Superconducting Magnet Division

Magnet Note

Author: A. Jain, P. Wanderer, E. Willen

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Topic: LHC

Title: Expected Harmonics in BNL-Built Twin Aperture Dipoles for LHC (D2, D4a, D4b) Version 2.0

M. Anerella
A. Blake (c)
J. Cozzolino
J. Escallier (c)
G. Ganetis
M. Garber (c)
A. Ghosh
R. Gupta
H. Hahn (c)
M. Harrison
J. Herrera
A. Jain
P. Joshi (c)
S. Kahn
W. Louie (c)
G. Morgan (c)
J. Muratore (c)
S. Ozaki (c)
B. Parker
S. Peggs
F. Pilat (c)
S. Plate (c)
C. Porretto (c)
W. Sampson (c)
J. Schmalzle (c)
J. Sondericker (c)
S. Tepikian (c)
R. Thomas (c)
D. Trbojevic (c)
P. Wanderer
J. Wei
T. Wild (c)
E. Willen

Version 1.0 Tables*

- Prepared in March, 1998. Many changes since then.
- Based mostly on RHIC production data (DRG/DR8).
- Ignores several important effects, such as changes in superconductor properties from RHIC cable, vendor to vendor differences, different operating temperatures, etc.
- It is now time to revise (magnet designs finalized, data from twin-aperture D4b prototypes available)

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* *Expected Harmonics (Version 1.0) in BNL-built LHC Dipoles*, A. Jain, Magnet Division Note RHIC-MD-276, March 10, 1998 (Also published as RHIC AP Note RHIC-AP-147)

Body Harmonics in D4b (at 4.5 K)

- D4b operates at 1.9 K. However, estimates at 4.5 K can be based on actual data in 2 prototypes.
- Recognize Left-Right differences in b_2, b_4, b_6, b_8 at both very low and high fields:
  (Low Fields: cross-talk, remnant field, s.c. magnetization.
  High Fields: cross-talk due to iron saturation)
- At mid-fields (2kA-3kA), both apertures are equivalent.
  4 apertures, rather than 2 magnets (better statistics)

  BUT,
- Data available at only one axial position in each aperture.
  (Use Warm measurement data to obtain "Body Avg." and "Center" differences; apply to "Center" cold data to get an estimate of cold "Body Avg.")

Body Harmonics in D4b (at 4.5 K, contd.)

- Average measured data at 2000A, 2400A, 2800A to get "Up Ramp" values at ~2400A in each aperture.
  Indicator of "geometric" values
- Obtain "Mean", "Sigma" and "Delta" applicable at mid-field. ("Delta" = Maximum deviation of a data point from mean.)
- Obtain offsets from 2400A value at 300A, 5600A and 6000A (Small magnet-to-magnet variation expected; Left-Right differences may be seen.)
- Group offsets into "Left", "Right" and "Both" types.
- Obtain "Mean of offset", "Sigma of offset" and "Delta of offset". (For L-R asymmetric terms, use absolute values of offsets 4 data points for such terms also.)

Body Harmonics in D4b (at 4.5 K, contd.)

- Obtain "Expected Mean" values at 300A, 5600A and 6000A by adding (or subtracting, where appropriate) the calculated offsets (deviations from 2400A) to the 2400A data.
- Obtain "Expected Delta" by adding "Delta" at 2400A to the "Delta" of current dependence.
- Obtain "Expected Sigma" by adding (in quadrature) the "Sigma" at 2400A to the "Sigma" of current dependence.

(See next panel for Exceptions and Limitations)

Body Harmonics in D4b (at 4.5 K, contd.)

Exception:

- Right aperture in DMP401 has large skew quadrupole, resulting in a non-zero mean, and a large "sigma". This data point is excluded to obtain the mean value, but included in estimating the "Delta". The "sigma" for this term is retained from Ver.1.0 table.

Limitations:

- Effect of cryostat on skew quadrupole has not been estimated yet, but this effect is expected to be negligible.
- Certain harmonics at low field must be adjusted due to use of wire from a vendor different from that for the D4b prototypes (Alsthom Vs Oxford)

Body Harmonics in D4a and D2 (at 4.5 K)

- Same table as D4b at 0.2T, except:
  b_2 cross-talk/remnant field contribution difficult to estimate.
  Larger uncertainties in b_2 for these magnets.
  Used 2 Units/1 Unit additional Δ at 0.2 T for D4a/D2 (<u>at 25 mm</u>)
  Used 1 Unit/0.5 Unit additional Δ at 3.55 T & 3.8 T for D4a/D2 (<u>at 25 mm</u>)
- At high fields, add calculated differences from D4b saturation behavior to the D4b table values to get the "Expected Mean" values.
- Use the same "Delta" and "Sigma" as in the D4b table.
- D2 and D4a will use the same wire as in the prototypes (Oxford)

Limitation:

- Effect of cryostat on skew quadrupole has not been estimated yet, but this effect is expected to be small.

Adjustments to Body Harmonics for 1.9 K Operation and Wire Properties

- D2 and D4a will use Oxford wire (same as the prototypes), whereas D4b will use wire from Alsthom (slightly lower I_c)
- D2 will operate at 4.5 K, and D4a/D4b at 1.9 K.
- No measurements of wire properties available at fields below 1 T. Extrapolations to 0.2 T proved to be model dependent and are not reliable. Also, no data available at 1.9 K.

Approximate Adjustment:

- Measured Up Ramp/Dn Ramp differences in the prototypes taken as estimates of persistent current (p.c.) contributions for the Oxford wire at 4.5 K and at various fields (0.2 T, 3.55 T, 3.8 T).
- These differences scaled by the ratio of I_c to obtain the p.c. contribution at 4.5 K with wire from a different vendor. For 0.2 T, I_c values at 1 T are used. For higher fields, the measured I_c values are interpolated.

Adjustments to Body Harmonics for 1.9 K Operation and Wire Properties (contd.)

- The estimated persistent current contribution at 1.9 K is assumed to be 50% more than at 4.5 K (all fields).
- Adjustments to each harmonic are calculated based on the operating temperature and the wire to be used for each magnet type.
- The mean values in the tables of expected body harmonics (at 4.5 K and Oxford wire) are adjusted by the above amount to arrive at mean values for the relevant temperature and wire vendor.
- 20% of the adjustment required is also added to the "Delta" values to account for the uncertainties introduced by various assumptions.
- In practice, adjustments are negligible for most harmonics, except for the lowest order terms at 0.2 T.
- The actual uncertainties may be much more than 20%. In particular, values at 0.2 T will be extremely sensitive to detailed superconductor properties.

End Harmonics in D2/D4a/D4b (Generic)

- Only Warm Z-Scan data available in D4b prototypes.
- Lead End not configured as in cryostated magnets (no end volume, etc.)
  Lead End harmonics in production may differ from the prototypes.
- Use data anyway.
- Obtain Warm-Cold offsets at various fields from RHIC production data.
- Apply to the warm Z-scan data in the D4b prototypes to obtain "Expected Mean" values. **Ignore temperature/vendor effects**.
- Delta's and Sigma's are left unchanged from Ver.1.0 (based on DRG data). ***Several measured Lead End Skew harmonics fall outside Ver.1.0 ($\Delta + \sigma$) band !!***
- No systematic Left-Right asymmetry seen for end harmonics in the prototypes.

