DAΦNE TECHNICAL NOTE

INFN - LNF, Accelerator Division

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Note: **MM-10**

FIELD QUALITY OF THE SMALL QUADRUPOLES FOR THE DAΦNE MAIN RINGS

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1. Introduction

The field quality of 60 "small" quadrupoles of the same kind of those installed in the DAΦNE Accumulator [1,2] has been measured to check if each magnet meets the Specifications and to obtain the high order harmonic distributions for beam tracking simulations.

The measurements have been performed by means of the DANFYSIK rotating coil system [3]. The integrated gradient, the average value of the field deviation from the pure quadrupole component at the boundary of the good field region (30 mm from the magnet axis) and the contribution of each individual high order component have been measured at five different excitation currents (corresponding roughly to 2, 4, 8, 12 and 15 T/m).

The position of the magnetic center has also been recorded with respect to the reference optical devices placed on top of the magnets. The mechanical center positions, however, have not yet been measured for lack of time, and therefore the distance between magnetic and mechanical centres is not yet available. This important part of the magnet characterisation, which takes into account the tilt of the magnet axis (not detectable by the rotating coil system) will be performed as soon as possible by the Alignment Group.

This Technical Note contains all the measured values for the 60 quadrupoles. A discussion of the results is given in the text, together with the most significant plots and tables. The measured values for each magnet at the above mentioned excitation currents are given in the Appendix. Although the measurement have been performed up to ≈15 T/m, the gradients on the nominal working points of the DAΦNE Main Rings never exceed ≈9 T/m. For sake of simplicity, we show therefore the distributions at 8 T/m, and, when useful, at the maximum current, where there is a small amount of saturation.

2. Integrated gradient

The measurements have been performed by setting the power supplies always at the same nominal values, and the current detected by means of the precision DCCT system of the DANFYSIK system. The measured readings are constant within $\approx 10^{-5}$, much less than the measured width of the distributions, mainly due to small differences in steel length between the magnets. We recall, however, that each quadrupole in the Main Rings has its own power supply and can therefore be calibrated individually. Figure 1 shows the average gradient as a function of the excitation current. Since the r.m.s. width of the distribution is too small to be seen in the Figure, it is given in Table I. Figure 2 shows the distribution of the measured gradients at ≈8 T/m (the magnetic length of the magnets is ≈30 cm [1]).

TABLE I - Integrated gradients and distribution widths

Current (A)	$\int$ Gdl (T)	r.m.s. (T)	r.m.s. (%)
65.36	0.60048	0.00064	0.11
130.65	1.19950	0.00120	0.10
262.29	2.39980	0.00190	0.08
401.76	3.54130	0.00530	0.15
587.45	4.46600	0.00550	0.12

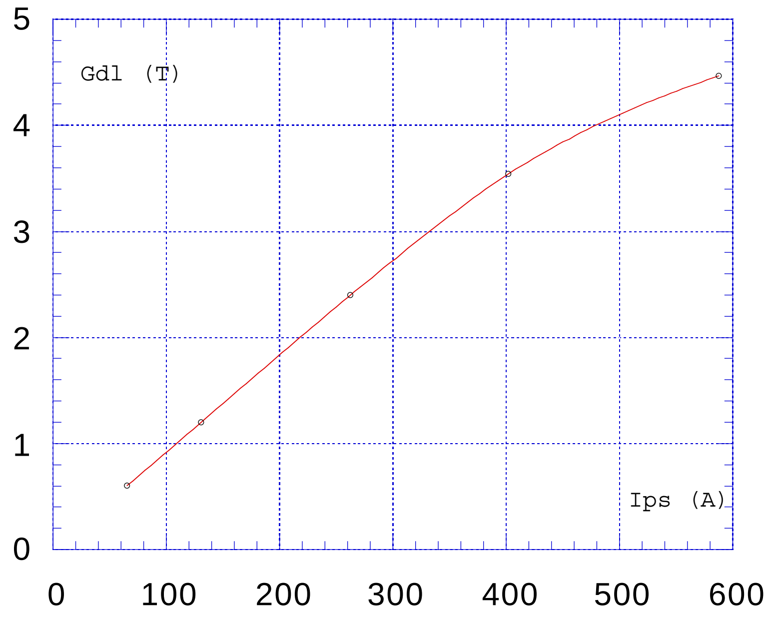

Fig. 1 - Average integrated gradient versus excitation current.

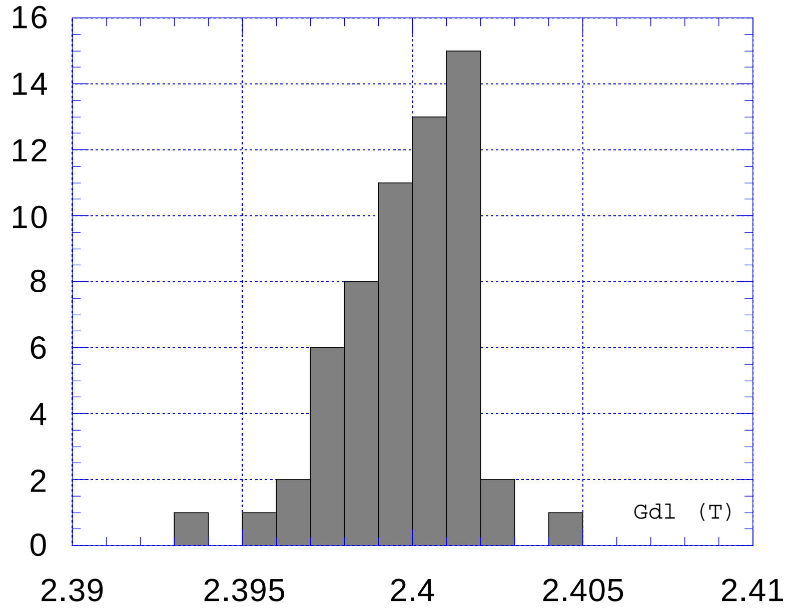

Fig. 2 - Integrated gradient distribution (262.29 A).

