variation is seen in the unallowed sextupole terms. It should be noted that magnets QRI103 and QRI104 had completed ends when measured, whereas the rest of the magnets did not have completed ends. This is the reason for the smaller dodecapole (b_5) and 20-pole (b_9) terms in these two magnets. In reporting the average and standard deviation in Table I, the magnets QRI103 and QRI104 are, therefore, not included. It should be recalled that the magnets were measured without the nominal "tuning shims". However, for one of the magnets (QRI104), the integral harmonics are available both with and without the shims. The magnet with shims is denoted by QRI104* in Table I. As seen from a comparison of QRI104 and QRI104*, the values of integral b_5 and b_9 are changed by about -2.8 units and -0.3 units respectively when the nominal tuning shims are used. The computed values of the changes in b_5 and b_9 were -2.4 and -0.23 unit respectively. The warm measurements were expected to give a slightly larger change than computed since the tuning shims may not have attached themselves firmly to the yoke at low fields.

The body harmonics in the two halves of the magnet are tabulated in Tables II and III. The lower order unallowed terms show significant differences in the two halves for most of the magnets. This is consistent with the earlier experience with magnets 1 through 4 in the series measured cold with the 9" long coil-37. The allowed terms b_5 and b_9, however, are nearly the same in the two halves. Also, the body harmonics obtained for QRI103 and QRI104 by this technique are generally consistent with those measured earlier with coil-37. This places a reasonable degree of confidence in the body harmonics obtained by this subtraction technique. The body harmonics averaged over the entire magnet are assumed to be the averages of harmonics in Tables II and III. These average body harmonics are given in Table IV. It should be noted that QRI104 was measured with the nominal values of the magnetic tuning shims, thus giving somewhat different harmonics than the other magnets. For this reason, the magnet QRI104 was excluded in the calculation of averages and standard deviations in Tables II through IV. The measured average b_5 and b_9 in the body are 3.1 units and 0.7 unit respectively. The expected values for b_5 and b_9 with the out of specification spacers are 2.1 and 0.3 unit.

Although Eqs.(2)-(5) yield both the lead end and the non-lead end harmonics, only the non-lead end harmonics are given in Table V. This is because the non-lead ends were the same in all the magnets tested, whereas the lead end could vary significantly due to the temporary nature of the connections. The magnet to magnet RMS variations of the b_5 and b_9 terms in the non-lead end are 0.28 and 0.03 unit respectively, which are about the same as for the corresponding body harmonics.

Reference:

[1] R.C. Gupta and P.A. Thompson, *Iterated Design for the 130 mm Aperture Quadrupoles for RHIC Interaction Region*, Magnet Division Note 510-16 (RHIC-MD-214), August 5, 1993.