Integral Harmonics in D2/D4a/D4b

- "Expected Mean" obtained by adding "Expected Mean" for "Body" and the "Expected Mean" of ends:

Integral = Body + (Lead End + Return End)/9.45m

- Keep the same "Delta's" and "Sigma's", as in the tables for expected "Body" harmonics.
  (uncertainties in the ends likely to contribute only a small amount to the uncertainties in the integral due to 9.45m length)

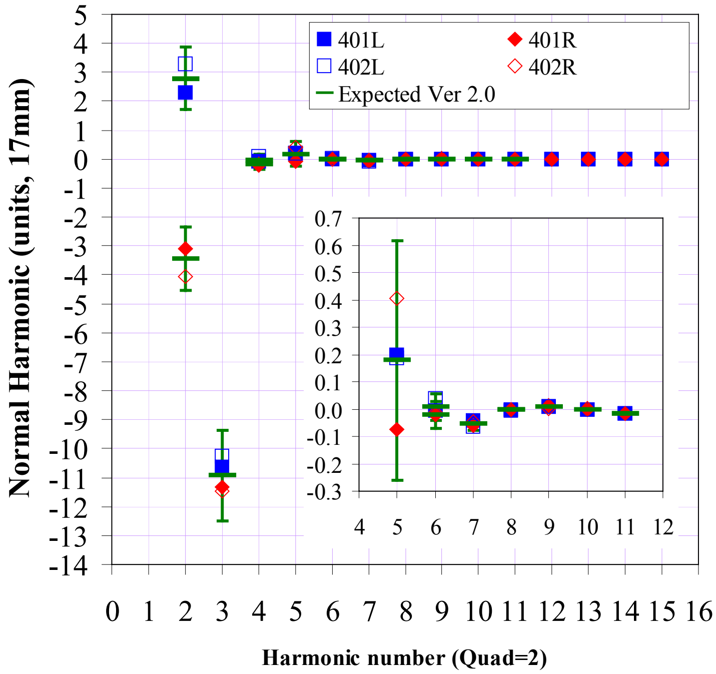
Comparison of Harmonics Measured in the D4b Prototypes and Expected Ver. 2.0

- The tables presented in this note for D4b are at 1.9 K and for Alsthom wire.
- The prototype D4b magnets were built with the Oxford wire and were tested at 4.5 K.
- The expected values for D4b, before making adjustments for 1.9 K operation and a change of wire vendor, are compared against the measured harmonics in the following figures.
- Note that there are two expected values (one for each aperture) for some of the normal terms.

Body Harmonics (Normal) at 0.2 T Dipole Field

Measured in Prototypes Vs Expected V2.0 (D4b unadjusted)

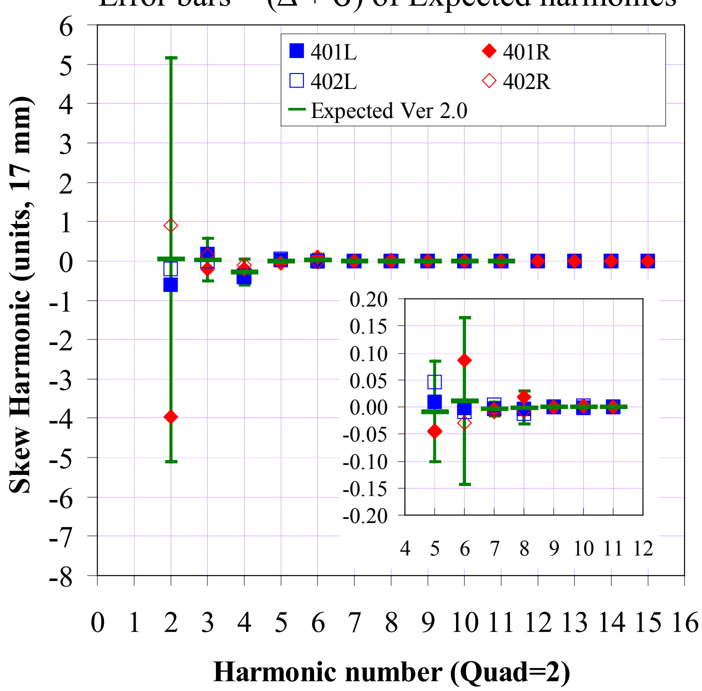
Error bars = ($\Delta + \sigma$) of Expected harmonics



Body Harmonics (Skew) at 0.2 T Dipole Field

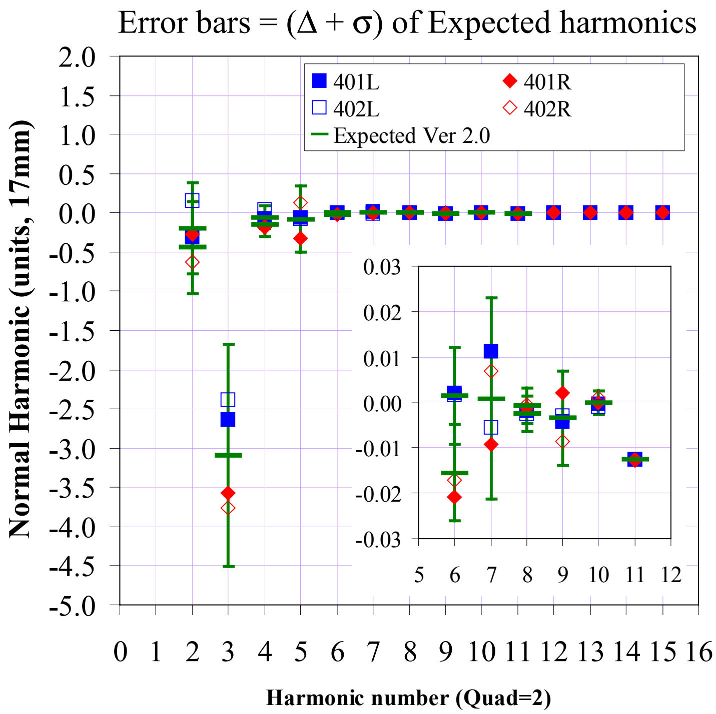
Measured in Prototypes Vs. Expected V2.0 (D4b unadjusted)