2. Average deviation from the ideal field

The Specification for the field quality has been set as $5x10^{-4}$ at the boundary of the good field region (a circle of 30 mm radius around the magnet axis) up to 12 T/m. Of course, the rotating coil system checks the integrated field only. In order to verify that the Specification is met for all the magnets, the output of the rotating coil system has been used as an input deck for a computer code, whose output consists in a Table which lists the field contribution of each harmonic component at 30 mm from the axis, its phase and the ratio between the absolute value of the component and the main quadrupole one, always at 30 mm. In addition, the code computes the sum of all high order radial components, as well as the azimuthal ones, and takes their vector sum, divided by the main quadrupole component, in steps of two degrees along the azimuthal coordinate. The result is the overall deviation from the ideal field, and it is given as a plot, like that shown in Fig. 3.

There are two possibilities of checking that all the magnets meet the Specification: the first one is to require that the average value of the full line in Fig. 3 (|B|) on the circle of 30 mm radius be less than $5x10^{-4}$. The distribution of this average value among the 60 quadrupoles is shown in Fig. 4, from which it can be seen that only two magnets do not meet the Specification (Serial #17 with $5.3x10^{-4}$ and Serial #42 with $5.5x10^{-4}$). All the magnets are within the prescribed limit at 8 T/m (see Fig. 5). A more stringent interpretation of the Specification is that the $5x10^{-4}$ limit be not exceeded at any azimuth in Fig. 3. In this case there 11 quadrupoles outside the limit, as shown in the following Table II.

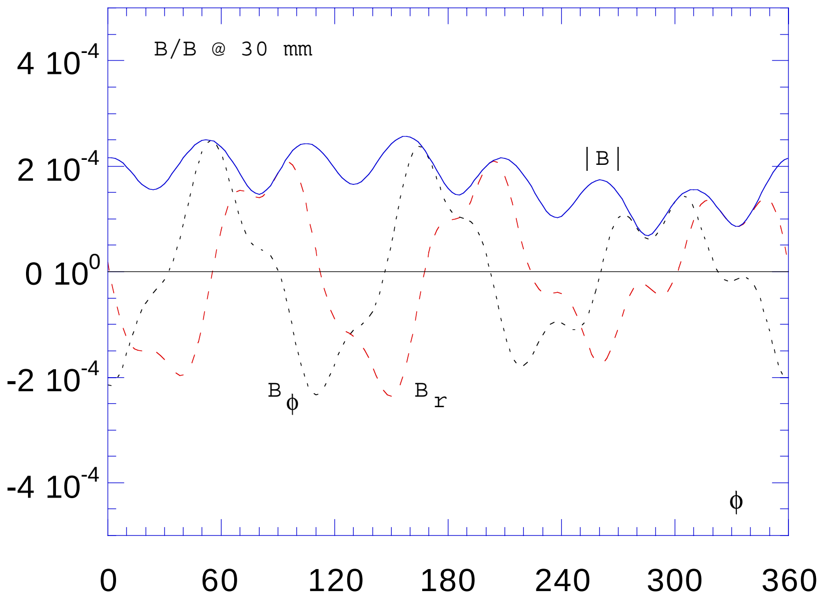

Fig. 3 - Field quality of Quadrupole Serial #49 at 130.658A.

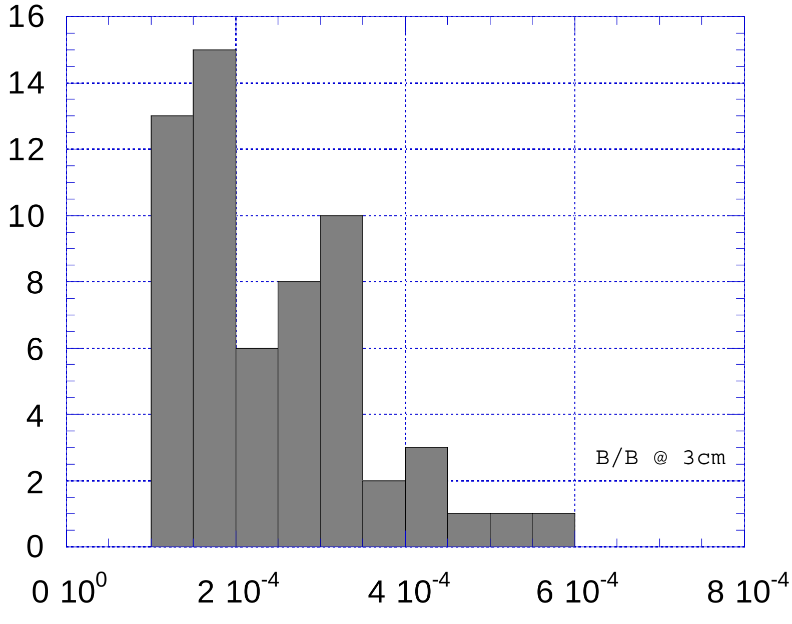

Fig. 4 - Distribution of the average field error at the boundary of the good field region @ 12 T/m.