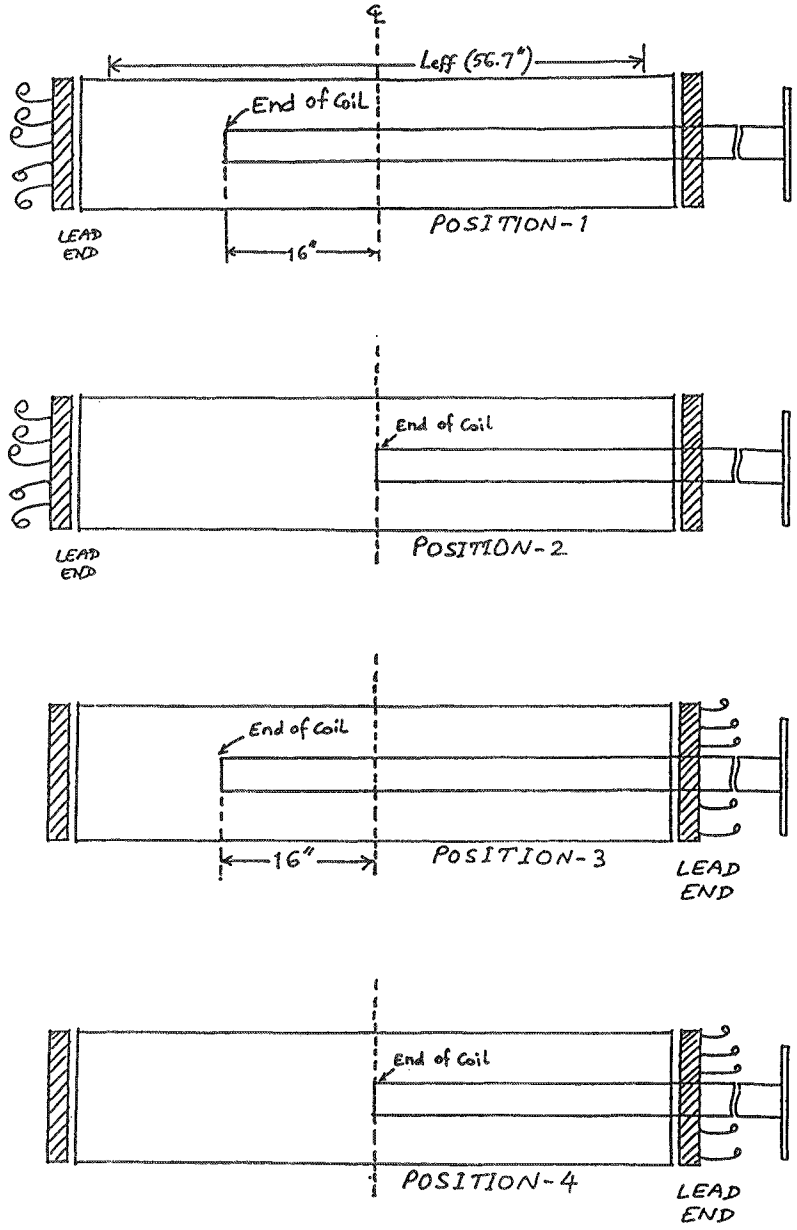

Fig.1 *Schematic showing the four positions of 2.78 meter long measuring coil (Coil-75) used for measurement of body harmonics in the insertion quadrupoles.*

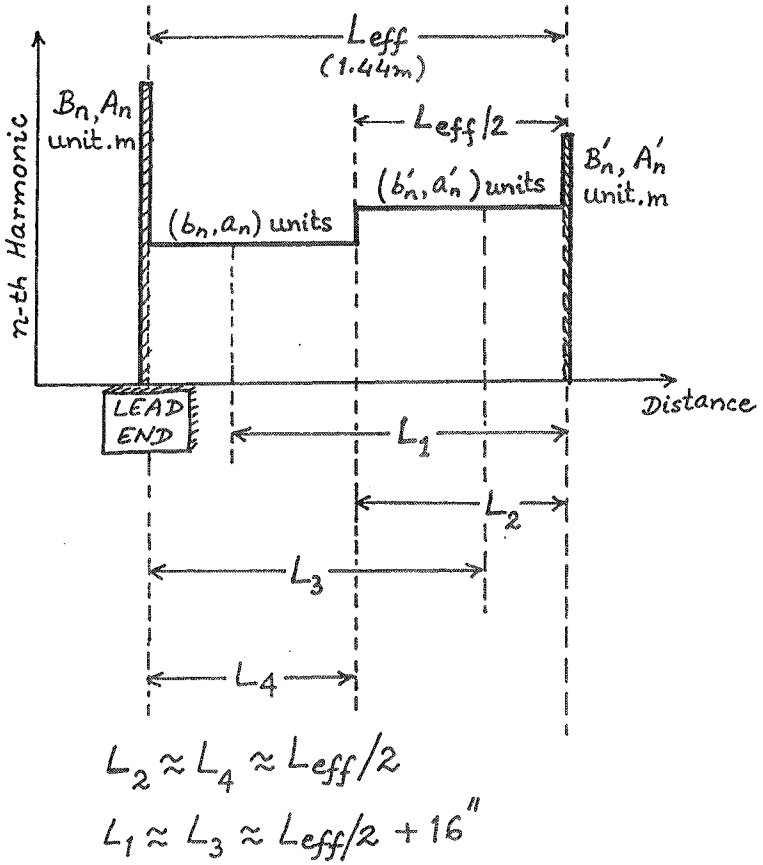

Fig.2 *Variation of a given multipole along the length of the magnet. The model treats the ends as delta-functions. The body harmonics are assumed to be constant in one half of the magnet length.*