Error bars = ($\Delta + \sigma$) of Expected harmonics



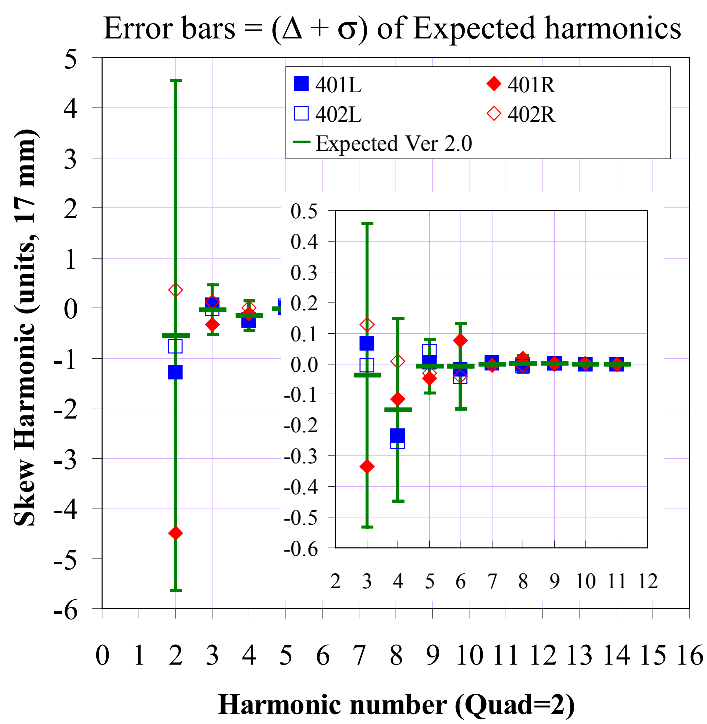
Body Harmonics (Normal) at 3.55 T Dipole Field

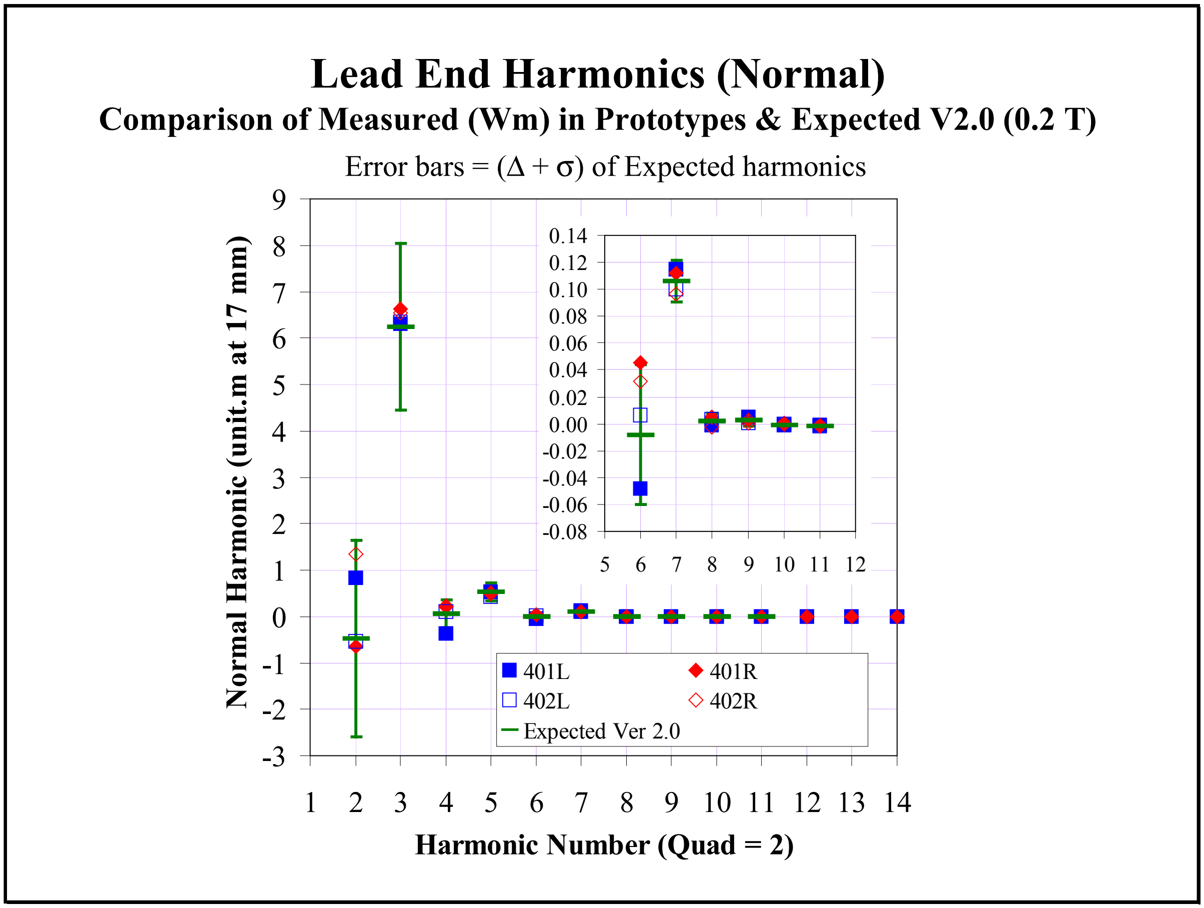
Measured in Prototypes Vs. Expected V2.0 (D4b unadjusted)