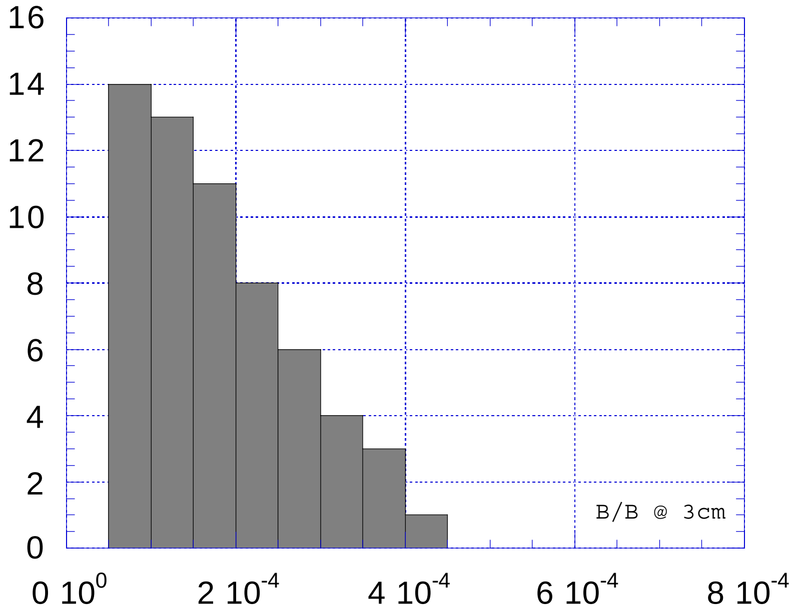

Fig. 5 - Distribution of the average field error at the boundary of the good field region @ 8 T/m.

As it can be observed from Table II, there is a larger contribution to the maximum deviation at high excitation current, which comes from saturation. As explained in detail in the next paragraph, this contribution comes mainly from the sextupole component, which can be split in two parts: the first one depends on the magnet shape, and can be observed at low excitation current, while the second comes from saturation, and becomes dominant at high current. In some cases these two contributions are in phase, and in others they tend to cancel out, and this explains why for few quads the limit is exceeded at low current and in most others at high current. The behaviour of the average deviation from the ideal field at the boundary of the good field region is shown in Fig. 6 versus the excitation current. The error bars are the r.m.s. deviation from the average (the distributions are not Gaussian).

TABLE II - Maximum fractional deviation from the ideal field at 30 mm (units of 10^{-4})

Serial #	2 T/m	4 T/m	8 T/m	12 T/m
3	6.0			
17				6.8
20	5.2	5.1	5.1	
21	6.0	6.1	5.5	5.8
22	5.4	5.7	5.5	6.0
23	5.2	5.5		
26				5.3
27				5.4
34				6.7
38				6.3
42				7.4
43				5.2
44	5.4			5.4
57				6.0

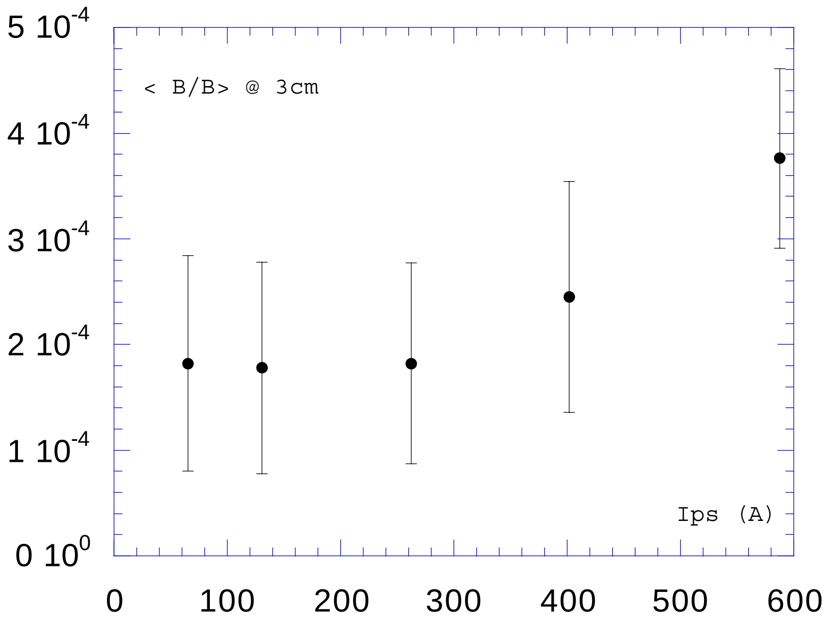

Fig. 6 - Average deviation from the ideal field versus excitation current (error bars are the r.m.s widths of the non Gaussian distributions).

3. Sextupole term

The sensitivity of the DANFYSIK rotating coil system to the high order components in the field is specified as $3x10^{-4}$. The sensitivity, whose lower limit is set by the overall noise in the system, improves with the order of the multipole. The above quoted limit refers to the radius of the coil (49 mm): scaling to the radius of the good field region (30 mm), the sensitivity to the sextupole contribution drops to $\approx 1.1x10^{-4}$. Of course, the limit is lower for higher multipole components. It is important to take the sensitivity into account because the sextupole contribution is in most cases the largest one. To make sure that this contribution does not come from noise in the measuring system, we have reported in the Appendix a Table (Table A4), showing the phase of the sextupole term as a function of the excitation current. It can be seen from that Table that the phase does not change significantly up to 8 T/m (262 A). For higher currents, saturation in the iron brings in an additional sextupole term (see also Fig. 9), with a different phase. The few magnets, where the phase changes by a substantial amount even at low current, are those where the absolute value of the sextupole contribution (reported in Table A3 in the Appendix) is of the order of the sensitivity ($\approx 10^{-4}$).