Table I. Integral Harmonics (Warm) in QRI Magnets

NORMAL TERMS

Magnet	b2 (units)	b3 (units)	b4 (units)	b5 (units)	b6 (units)	b7 (units)	b8 (units)	b9 (units)	b10 (units)	b11 (units)	b12 (units)	b13 (units)	Trans. Func. (T/kA)
QRI103	-2.11	-0.70	0.04	**6.46**	0.16	-0.36	0.02	**0.32**	0.00	-0.02	0.00	**-0.04**	13.592
QRI104	2.02	0.36	-0.29	**6.36**	0.01	-0.32	-0.14	**0.37**	-0.01	0.00	0.01	**-0.04**	13.597
QRI104*	2.04	-0.62	-0.66	**3.55**	0.10	-0.32	-0.15	**0.06**	-0.01	-0.02	0.02	**-0.01**	13.680
QRI105	-1.84	1.82	1.10	**8.97**	0.04	-0.21	-0.05	**0.51**	0.02	-0.01	0.01	**0.00**	13.630
QRI106	-4.22	0.11	0.69	**9.07**	-0.41	-0.37	0.08	**0.48**	0.00	-0.01	0.01	**0.00**	13.626
QRI107	1.85	2.08	0.25	**7.89**	0.11	-0.31	-0.05	**0.50**	0.02	0.00	-0.01	**0.00**	13.624
QRI108	-2.28	0.92	0.83	**8.04**	-0.04	-0.29	0.08	**0.49**	-0.02	-0.02	0.00	**-0.01**	13.629
QRI109	-1.03	0.83	1.08	**7.70**	0.30	-0.32	-0.04	**0.51**	0.01	-0.02	0.00	**0.02**	13.630
QRI110	-0.13	0.76	0.77	**8.00**	-0.17	-0.42	0.07	**0.48**	-0.01	0.00	-0.01	**-0.02**	13.636
AVG.	-1.28	1.09	0.78	**8.28**	-0.03	-0.32	0.01	**0.50**	0.00	-0.01	0.00	**0.00**	13.629
Std. Dev.	2.06	0.73	0.31	**0.59**	0.24	0.07	0.07	**0.01**	0.02	0.01	0.01	**0.01**	0.004

SKEW TERMS

Magnet	a2 (units)	a3 (units)	a4 (units)	a5 (units)	a6 (units)	a7 (units)	a8 (units)	a9 (units)	a10 (units)	a11 (units)	a12 (units)	a13 (units)
QRI103	1.20	-1.21	0.07	**0.21**	0.11	-0.04	-0.02	**0.13**	0.03	-0.01	0.01	**-0.02**
QRI104	0.50	0.59	0.35	**-0.33**	-0.02	-0.09	-0.02	**0.14**	-0.02	0.00	-0.02	**-0.02**
QRI104*	0.39	0.68	0.54	**-0.62**	-0.02	-0.12	-0.08	**0.14**	-0.03	0.01	0.00	**-0.03**
QRI105	3.32	1.49	0.89	**-2.30**	0.11	0.13	0.06	**0.13**	0.01	0.01	0.01	**-0.04**
QRI106	1.85	0.27	1.00	**-2.00**	-0.19	0.19	0.01	**0.18**	0.01	0.02	0.00	**-0.01**
QRI107	-2.05	1.31	0.18	**-1.22**	-0.04	0.15	0.05	**0.17**	0.00	0.01	-0.01	**0.01**
QRI108	-2.40	1.76	-1.03	**-1.98**	0.25	-0.02	0.06	**0.18**	0.03	0.00	-0.01	**-0.02**
QRI109	2.67	1.44	1.33	**-1.58**	0.02	0.14	0.10	**0.19**	0.02	-0.01	0.03	**0.00**
QRI110	-0.04	1.87	0.28	**-1.72**	0.15	0.23	0.12	**0.17**	0.02	0.00	-0.01	**0.02**
AVG.	0.56	1.36	0.44	**-1.80**	0.05	0.14	0.07	**0.17**	0.02	0.01	0.00	**-0.01**
Std. Dev.	2.44	0.57	0.85	**0.38**	0.15	0.08	0.04	**0.02**	0.01	0.01	0.02	**0.02**