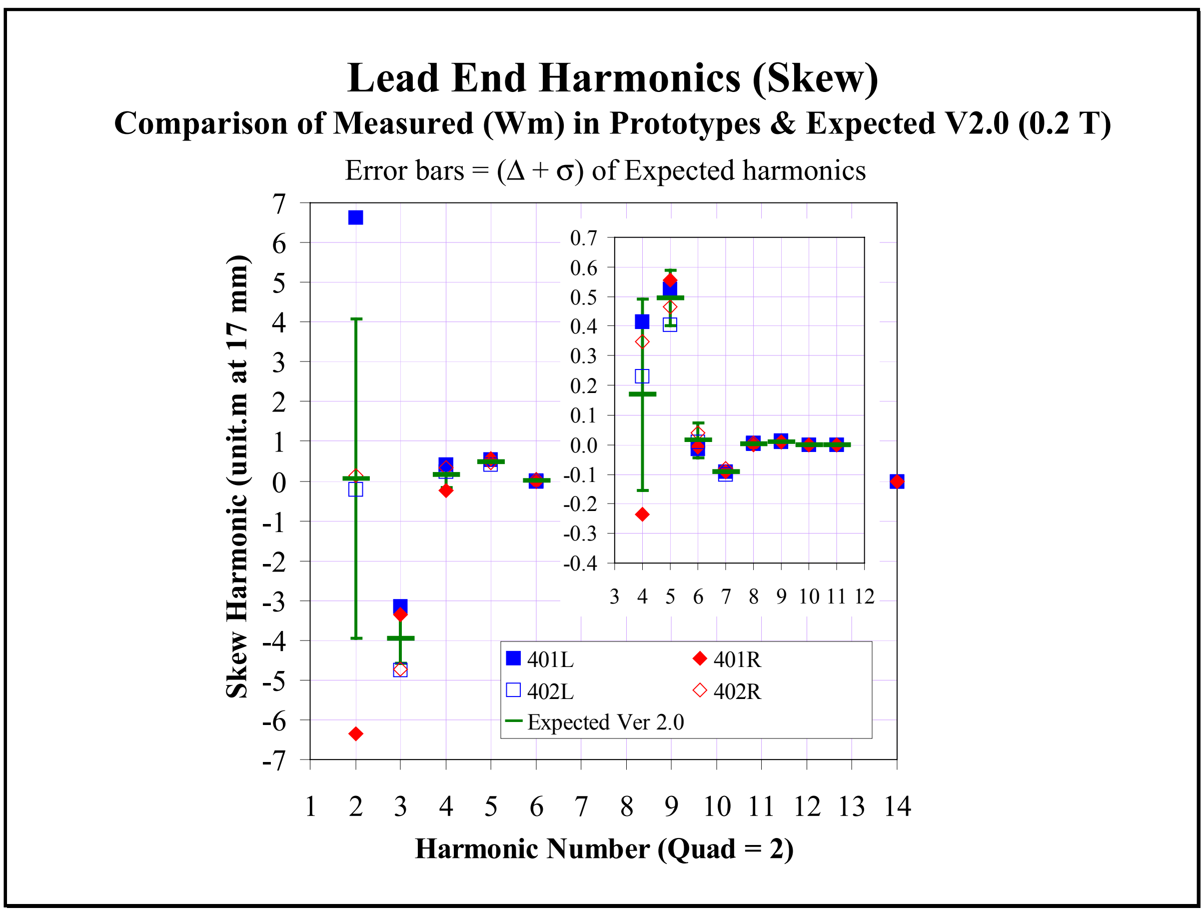


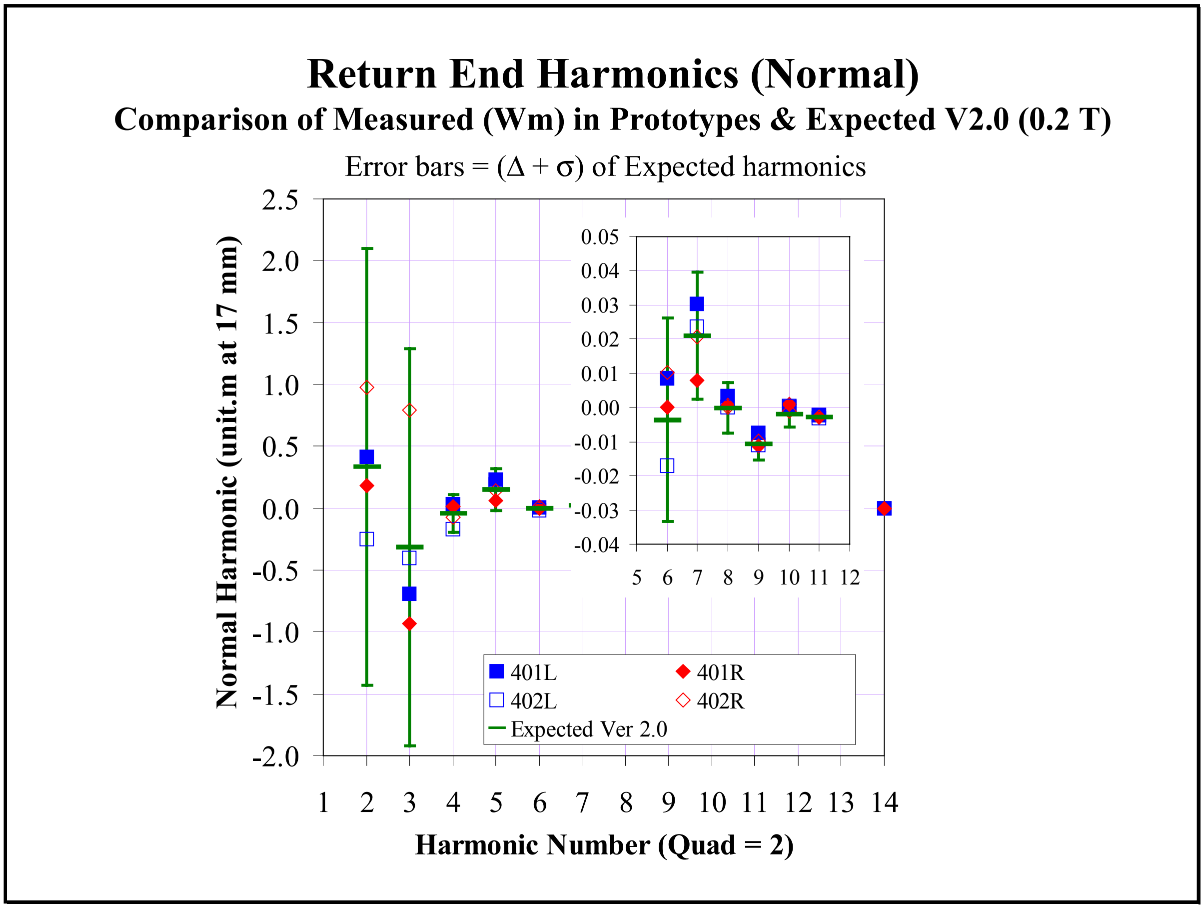
Body Harmonics (Skew) at 3.55 T Dipole Field

Measured in Prototypes Vs. Expected V2.0 (D4b unadjusted)




Lead End Harmonics (Normal)
Comparison of Measured (Wm) in Prototypes & Expected V2.0 (0.2 T)
Error bars = (Δ + σ) of Expected harmonics
Normal Harmonic (unit.m at 17 mm)
Harmonic Number (Quad = 2)
401L
401R
402L
402R
Expected Ver 2.0


Lead End Harmonics (Skew)
Comparison of Measured (Wm) in Prototypes & Expected V2.0 (0.2 T)
Error bars = (Δ + σ) of Expected harmonics
Skew Harmonic (unit.m at 17 mm)
Harmonic Number (Quad = 2)
401L
401R
402L
402R
Expected Ver 2.0


Return End Harmonics (Normal)
Comparison of Measured (Wm) in Prototypes & Expected V2.0 (0.2 T)
Error bars = (Δ + σ) of Expected harmonics
Normal Harmonic (unit.m at 17 mm)
Harmonic Number (Quad = 2)
401L
401R
402L
402R
Expected Ver 2.0