Figure 7 shows the distribution of the sextupole term at 8 T/m, Fig. 8 is the same at the maximum gradient of 15 T/m, while Fig. 9 gives the average value and the r.m.s. width of the distribution as a function of the excitation current.

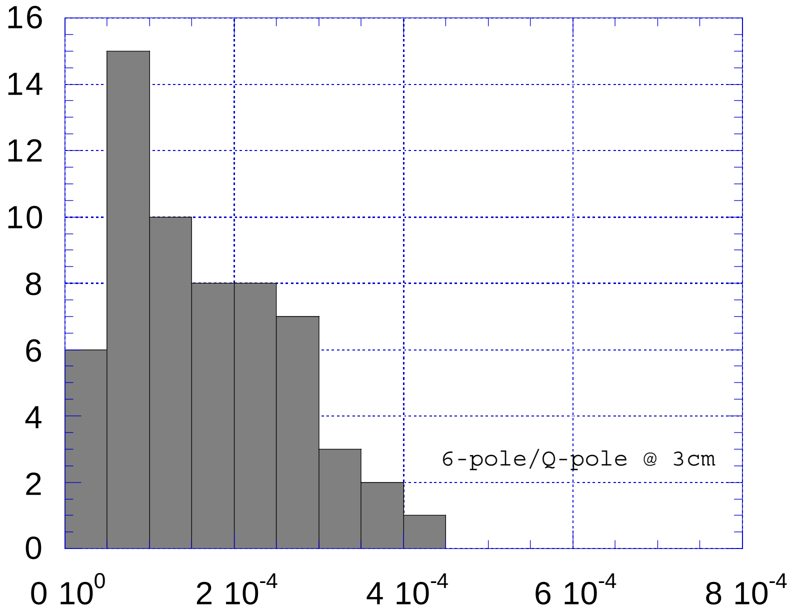

Fig. 7 - Distribution of the sextupole component at 8 T/m.

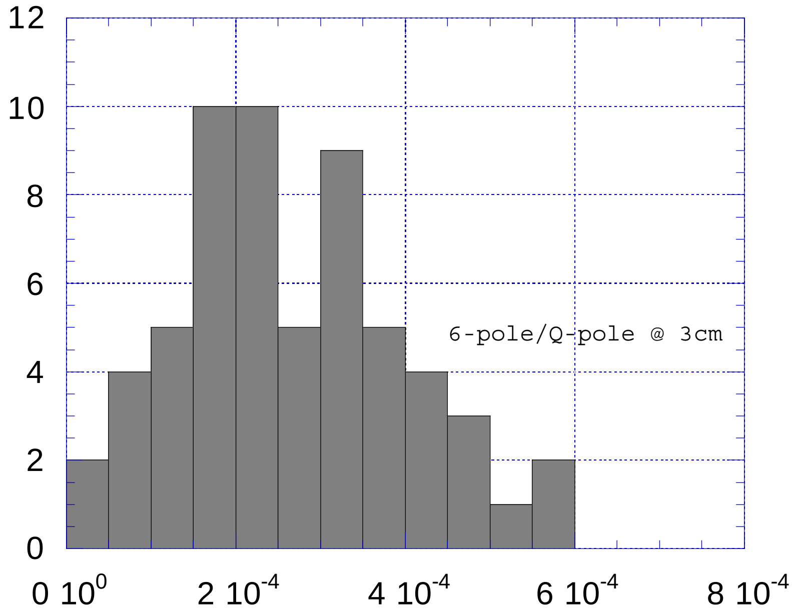

Fig. 8 - Distribution of the sextupole component at 15 T/m.

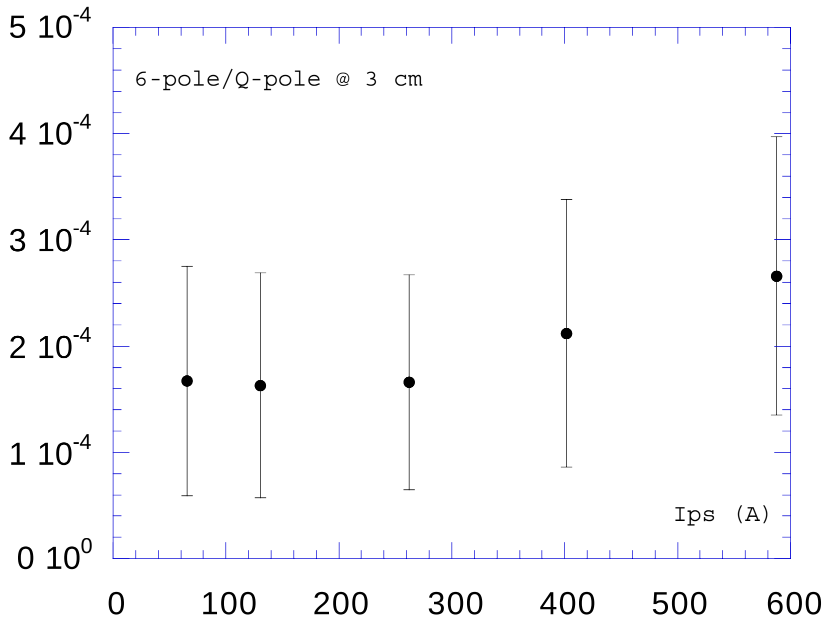

Fig. 9 - Sextupole contribution on the boundary of the good field region.