Notes: 1. QRI103 and QRI104 had Completed Ends with Spiral Leads.

2. QRI104* is with nominal magnetic tuning shims.

3. QRI103 and QRI104 Excluded from Average and STD Deviation.

4. QRI105 and QRI106 possibly measured with the leads clamped far from the magnet.

Table II. Body Harmonics(Warm) in the Lead End Half of QRI Magnets

NORMAL TERMS

Magnet	b2 (units)	b3 (units)	b4 (units)	b5 (units)	b6 (units)	b7 (units)	b8 (units)	b9 (units)	b10 (units)	b11 (units)	b12 (units)	b13 (units)
QRI103	-0.83	-1.05	0.08	2.80	0.14	-0.29	-0.14	0.69	0.01	-0.05	-0.03	-0.03
QRI104	2.19	-0.43	-0.62	0.50	0.17	-0.41	-0.11	0.38	-0.10	0.02	0.13	-0.03
QRI105	0.75	1.08	0.66	3.51	0.01	-0.27	-0.01	0.71	-0.01	-0.03	-0.01	0.04
QRI106	-2.40	1.43	0.10	3.13	-0.22	-0.27	0.10	0.70	-0.06	0.03	0.01	-0.06
QRI107	3.27	2.09	-0.24	2.84	0.01	-0.28	-0.10	0.67	-0.03	0.00	0.04	-0.03
QRI108	-2.95	2.51	0.51	3.43	-0.18	-0.32	-0.04	0.69	-0.01	0.01	0.03	-0.04
QRI109	1.82	1.38	0.01	3.24	-0.07	-0.36	0.00	0.76	-0.02	0.05	-0.17	-0.15
QRI110	0.36	1.17	0.48	2.77	-0.12	-0.35	0.09	0.69	-0.04	-0.01	0.01	0.00
AVG.	0.00	1.23	0.23	3.10	-0.06	-0.30	-0.01	0.70	-0.02	0.00	-0.02	-0.04
STD. DEV.	2.23	1.13	0.32	0.31	0.12	0.04	0.09	0.03	0.02	0.03	0.07	0.06

SKEW TERMS

Magnet	a2 (units)	a3 (units)	a4 (units)	a5 (units)	a6 (units)	a7 (units)	a8 (units)	a9 (units)	a10 (units)	a11 (units)	a12 (units)	a13 (units)
QRI103	1.82	-0.39	-0.04	0.63	0.20	-0.06	0.06	0.00	0.06	0.01	0.01	0.03
QRI104	-0.10	0.45	-0.60	0.18	0.05	-0.06	0.01	-0.08	0.03	0.11	-0.05	-0.17
QRI105	-3.15	1.85	-0.84	-0.69	-0.14	0.10	-0.03	-0.07	-0.02	0.03	0.03	0.00
QRI106	0.24	-1.23	0.16	-0.33	-0.06	0.04	0.05	-0.04	0.02	0.03	-0.06	0.05
QRI107	-1.17	-0.08	0.28	0.15	-0.28	0.01	0.04	-0.02	-0.03	0.03	-0.01	-0.09
QRI108	-2.79	-0.21	0.01	0.24	0.26	-0.10	0.02	-0.01	0.01	-0.03	-0.03	-0.10
QRI109	2.93	0.74	0.92	0.17	0.11	0.02	0.09	-0.03	0.03	-0.08	-0.14	0.21
QRI110	1.40	-0.23	0.56	0.04	0.01	0.08	0.05	0.00	-0.01	0.02	-0.01	0.02
AVG.	-0.10	0.07	0.15	0.03	0.01	0.01	0.04	-0.03	0.01	0.00	-0.03	0.01
STD. DEV.	2.34	0.97	0.55	0.42	0.19	0.07	0.04	0.02	0.03	0.04	0.05	0.10