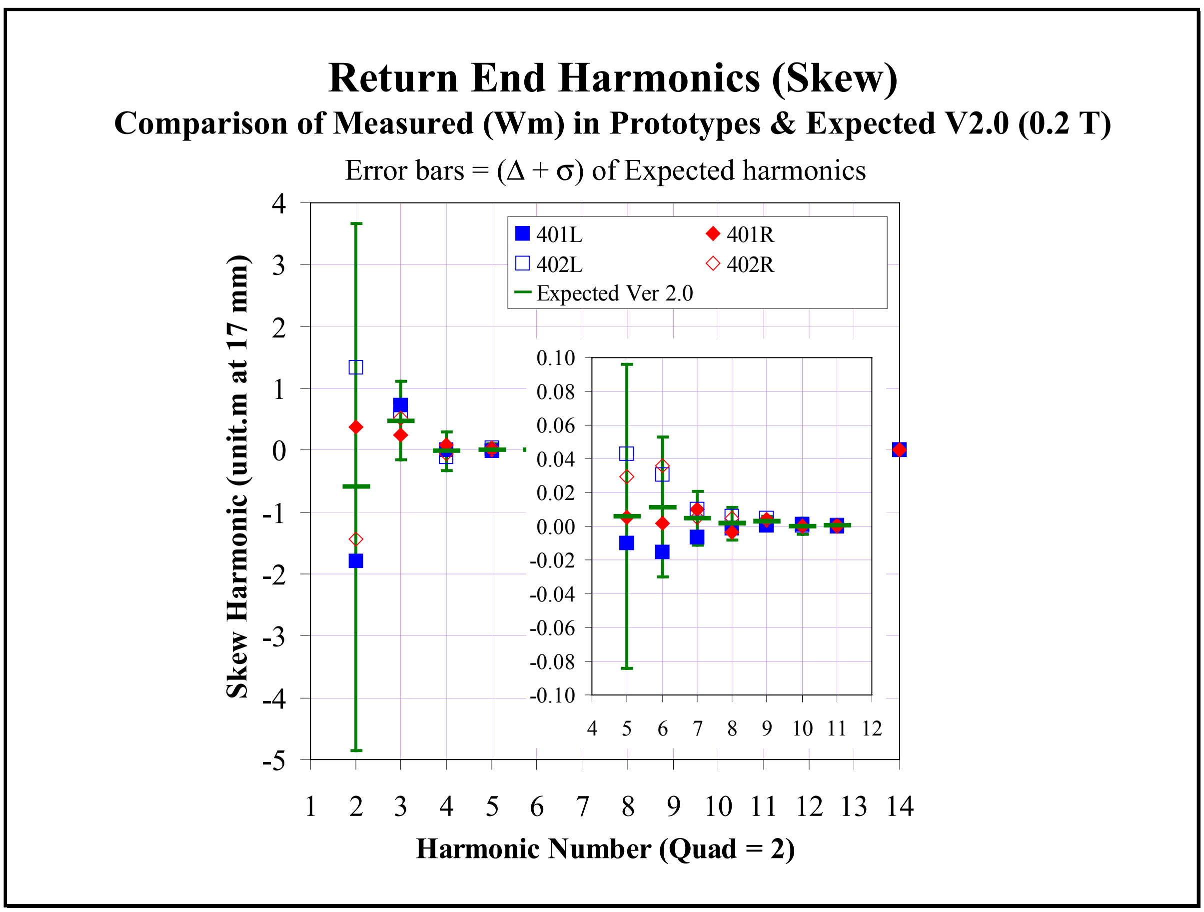

Return End Harmonics (Skew)
Comparison of Measured (Wm) in Prototypes & Expected V2.0 (0.2 T)
Error bars = (Δ + σ) of Expected harmonics
Skew Harmonic (unit.m at 17 mm)
Harmonic Number (Quad = 2)
401L
401R
402L
402R
Expected Ver 2.0

Table I. Expected Values of Body Harmonics in D4b Magnets (1.9 K; Alsthom Wire)

A. Body Harmonics at 17 mm, 0.2 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.263	0.762	0.427	–0.044	4.081	1.061
2(R)	–2.937	0.762	0.427	–0.044	4.081	1.061
3	–14.236	1.653	0.692	–0.316	0.348	0.204
4(L)	–0.028	0.114	0.063	–0.260	0.204	0.130
4(R)	–0.178	0.114	0.063	–0.260	0.204	0.130
5	0.237	0.258	0.182	0.045	0.054	0.039
6(L)	0.0066	0.0298	0.0180	0.0135	0.0974	0.0568
6(R)	–0.0228	0.0298	0.0180	0.0135	0.0974	0.0568
7	–0.0711	0.0218	0.0105	–0.0126	0.0080	0.0050
8(L)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
8(R)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
9	0.0105	0.0073	0.0046	0.0014	0.0015	0.0008
10	–0.0010	0.0024	0.0012	0.0007	0.0025	0.0014
11	–0.0181	0.0011	0.0005	0.0004	0.0005	0.0003

B. Body Harmonics at 17 mm, 3.55 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.373	0.373	0.222	–0.437	4.041	1.054
2(R)	–0.492	0.373	0.222	–0.437	4.041	1.054
3	–2.231	0.751	0.681	–0.385	0.299	0.197
4(L)	–0.052	0.092	0.057	–0.123	0.172	0.126
4(R)	–0.152	0.092	0.057	–0.123	0.172	0.126
5	–0.012	0.243	0.181	0.046	0.048	0.038
6(L)	–0.0004	0.0070	0.0037	–0.0022	0.0838	0.0558
6(R)	–0.0173	0.0070	0.0037	–0.0022	0.0838	0.0558
7	0.0106	0.0122	0.0102	–0.0106	0.0058	0.0047
8(L)	–0.0003	0.0021	0.0018	0.0009	0.0171	0.0113
8(R)	–0.0022	0.0021	0.0018	0.0009	0.0171	0.0113
9	–0.0040	0.0058	0.0046	0.0022	0.0009	0.0007
10	–0.0002	0.0016	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	0.0000	0.0006	0.0003

C. Body Harmonics at 17 mm, 3.8 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.352	0.367	0.220	–0.454	4.042	1.054
2(R)	–0.514	0.367	0.220	–0.454	4.042	1.054
3	–2.135	0.770	0.681	–0.389	0.317	0.198
4(L)	–0.011	0.091	0.057	–0.121	0.175	0.126
4(R)	–0.192	0.091	0.057	–0.121	0.175	0.126
5	–0.040	0.244	0.182	0.046	0.051	0.038
6(L)	0.0051	0.0067	0.0037	–0.0027	0.0840	0.0558
6(R)	–0.0229	0.0067	0.0037	–0.0027	0.0840	0.0558
7	0.0137	0.0121	0.0102	–0.0104	0.0062	0.0047
8(L)	0.0001	0.0023	0.0019	0.0007	0.0169	0.0113
8(R)	–0.0027	0.0023	0.0019	0.0007	0.0169	0.0113
9	–0.0041	0.0058	0.0046	0.0021	0.0010	0.0007
10	–0.0002	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	–0.0001	0.0006	0.0004

Table II. Expected Values of Body Harmonics in D4a Magnets (1.9 K, Oxford Wire)