4. Octupole and decapole terms

The contribution of the octupole term to the overall deviation is very small, of the order of the expected sensitivity. We find an average value, independent from the excitation current, of $\approx(5.2\pm3.5)\times10^{-5}$.

The same happens for the decapole term, again in the order of the expected sensitivity. We find $\approx(1.9\pm1.3)\times10^{-5}$. In both cases, the multipole phase is distributed at random; we conclude therefore that the octupole and decapole contributions are smaller than the sensitivity of the measuring system.

5. Twelve-pole term

The 12-pole term is a systematic high order component, with the same symmetry of the main quadrupole term. Its contribution to the overall deviation from the ideal field has been minimised by chamfering the end caps of the poles in the prototype magnet [1]. The depth of the chamfer has been optimised at 8 T/m: at higher excitation currents the contribution of the 12-pole becomes larger, although well within the Specification, as shown in Fig. 10. The systematic nature of this high order harmonic appears clearly in the same figure from the small error bars around the average points, which represent the r.m.s. width of the distributions, in this case similar to Gaussians (see Fig. 11). In the saturation region, where the 12-pole contribution becomes significant, the phase of the harmonic is opposite to the main quadrupole one.

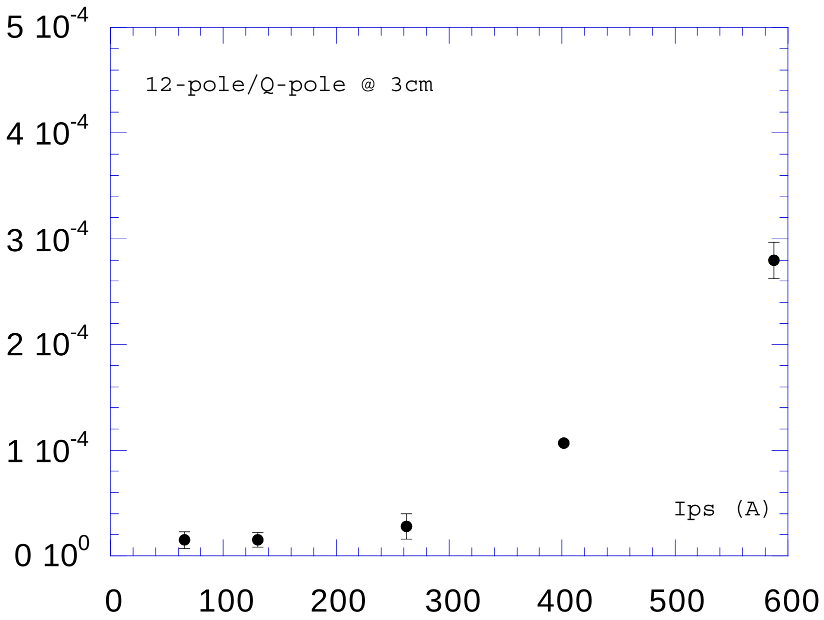

Fig. 10 - Average 12-polar deviation from the ideal field versus excitation current (error bars are the r.m.s widths of the Gaussian-like distributions).

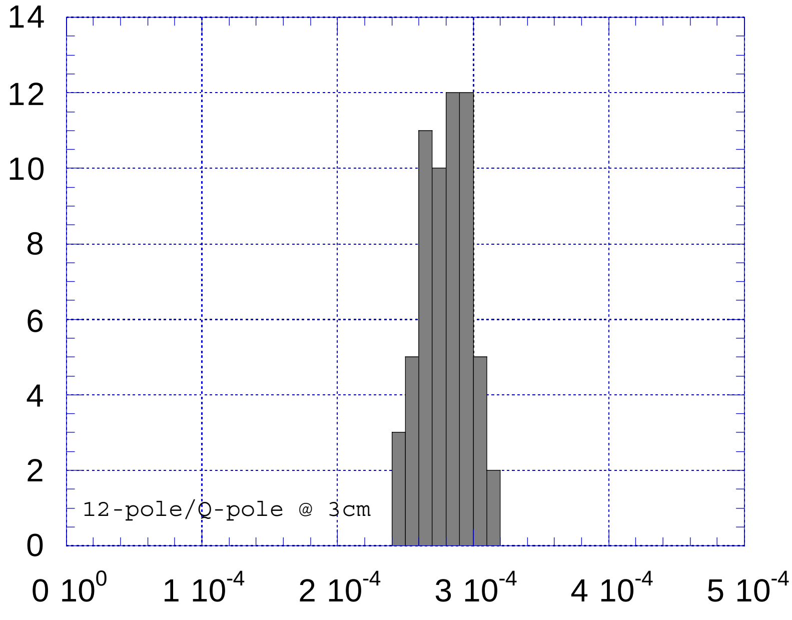

Fig. 11 - Distribution of the 12-pole term at 15 T/m.

6. Twenty-pole term

As well as the 12-pole term, also the 20-pole is a systematic high order harmonic with the same symmetry of the main quadrupole component. In our quadrupoles this component is very small ($\approx 5\times10^{-5}$), but larger than the sensitivity of the measurement system.

Figure 12 shows the average 20-pole component versus the excitation current on an expanded vertical scale. The increase with saturation is clearly larger than the width of the distribution. Also in this case the distribution is Gaussian-like (see Fig. 13). The phase is always opposite to the main quadrupole one.