Note: QRI104 had nominal Tuning Shims when Measured.
QRI104 Excluded from Average and STD Deviation reported above.

Table III. Body Harmonics(Warm) in the Non-Lead End Half of QRI Magnets

NORMAL TERMS

Magnet	b2 (units)	b3 (units)	b4 (units)	b5 (units)	b6 (units)	b7 (units)	b8 (units)	b9 (units)	b10 (units)	b11 (units)	b12 (units)	b13 (units)
QRI103	-1.99	-1.97	1.14	2.93	0.23	-0.32	-0.19	0.67	0.03	-0.03	-0.04	-0.09
QRI104	0.32	-0.40	0.37	0.81	0.52	-0.21	-0.32	0.36	-0.04	0.04	-0.09	0.02
QRI105	-0.79	2.31	0.11	3.67	0.08	-0.26	-0.06	0.71	0.02	0.00	0.00	0.01
QRI106	-2.31	1.23	-0.95	3.42	0.05	-0.46	0.11	0.69	0.00	0.02	0.03	-0.18
QRI107	0.57	2.25	-0.45	2.83	0.10	-0.33	-0.08	0.70	0.04	0.03	0.00	-0.01
QRI108	-3.58	1.44	0.26	3.14	-0.12	-0.43	-0.06	0.70	0.20	-0.20	-0.27	0.56
QRI109	-0.56	1.25	-1.46	3.16	0.00	-0.22	0.09	0.77	0.01	-0.01	-0.05	-0.06
QRI110	-0.52	1.30	1.20	2.80	-0.10	-0.24	0.02	0.61	0.02	0.10	-0.10	-0.21
AVG.	-1.31	1.12	-0.02	3.14	0.03	-0.32	-0.02	0.69	0.04	-0.01	-0.06	0.00
STD. DEV.	1.39	1.44	1.00	0.32	0.12	0.09	0.11	0.05	0.07	0.09	0.10	0.26

SKEW TERMS

Magnet	a2 (units)	a3 (units)	a4 (units)	a5 (units)	a6 (units)	a7 (units)	a8 (units)	a9 (units)	a10 (units)	a11 (units)	a12 (units)	a13 (units)
QRI103	1.43	-0.84	-0.52	0.77	0.25	-0.06	0.17	0.04	0.04	0.00	-0.05	-0.02
QRI104	1.13	1.04	0.50	0.49	-0.02	-0.26	-0.03	-0.01	0.01	0.03	-0.04	0.13
QRI105	-2.03	1.05	-0.26	-0.10	-0.12	0.10	-0.04	0.07	-0.02	0.04	0.01	0.01
QRI106	0.23	-0.65	0.56	0.11	-0.22	-0.01	0.03	0.06	0.01	0.04	-0.07	0.00
QRI107	-2.98	-0.67	0.47	0.02	-0.21	-0.01	0.01	0.08	-0.01	0.01	-0.03	0.00
QRI108	-1.53	-0.12	-0.45	0.08	0.14	-0.14	0.11	0.20	-0.02	-0.29	0.47	0.11
QRI109	2.47	0.62	1.91	-0.03	0.14	-0.06	-0.03	0.04	-0.04	-0.05	-0.02	0.06
QRI110	2.62	0.25	-0.29	-0.16	0.24	0.08	0.07	0.07	0.03	-0.04	-0.20	0.17
AVG.	0.03	-0.05	0.20	0.10	0.03	-0.02	0.05	0.08	0.00	-0.04	0.02	0.05
STD. DEV.	2.25	0.72	0.87	0.31	0.21	0.08	0.08	0.05	0.03	0.11	0.21	0.07

Note: QRI104 had nominal Tuning Shims when Measured.
QRI104 Excluded from Average and STD Deviation reported above.