A. Body Harmonics at 17 mm, 0.2 T, Up Ramp, 1.9 K, in D4a Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.246	2.128	0.427	0.010	4.081	1.061
2(R)	–2.892	2.128	0.427	0.010	4.081	1.061
3	–15.105	1.701	0.692	0.053	0.348	0.204
4(L)	–0.029	0.114	0.063	–0.276	0.204	0.130
4(R)	–0.180	0.114	0.063	–0.276	0.204	0.130
5	0.165	0.258	0.182	–0.008	0.054	0.039
6(L)	0.0079	0.0298	0.0180	0.0108	0.0974	0.0568
6(R)	–0.0216	0.0298	0.0180	0.0108	0.0974	0.0568
7	–0.0865	0.0222	0.0105	–0.0034	0.0080	0.0050
8(L)	–0.0024	0.0024	0.0019	–0.0008	0.0185	0.0116
8(R)	–0.0024	0.0024	0.0019	–0.0008	0.0185	0.0116
9	0.0116	0.0074	0.0046	–0.0001	0.0015	0.0008
10	–0.0007	0.0024	0.0012	0.0007	0.0025	0.0014
11	–0.0177	0.0011	0.0005	0.0004	0.0005	0.0003

B. Body Harmonics at 17 mm, 3.55 T, Up Ramp, 1.9 K in D4a Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.312	1.055	0.222	–0.546	4.041	1.054
2(R)	–0.334	1.055	0.222	–0.546	4.041	1.054
3	–3.297	0.753	0.681	–0.037	0.299	0.197
4(L)	–0.099	0.092	0.057	–0.151	0.172	0.126
4(R)	–0.109	0.092	0.057	–0.151	0.172	0.126
5	–0.111	0.243	0.181	–0.008	0.048	0.038
6(L)	–0.0045	0.0070	0.0037	–0.0068	0.0838	0.0558
6(R)	–0.0095	0.0070	0.0037	–0.0068	0.0838	0.0558
7	–0.0018	0.0122	0.0102	–0.0009	0.0058	0.0047
8(L)	–0.0010	0.0021	0.0018	0.0007	0.0171	0.0113
8(R)	–0.0022	0.0021	0.0018	0.0007	0.0171	0.0113
9	–0.0035	0.0058	0.0046	0.0007	0.0009	0.0007
10	–0.0001	0.0016	0.0010	–0.0001	0.0016	0.0010
11	–0.0127	0.0004	0.0002	0.0000	0.0006	0.0003

C. Body Harmonics at 17 mm, 3.8 T, Up Ramp, 1.9 K, in D4a Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.197	1.049	0.220	–0.563	4.042	1.054
2(R)	–0.449	1.049	0.220	–0.563	4.042	1.054
3	–3.303	0.772	0.681	–0.040	0.317	0.198
4(L)	–0.090	0.091	0.057	–0.149	0.175	0.126
4(R)	–0.118	0.091	0.057	–0.149	0.175	0.126
5	–0.169	0.244	0.182	–0.008	0.051	0.038
6(L)	–0.0049	0.0067	0.0037	–0.0073	0.0840	0.0558
6(R)	–0.0093	0.0067	0.0037	–0.0073	0.0840	0.0558
7	–0.0003	0.0121	0.0102	–0.0007	0.0062	0.0047
8(L)	–0.0011	0.0023	0.0019	0.0005	0.0169	0.0113
8(R)	–0.0023	0.0023	0.0019	0.0005	0.0169	0.0113
9	–0.0036	0.0058	0.0046	0.0006	0.0010	0.0007
10	–0.0001	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0126	0.0004	0.0002	0.0000	0.0006	0.0004

Table III. Expected Values of Body Harmonics in D2 Magnets (4.5 K, Oxford Wire)

A. Body Harmonics at 17 mm, 0.2 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.786	1.340	0.427	0.035	4.076	1.061
2(R)	–3.433	1.340	0.427	0.035	4.076	1.061
3	–10.928	0.866	0.692	0.032	0.344	0.204
4(L)	–0.029	0.113	0.063	–0.279	0.203	0.130
4(R)	–0.179	0.113	0.063	–0.279	0.203	0.130
5	0.179	0.256	0.182	–0.008	0.054	0.039
6(L)	0.0077	0.0298	0.0180	0.0112	0.0973	0.0568
6(R)	–0.0218	0.0298	0.0180	0.0112	0.0973	0.0568
7	–0.0525	0.0154	0.0105	–0.0033	0.0080	0.0050
8(L)	–0.0022	0.0024	0.0019	–0.0011	0.0184	0.0116
8(R)	–0.0022	0.0024	0.0019	–0.0011	0.0184	0.0116
9	0.0082	0.0067	0.0046	–0.0001	0.0015	0.0008
10	–0.0006	0.0024	0.0012	0.0006	0.0025	0.0014
11	–0.0158	0.0007	0.0005	0.0004	0.0005	0.0003

B. Body Harmonics at 17 mm, 3.55 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.226	0.701	0.222	–0.543	4.040	1.054
2(R)	–0.421	0.701	0.222	–0.543	4.040	1.054
3	–2.997	0.734	0.681	–0.037	0.299	0.197
4(L)	–0.052	0.092	0.057	–0.150	0.172	0.126
4(R)	–0.156	0.092	0.057	–0.150	0.172	0.126
5	–0.075	0.242	0.181	–0.008	0.048	0.038
6(L)	0.0023	0.0069	0.0037	–0.0070	0.0837	0.0558
6(R)	–0.0164	0.0069	0.0037	–0.0070	0.0837	0.0558
7	0.0010	0.0120	0.0102	–0.0009	0.0058	0.0047
8(L)	–0.0007	0.0021	0.0018	0.0007	0.0170	0.0113
8(R)	–0.0027	0.0021	0.0018	0.0007	0.0170	0.0113
9	–0.0035	0.0058	0.0046	0.0007	0.0009	0.0007
10	–0.0001	0.0015	0.0010	–0.0001	0.0016	0.0010
11	–0.0126	0.0004	0.0002	0.0000	0.0006	0.0003

C. Body Harmonics at 17 mm, 3.8 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$\langle b_n \rangle$	$\Delta(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.231	0.695	0.220	–0.561	4.042	1.054
2(R)	–0.416	0.695	0.220	–0.561	4.042	1.054
3	–2.870	0.755	0.681	–0.040	0.317	0.198
4(L)	–0.007	0.091	0.057	–0.148	0.175	0.126
4(R)	–0.201	0.091	0.057	–0.148	0.175	0.126
5	–0.096	0.244	0.182	–0.008	0.051	0.038
6(L)	0.0081	0.0067	0.0037	–0.0073	0.0840	0.0558
6(R)	–0.0222	0.0067	0.0037	–0.0073	0.0840	0.0558
7	0.0042	0.0120	0.0102	–0.0007	0.0062	0.0047
8(L)	–0.0003	0.0023	0.0019	0.0006	0.0169	0.0113
8(R)	–0.0030	0.0023	0.0019	0.0006	0.0169	0.0113
9	–0.0036	0.0058	0.0046	0.0006	0.0010	0.0007
10	–0.0001	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0126	0.0004	0.0002	–0.0001	0.0006	0.0004