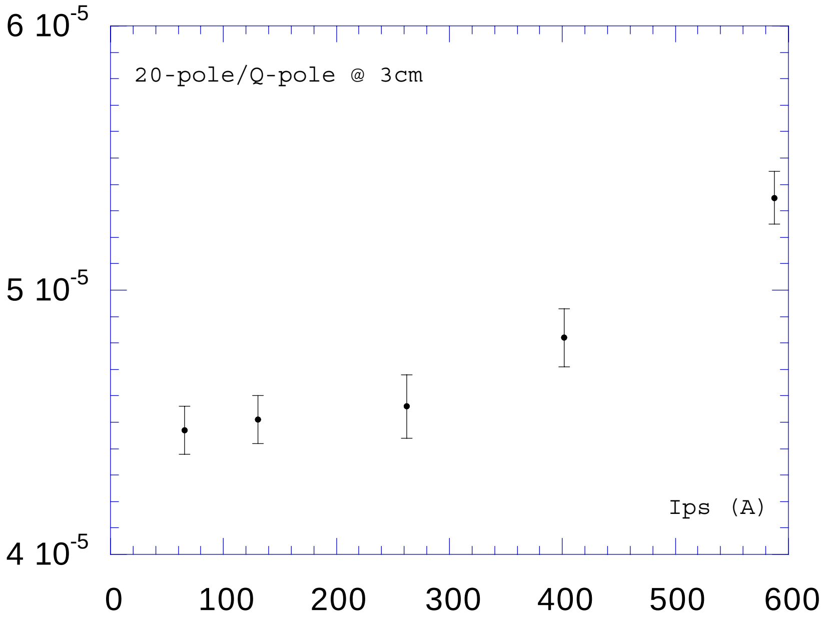

Fig. 12 - 20-pole contribution at 3 cm from the axis (expanded scale).

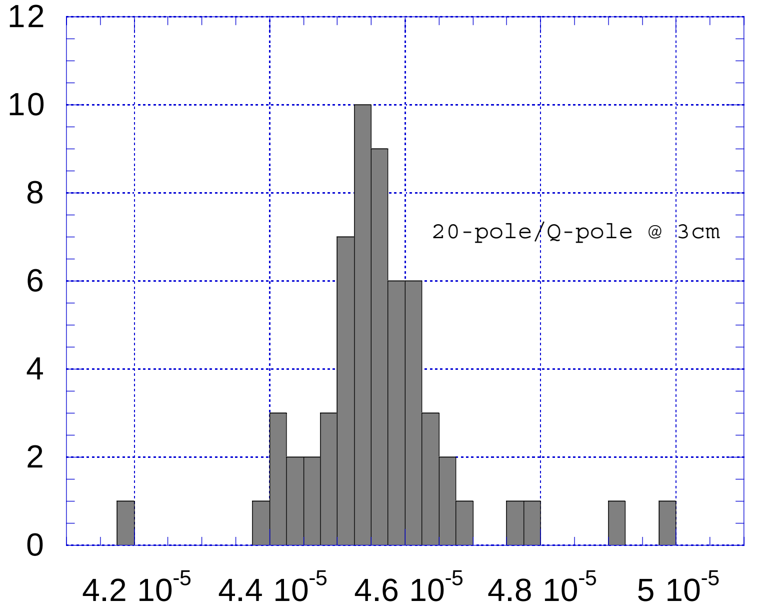

Fig. 13 - 20-pole distribution at 8 T/m (expanded scale).

7. Conclusions

The Specification on the small Main Ring quadrupole field quality is practically always met at the gradients foreseen on the nominal operating points of DAΦNE. Table II can be used to arrange the magnets in the rings in such a way that those quads where the tolerance is exceeded by the largest amount are employed where low gradients are required.

Although from the results reported in this paper it is possible to simulate the real machine with errors, it seems more practical to assume the average values of the high order multipoles as systematic errors and the widths of the distribution as random ones. Table III summarises these values (averaged over the three lower excitation currents), to be used in a simulation tracking program.

TABLE III - Systematic and random multipoles
(expressed as fraction of main quadrupole field at 30 mm, units of 10^{-4})

Multipole	Systematic	Phase (deg)	Random (rms)	Phase (deg)
6-pole	1.65	random	1.05	random
12-pole	0.20	random	0.10	random
20-pole	0.45	180	0.01	180

References

1 B. Bolli, F. Iungo, M. Modena, M. Preger, C. Sanelli, F. Sgamma, M. Troiani, S. Vescovi "Measurements on TESLA quadrupole prototype for the DAΦNE Accumulator and Main Rings" - DAΦNE Technical Note MM-4 (2/12/1994).

2 B. Bolli, F. Iungo, F. Losciale, M. Paris, M. Preger, C. Sanelli, F. Sardone, F. Sgamma, M. Troiani "Field quality and alignment of the DAΦNE Accumulator quadrupoles" - DAΦNE Technical Note MM-8 (21/8/1995).