Table IV. Average Body Harmonics (Warm) in QRI Magnets

NORMAL TERMS

Magnet	b2 (units)	b3 (units)	b4 (units)	b5 (units)	b6 (units)	b7 (units)	b8 (units)	b9 (units)	b10 (units)	b11 (units)	b12 (units)	b13 (units)
QRI103	-1.41	-1.51	0.61	2.87	0.18	-0.30	-0.17	0.68	0.02	-0.04	-0.03	-0.06
QRI104	1.26	-0.41	-0.13	0.66	0.35	-0.31	-0.21	0.37	-0.07	0.03	0.02	-0.01
QRI105	-0.02	1.69	0.38	3.59	0.04	-0.27	-0.03	0.71	0.00	-0.02	0.00	0.02
QRI106	-2.35	1.33	-0.43	3.27	-0.09	-0.36	0.11	0.70	-0.03	0.03	0.02	-0.12
QRI107	1.92	2.17	-0.35	2.84	0.06	-0.30	-0.09	0.69	0.01	0.01	0.02	-0.02
QRI108	-3.26	1.98	0.38	3.29	-0.15	-0.37	-0.05	0.69	0.09	-0.10	-0.12	0.26
QRI109	0.63	1.32	-0.73	3.20	-0.03	-0.29	0.04	0.76	-0.01	0.02	-0.11	-0.10
QRI110	-0.08	1.24	0.84	2.79	-0.11	-0.29	0.05	0.65	-0.01	0.05	-0.05	-0.11
AVG.	-0.66	1.17	0.10	3.12	-0.02	-0.31	-0.02	0.70	0.01	-0.01	-0.04	-0.02
STD. DEV.	1.79	1.23	0.60	0.30	0.12	0.04	0.09	0.04	0.04	0.05	0.06	0.13

SKEW TERMS

Magnet	a2 (units)	a3 (units)	a4 (units)	a5 (units)	a6 (units)	a7 (units)	a8 (units)	a9 (units)	a10 (units)	a11 (units)	a12 (units)	a13 (units)
QRI103	1.62	-0.61	-0.28	0.70	0.22	-0.06	0.12	0.02	0.05	0.01	-0.02	0.00
QRI104	0.51	0.74	-0.05	0.34	0.01	-0.16	-0.01	-0.05	0.02	0.07	-0.05	-0.02
QRI105	-2.59	1.45	-0.55	-0.39	-0.13	0.10	-0.04	0.00	-0.02	0.04	0.02	0.00
QRI106	0.23	-0.94	0.36	-0.11	-0.14	0.01	0.04	0.01	0.01	0.03	-0.06	0.02
QRI107	-2.07	-0.38	0.38	0.08	-0.24	0.00	0.02	0.03	-0.02	0.02	-0.02	-0.05
QRI108	-2.16	-0.16	-0.22	0.16	0.20	-0.12	0.07	0.09	0.00	-0.16	0.22	0.00
QRI109	2.70	0.68	1.42	0.07	0.12	-0.02	0.03	0.00	-0.01	-0.07	-0.08	0.13
QRI110	2.01	0.01	0.13	-0.06	0.13	0.08	0.06	0.04	0.01	-0.01	-0.11	0.10
AVG.	-0.04	0.01	0.18	0.07	0.02	0.00	0.04	0.03	0.00	-0.02	-0.01	0.03
STD. DEV.	2.22	0.82	0.65	0.33	0.19	0.08	0.05	0.03	0.02	0.07	0.11	0.06

Note: QRI104 had nominal Tuning Shims when Measured.
QRI104 Excluded from Average and STD Deviation reported above.