Table IV. Expected Values of End Harmonics (unit.m) in D2/D4a/D4b Magnets

A. Lead End Harmonics (unit.m) at 17 mm, 0.2 T, Up Ramp, in D2/D4a/D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2	–0.468	1.466	0.651	0.068	2.887	1.138
3	6.232	1.308	0.490	–3.948	0.462	0.180
4	0.063	0.226	0.069	0.170	0.239	0.084
5	0.523	0.150	0.045	0.496	0.065	0.028
6	–0.0082	0.0363	0.0159	0.0144	0.0444	0.0138
7	0.1059	0.0105	0.0049	–0.0916	0.0125	0.0055
8	0.0022	0.0041	0.0017	0.0020	0.0050	0.0022
9	0.0025	0.0030	0.0011	0.0103	0.0025	0.0010
10	–0.0008	0.0023	0.0007	0.0000	0.0016	0.0005
11	–0.0015	0.0007	0.0003	–0.0006	0.0005	0.0002

B. Lead End Harmonics (unit.m) at 17 mm, 3.55 T/3.8 T, Up Ramp, in D2/D4a/D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2	–0.561	1.537	0.671	0.726	2.905	1.203
3	7.826	1.356	0.510	–3.908	0.468	0.181
4	0.059	0.229	0.071	0.236	0.237	0.092
5	0.486	0.147	0.047	0.491	0.064	0.027
6	–0.0045	0.0425	0.0174	0.0189	0.0423	0.0144
7	0.0920	0.0108	0.0048	–0.0942	0.0129	0.0057
8	0.0020	0.0043	0.0017	0.0016	0.0052	0.0022
9	0.0036	0.0035	0.0012	0.0107	0.0025	0.0010
10	–0.0007	0.0025	0.0008	0.0000	0.0013	0.0005
11	–0.0016	0.0007	0.0003	–0.0006	0.0005	0.0002

C. Return End Harmonics (unit.m) at 17 mm, 0.2 T, Up Ramp, in D2/D4a/D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2	0.337	1.314	0.451	–0.591	3.117	1.145
3	–0.316	1.114	0.490	0.475	0.483	0.152
4	–0.044	0.107	0.048	–0.018	0.214	0.092
5	0.148	0.122	0.047	0.006	0.067	0.023
6	–0.0036	0.0220	0.0077	0.0113	0.0301	0.0115
7	0.0209	0.0128	0.0058	0.0046	0.0117	0.0044
8	–0.0001	0.0056	0.0019	0.0015	0.0071	0.0024
9	–0.0107	0.0031	0.0014	0.0031	0.0020	0.0009
10	–0.0020	0.0026	0.0011	–0.0002	0.0032	0.0015
11	–0.0028	0.0007	0.0003	0.0004	0.0005	0.0002

D. Return End Harmonics (unit.m) at 17 mm, 3.55 T/3.8 T, Up Ramp, in D2/D4a/D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2	–0.473	1.228	0.450	0.301	3.061	1.300
3	1.059	1.233	0.537	0.615	0.477	0.156
4	–0.035	0.114	0.050	0.028	0.231	0.098
5	0.155	0.142	0.049	0.021	0.066	0.023
6	–0.0130	0.0246	0.0091	0.0251	0.0355	0.0143
7	0.0069	0.0130	0.0062	0.0026	0.0122	0.0045
8	0.0017	0.0047	0.0017	0.0001	0.0072	0.0025
9	–0.0084	0.0035	0.0015	0.0039	0.0022	0.0008
10	–0.0004	0.0024	0.0011	0.0001	0.0031	0.0014
11	–0.0029	0.0007	0.0003	0.0004	0.0004	0.0002

Table V. Expected Values of Integral Harmonics in D4b Magnets (1.9 K, Alsthom Wire)

A. Integral Harmonics at 17 mm, 0.2 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.263	0.762	0.427	–0.044	4.081	1.061
2(R)	–2.937	0.762	0.427	–0.044	4.081	1.061
3	–14.236	1.653	0.692	–0.316	0.348	0.204
4(L)	–0.028	0.114	0.063	–0.260	0.204	0.130
4(R)	–0.178	0.114	0.063	–0.260	0.204	0.130
5	0.237	0.258	0.182	0.045	0.054	0.039
6(L)	0.0066	0.0298	0.0180	0.0135	0.0974	0.0568
6(R)	–0.0228	0.0298	0.0180	0.0135	0.0974	0.0568
7	–0.0711	0.0218	0.0105	–0.0126	0.0080	0.0050
8(L)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
8(R)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
9	0.0105	0.0073	0.0046	0.0014	0.0015	0.0008
10	–0.0010	0.0024	0.0012	0.0007	0.0025	0.0014
11	–0.0181	0.0011	0.0005	0.0004	0.0005	0.0003

B. Integral Harmonics at 17 mm, 3.55 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.373	0.373	0.222	–0.437	4.041	1.054
2(R)	–0.492	0.373	0.222	–0.437	4.041	1.054
3	–2.231	0.751	0.681	–0.385	0.299	0.197
4(L)	–0.052	0.092	0.057	–0.123	0.172	0.126
4(R)	–0.152	0.092	0.057	–0.123	0.172	0.126
5	–0.012	0.243	0.181	0.046	0.048	0.038
6(L)	–0.0004	0.0070	0.0037	–0.0022	0.0838	0.0558
6(R)	–0.0173	0.0070	0.0037	–0.0022	0.0838	0.0558
7	0.0106	0.0122	0.0102	–0.0106	0.0058	0.0047
8(L)	–0.0003	0.0021	0.0018	0.0009	0.0171	0.0113
8(R)	–0.0022	0.0021	0.0018	0.0009	0.0171	0.0113
9	–0.0040	0.0058	0.0046	0.0022	0.0009	0.0007
10	–0.0002	0.0016	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	0.0000	0.0006	0.0003

C. Integral Harmonics at 17 mm, 3.8 T, Up Ramp, 1.9 K, in D4b Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.352	0.367	0.220	–0.454	4.042	1.054
2(R)	–0.514	0.367	0.220	–0.454	4.042	1.054
3	–2.135	0.770	0.681	–0.389	0.317	0.198
4(L)	–0.011	0.091	0.057	–0.121	0.175	0.126
4(R)	–0.192	0.091	0.057	–0.121	0.175	0.126
5	–0.040	0.244	0.182	0.046	0.051	0.038
6(L)	0.0051	0.0067	0.0037	–0.0027	0.0840	0.0558
6(R)	–0.0229	0.0067	0.0037	–0.0027	0.0840	0.0558
7	0.0137	0.0121	0.0102	–0.0104	0.0062	0.0047
8(L)	0.0001	0.0023	0.0019	0.0007	0.0169	0.0113
8(R)	–0.0027	0.0023	0.0019	0.0007	0.0169	0.0113
9	–0.0041	0.0058	0.0046	0.0021	0.0010	0.0007
10	–0.0002	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	–0.0001	0.0006	0.0004

Table VI. Expected Values of Integral Harmonics in D4a Magnets (1.9 K, Oxford Wire)