3 F. Iungo, M. Modena, Q. Qiao, C. Sanelli "DAΦNE magnetic measurement systems" - DAΦNE Technical Note MM-1 (2/12/1994).

APPENDIX

TABLE A1 - Integrated gradients (T)

Serial #	65.36A	130.65A	363.39A	401.76A	587.45A
1	0.59991	1.19818	2.39655	3.53016	4.45714
2	0.60067	1.19980	2.39916	3.53296	4.45924
3	0.59734	1.19399	2.40024	3.54161	4.45621
4	0.60105	1.20046	2.40114	3.53531	4.46225
5	0.60120	1.20102	2.40232	3.53778	4.46354
6	0.60083	1.19996	2.40080	3.53649	4.46227
7	0.60083	1.20025	2.40127	3.53791	4.46976
8	0.60071	1.19981	2.39978	3.53523	4.46179
9	0.60061	1.19968	2.40005	3.53598	4.46802
10	0.60072	1.19977	2.39981	3.53555	4.46225
11	0.60064	1.19968	2.39996	3.53460	4.46019
12	0.60006	1.19981	2.39960	3.53613	4.45844
13	0.60014	1.19876	2.39838	3.53253	4.45560
14	0.60096	1.20034	2.40063	3.53547	4.46076
15	0.60093	1.20014	2.40063	3.53798	4.46386
16	0.60097	1.20038	2.40047	3.53627	4.46290
17	0.60100	1.20033	2.40153	3.53864	4.46246
18	0.60006	1.19857	2.39779	3.54475	4.46859
19	0.59999	1.19858	2.39777	3.54356	4.46560
20	0.59935	1.19718	2.39512	3.53802	4.46080
21	0.60007	1.19870	2.39774	3.53930	4.46353
22	0.59924	1.19701	2.39376	3.53525	4.45885
23	0.60009	1.19874	2.39829	3.54656	4.47081
24	0.59989	1.19855	2.39740	3.54336	4.46527
25	0.60024	1.19923	2.39869	3.54585	4.46705
26	0.60026	1.19898	2.39803	3.54558	4.46813
27	0.60044	1.19938	2.39914	3.54528	4.46897
28	0.60089	1.20037	2.40122	3.54762	4.47108
29	0.60056	1.19957	2.39972	3.54526	4.46961
30	0.60023	1.19911	2.39875	3.54546	4.47099

TABLE A1 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	0.60024	1.19905	2.39889	3.54509	4.46860
32	0.60070	1.20000	2.40020	3.55266	4.47574
33	0.60010	1.19883	2.39813	3.54734	4.47022
34	0.60016	1.19885	2.39844	3.53885	4.46090
35	0.60065	1.19986	2.39997	3.53938	4.46166
36	0.60006	1.19858	2.39731	3.53534	4.45979
37	0.60024	1.19916	2.39975	3.53623	4.45912
38	0.59976	1.19814	2.39738	3.53575	4.45772
39	0.59948	1.19751	2.39660	3.53658	4.46057
40	0.60074	1.20009	2.40115	3.54652	4.46867
41	0.60057	1.19986	2.40151	3.54720	4.46791
42	0.60046	1.19956	2.40080	3.54526	4.47047
43	0.60070	1.19994	2.40120	3.54672	4.47505
44	0.60080	1.20015	2.40151	3.54821	4.47168
45	0.60106	1.20057	2.40134	3.54771	4.47344
46	0.60003	1.19931	2.39929	3.54361	4.46590
47	0.60088	1.20039	2.40169	3.54961	4.47240
48	0.60118	1.20093	2.40236	3.54727	4.46897
49	0.60096	1.20038	2.40091	3.54758	4.47143
50	0.60095	1.20032	2.40149	3.54652	4.46828
51	0.60096	1.20052	2.40155	3.53761	4.46419
52	0.60100	1.20061	2.40176	3.53909	4.46494
53	0.60062	1.19988	2.40074	3.53746	4.46611
54	0.60096	1.20043	2.40186	3.53860	4.46515
55	0.60071	1.19995	2.40090	3.53766	4.46719
56	0.60109	1.20073	2.40200	3.54043	4.46894
57	0.60063	1.19995	2.40040	3.54468	4.47222
58	0.60038	1.19939	2.39970	3.55026	4.47601
59	0.60083	1.20035	2.40088	3.54523	4.47408
60	0.60177	1.20205	2.40437	3.54416	4.47835

TABLE A2 - Average $\Delta B/B$ at good field region boundary (units of 10^{-4})

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	1.980	2.192	2.203	3.449	5.574
2	2.915	2.812	2.936	3.110	3.020
3	3.745	2.811	2.709	3.090	6.288
4	0.615	0.650	0.655	1.491	2.989
5	2.318	2.612	2.588	2.512	3.207
6	2.524	2.569	2.596	2.604	3.268
7	1.909	1.412	1.698	1.723	3.410
8	1.940	1.700	1.400	1.977	3.203
9	1.678	1.481	1.778	2.391	3.951
10	1.840	1.636	1.767	2.349	2.917
11	0.904	0.839	0.887	1.386	2.920
12	1.062	0.886	0.933	1.565	3.844
13	1.106	1.460	1.001	1.458	4.324
14	0.993	0.785	0.707	2.091	4.240
15	1.636	1.748	1.683	2.175	2.844
16	1.141	1.181	1.100	1.071	2.754
17	2.625	2.035	2.265	5.294	6.081
18	0.744	0.750	0.768	1.481	3.315
19	1.489	1.201	1.192	1.700	3.182
20	4.297	3.984	3.933	1.161	2.712
21	4.604	4.834	4.415	4.320	4.619
22	3.614	3.645	3.499	3.437	4.765
23	3.253	3.377	3.131	3.211	3.390
24	1.040	1.079	1.106	1.627	3.311
25	1.993	2.036	2.212	2.461	3.699
26	1.377	1.209	1.333	3.206	5.062
27	2.169	2.279	2.497	3.556	4.328
28	0.589	0.658	0.743	1.801	3.090
29	2.204	2.218	2.026	2.892	3.198
30	1.626	1.518	1.610	3.052	4.188