Table V. Non-Lead End Harmonics (Warm) in QRI Magnets

NORMAL TERMS

Magnet	b2 unit.m	b3 unit.m	b4 unit.m	b5 unit.m	b6 unit.m	b7 unit.m	b8 unit.m	b9 unit.m	b10 unit.m	b11 unit.m	b12 unit.m	b13 unit.m
QRI103	-1.93	-0.16	-0.51	0.43	-0.05	0.00	0.16	-0.10	-0.01	0.00	0.03	0.05
QRI104	0.09	0.07	-0.96	-0.07	-0.20	-0.07	0.23	-0.08	0.05	-0.06	0.04	0.08
QRI105	0.29	-0.31	0.56	0.08	0.02	-0.01	0.06	-0.13	0.00	0.00	0.00	-0.03
QRI106	0.45	-0.04	0.55	0.19	-0.24	0.08	-0.03	-0.13	0.00	-0.05	-0.02	0.14
QRI107	1.61	-0.49	0.01	0.30	0.00	0.01	0.06	-0.14	-0.02	-0.04	-0.01	0.02
QRI108	1.65	-0.37	0.38	0.14	0.11	0.05	0.08	-0.15	-0.15	0.12	0.21	-0.41
QRI109	-0.60	-0.01	1.84	-0.37	0.16	-0.05	-0.02	-0.19	-0.04	-0.06	0.10	0.14
QRI110	-1.58	-0.38	-0.70	0.47	-0.12	-0.08	0.10	-0.08	-0.03	-0.09	0.09	0.12
AVG.	-0.02	-0.25	0.30	0.18	-0.02	0.00	0.06	-0.13	-0.04	-0.02	0.05	0.01
STD. DEV.	1.43	0.18	0.84	0.28	0.14	0.06	0.07	0.03	0.05	0.07	0.08	0.19

SKEW TERMS

Magnet	a2 unit.m	a3 unit.m	a4 unit.m	a5 unit.m	a6 unit.m	a7 unit.m	a8 unit.m	a9 unit.m	a10 unit.m	a11 unit.m	a12 unit.m	a13 unit.m
QRI103	-0.83	0.75	0.43	-0.13	-0.09	0.05	-0.08	-0.07	-0.02	0.00	0.05	0.01
QRI104	-1.49	0.18	-0.51	-0.17	-0.03	0.11	0.04	0.00	-0.02	-0.04	0.08	-0.07
QRI105	-1.38	-0.57	-0.09	0.13	0.08	-0.04	0.04	-0.05	0.01	-0.02	0.00	0.00
QRI106	1.60	0.31	0.19	-0.36	0.12	0.02	0.02	-0.05	-0.01	-0.02	0.08	0.01
QRI107	-1.85	0.10	-0.38	0.34	0.10	0.00	-0.01	-0.06	-0.01	-0.01	0.04	0.01
QRI108	-1.59	0.47	0.13	-0.10	0.11	0.02	-0.03	-0.16	0.03	0.20	-0.32	-0.09
QRI109	-1.68	0.08	-0.92	0.06	-0.02	0.02	0.06	-0.06	0.02	0.06	0.12	-0.11
QRI110	-0.78	-0.46	0.33	0.08	-0.04	-0.01	0.00	-0.06	-0.02	0.03	0.15	-0.12
AVG.	-0.93	0.10	-0.04	0.00	0.04	0.01	0.00	-0.07	0.00	0.03	0.02	-0.04
STD. DEV.	1.19	0.48	0.47	0.22	0.09	0.03	0.05	0.04	0.02	0.08	0.16	0.06

Note: QRI104 had nominal Tuning Shims when Measured.
QRI104 Excluded from Average and STD Deviation reported above.