A. Integral Harmonics at 17 mm, 0.2 T, Up Ramp, 1.9 K, in D4a Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.232	2.128	0.427	–0.045	4.081	1.061
2(R)	–2.906	2.128	0.427	–0.045	4.081	1.061
3	–14.479	1.701	0.692	–0.314	0.348	0.204
4(L)	–0.028	0.114	0.063	–0.260	0.204	0.130
4(R)	–0.178	0.114	0.063	–0.260	0.204	0.130
5	0.236	0.258	0.182	0.045	0.054	0.039
6(L)	0.0067	0.0298	0.0180	0.0135	0.0974	0.0568
6(R)	–0.0228	0.0298	0.0180	0.0135	0.0974	0.0568
7	–0.0731	0.0222	0.0105	–0.0127	0.0080	0.0050
8(L)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
8(R)	–0.0021	0.0024	0.0019	–0.0005	0.0185	0.0116
9	0.0107	0.0074	0.0046	0.0014	0.0015	0.0008
10	–0.0010	0.0024	0.0012	0.0007	0.0025	0.0014
11	–0.0182	0.0011	0.0005	0.0004	0.0005	0.0003

B. Integral Harmonics at 17 mm, 3.55 T, Up Ramp, 1.9 K, in D4a Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.422	1.055	0.222	–0.437	4.041	1.054
2(R)	–0.444	1.055	0.222	–0.437	4.041	1.054
3	–2.357	0.753	0.681	–0.385	0.299	0.197
4(L)	–0.097	0.092	0.057	–0.123	0.172	0.126
4(R)	–0.107	0.092	0.057	–0.123	0.172	0.126
5	–0.043	0.243	0.181	0.046	0.048	0.038
6(L)	–0.0063	0.0070	0.0037	–0.0022	0.0838	0.0558
6(R)	–0.0113	0.0070	0.0037	–0.0022	0.0838	0.0558
7	0.0087	0.0122	0.0102	–0.0106	0.0058	0.0047
8(L)	–0.0007	0.0021	0.0018	0.0009	0.0171	0.0113
8(R)	–0.0018	0.0021	0.0018	0.0009	0.0171	0.0113
9	–0.0040	0.0058	0.0046	0.0022	0.0009	0.0007
10	–0.0002	0.0016	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	0.0000	0.0006	0.0003

C. Integral Harmonics at 17 mm, 3.8 T, Up Ramp, 1.9 K, in D4a Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.307	1.049	0.220	–0.454	4.042	1.054
2(R)	–0.559	1.049	0.220	–0.454	4.042	1.054
3	–2.363	0.772	0.681	–0.389	0.317	0.198
4(L)	–0.087	0.091	0.057	–0.121	0.175	0.126
4(R)	–0.116	0.091	0.057	–0.121	0.175	0.126
5	–0.102	0.244	0.182	0.046	0.051	0.038
6(L)	–0.0067	0.0067	0.0037	–0.0027	0.0840	0.0558
6(R)	–0.0111	0.0067	0.0037	–0.0027	0.0840	0.0558
7	0.0102	0.0121	0.0102	–0.0104	0.0062	0.0047
8(L)	–0.0007	0.0023	0.0019	0.0007	0.0169	0.0113
8(R)	–0.0019	0.0023	0.0019	0.0007	0.0169	0.0113
9	–0.0041	0.0058	0.0046	0.0021	0.0010	0.0007
10	–0.0002	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0130	0.0004	0.0002	–0.0001	0.0006	0.0004

Table VII. Expected Values of Integral Harmonics in D2 Magnets (4.5 K, Oxford Wire)

A. Integral Harmonics at 17 mm, 0.2 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	2.772	1.340	0.427	–0.021	4.076	1.061
2(R)	–3.447	1.340	0.427	–0.021	4.076	1.061
3	–10.302	0.866	0.692	–0.335	0.344	0.204
4(L)	–0.027	0.113	0.063	–0.263	0.203	0.130
4(R)	–0.177	0.113	0.063	–0.263	0.203	0.130
5	0.250	0.256	0.182	0.045	0.054	0.039
6(L)	0.0064	0.0298	0.0180	0.0140	0.0973	0.0568
6(R)	–0.0230	0.0298	0.0180	0.0140	0.0973	0.0568
7	–0.0391	0.0154	0.0105	–0.0125	0.0080	0.0050
8(L)	–0.0020	0.0024	0.0019	–0.0007	0.0184	0.0116
8(R)	–0.0020	0.0024	0.0019	–0.0007	0.0184	0.0116
9	0.0073	0.0067	0.0046	0.0013	0.0015	0.0008
10	–0.0009	0.0024	0.0012	0.0006	0.0025	0.0014
11	–0.0162	0.0007	0.0005	0.0004	0.0005	0.0003

B. Integral Harmonics at 17 mm, 3.55 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.335	0.701	0.222	–0.435	4.040	1.054
2(R)	–0.530	0.701	0.222	–0.435	4.040	1.054
3	–2.057	0.734	0.681	–0.385	0.299	0.197
4(L)	–0.049	0.092	0.057	–0.122	0.172	0.126
4(R)	–0.154	0.092	0.057	–0.122	0.172	0.126
5	–0.007	0.242	0.181	0.046	0.048	0.038
6(L)	0.0004	0.0069	0.0037	–0.0024	0.0837	0.0558
6(R)	–0.0182	0.0069	0.0037	–0.0024	0.0837	0.0558
7	0.0115	0.0120	0.0102	–0.0106	0.0058	0.0047
8(L)	–0.0003	0.0021	0.0018	0.0009	0.0170	0.0113
8(R)	–0.0023	0.0021	0.0018	0.0009	0.0170	0.0113
9	–0.0040	0.0058	0.0046	0.0022	0.0009	0.0007
10	–0.0002	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	0.0000	0.0006	0.0003

C. Integral Harmonics at 17 mm, 3.8 T, Up Ramp, 4.5 K, in D2 Magnets (Ver. 2.0)

n	$<b_n>$	$\Delta(b_n)$	$\sigma(b_n)$	$<a_n>$	$\Delta(a_n)$	$\sigma(a_n)$
2 (L)	–0.340	0.695	0.220	–0.452	4.042	1.054
2(R)	–0.525	0.695	0.220	–0.452	4.042	1.054
3	–1.930	0.755	0.681	–0.389	0.317	0.198
4(L)	–0.004	0.091	0.057	–0.119	0.175	0.126
4(R)	–0.199	0.091	0.057	–0.119	0.175	0.126
5	–0.029	0.244	0.182	0.046	0.051	0.038
6(L)	0.0062	0.0067	0.0037	–0.0027	0.0840	0.0558
6(R)	–0.0240	0.0067	0.0037	–0.0027	0.0840	0.0558
7	0.0146	0.0120	0.0102	–0.0104	0.0062	0.0047
8(L)	0.0001	0.0023	0.0019	0.0008	0.0169	0.0113
8(R)	–0.0027	0.0023	0.0019	0.0008	0.0169	0.0113
9	–0.0041	0.0058	0.0046	0.0022	0.0010	0.0007
10	–0.0002	0.0015	0.0010	0.0000	0.0016	0.0010
11	–0.0131	0.0004	0.0002	–0.0001	0.0006	0.0004