TABLE A2 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	1.543	1.502	1.518	1.354	3.353
32	1.376	1.359	1.265	2.819	4.102
33	1.145	1.234	1.418	1.510	3.235
34	0.892	0.873	0.997	4.415	5.090
35	2.610	2.356	2.319	1.569	2.927
36	3.188	3.213	3.436	2.967	3.767
37	0.710	0.978	1.154	1.273	2.905
38	2.907	2.802	3.044	4.292	4.404
39	1.334	1.400	1.543	2.527	3.361
40	3.024	2.728	2.774	1.520	3.158
41	0.642	0.560	0.837	1.538	3.086
42	1.682	2.060	2.120	5.541	5.477
43	1.751	1.483	1.670	3.937	5.259
44	3.839	3.763	3.504	3.210	3.878
45	1.523	1.382	1.104	3.409	4.803
46	0.732	0.708	0.824	1.442	3.177
47	1.850	1.877	1.987	1.841	3.470
48	0.739	0.722	0.755	1.356	3.457
49	1.742	1.823	1.491	1.940	3.684
50	0.612	0.739	0.995	1.303	2.977
51	0.742	0.673	1.097	1.708	3.463
52	2.405	2.523	2.500	3.245	4.323
53	0.562	0.523	0.655	1.472	3.810
54	0.701	0.676	0.786	1.085	2.684
55	1.232	1.263	1.155	1.514	3.881
56	1.874	1.610	1.813	2.950	3.535
57	1.906	1.774	1.862	4.741	3.936
58	3.607	3.702	3.737	2.338	3.597
59	0.607	0.620	0.699	1.821	3.099
60	1.740	2.342	2.470	2.867	4.308

TABLE A3 - Sextupole contribution at 30 mm from quadrupole axis (units of 10^{-4})

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	1.861	2.067	2.097	3.325	5.180
2	2.848	2.763	2.876	2.974	1.695
3	3.521	2.671	2.655	2.972	5.936
4	0.259	0.518	0.344	1.118	1.490
5	2.285	2.585	2.546	2.331	2.017
6	2.483	2.546	2.552	2.447	2.242
7	1.859	1.320	1.620	1.439	2.430
8	1.879	1.650	1.327	1.799	2.265
9	1.467	1.033	1.462	2.060	3.056
10	1.790	1.586	1.722	2.227	1.599
11	0.499	0.469	0.671	1.090	1.557
12	0.909	0.665	0.788	1.276	3.228
13	1.026	1.394	0.904	1.224	3.870
14	0.661	0.506	0.367	1.939	3.706
15	1.573	1.700	1.634	2.046	1.511
16	1.053	1.114	1.037	0.228	1.280
17	2.580	1.993	2.219	5.224	5.719
18	0.226	0.073	0.150	0.787	2.082
19	1.397	1.099	0.995	1.475	2.124
20	4.263	3.944	3.888	0.618	1.107
21	4.574	4.807	4.382	4.211	4.076
22	3.399	3.314	3.220	3.050	4.055
23	3.090	3.220	2.994	2.997	1.809
24	0.804	0.805	0.732	1.144	1.875
25	1.857	1.869	2.049	2.152	2.654
26	0.756	0.699	0.840	2.991	4.482
27	2.026	2.154	2.412	3.382	3.550
28	0.072	0.268	0.381	1.456	0.423
29	2.108	2.139	1.931	2.752	1.836
30	1.549	1.382	1.480	2.889	3.459

TABLE A3 (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	1.271	1.321	1.355	0.316	1.800
32	1.183	1.164	1.072	2.590	3.200
33	1.046	1.125	1.249	1.127	1.640
34	0.669	0.587	0.752	4.298	4.568
35	2.570	2.320	2.279	1.100	0.876
36	3.168	3.183	3.379	2.811	2.847
37	0.534	0.874	1.070	0.741	1.247
38	2.856	2.698	2.981	4.145	3.778
39	1.124	1.198	1.349	2.189	2.113
40	2.978	2.664	2.708	0.710	0.687
41	0.266	0.316	0.659	0.987	0.977
42	1.615	1.951	2.026	5.436	4.980
43	1.664	1.331	1.541	3.796	4.742
44	3.748	3.728	3.440	2.958	3.074
45	1.479	1.300	0.950	3.250	4.241
46	0.640	0.606	0.703	1.041	1.894
47	1.778	1.797	1.914	1.586	2.467
48	0.628	0.569	0.504	0.877	2.214
49	1.673	1.761	1.403	1.677	2.779
50	0.460	0.593	0.877	0.711	0.891
51	0.639	0.495	0.959	1.406	2.592
52	2.325	2.456	2.427	3.104	3.726
53	0.372	0.166	0.469	1.164	3.166
54	0.605	0.550	0.681	0.352	0.476
55	1.088	1.160	0.995	1.208	3.281
56	1.818	1.556	1.760	2.822	2.727
57	1.858	1.724	1.784	4.641	3.248
58	3.537	3.628	3.673	1.973	2.390
59	0.213	0.197	0.365	0.154	1.290
60	1.475	2.207	2.278	2.498	3.289

TABLE A4 - Sextupole phase (deg)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	227.9	236.1	223.1	160.5	161.4
2	68.8	64.1	59.5	44.4	33.4
3	241.1	248.2	315.1	282.8	225.9
4	75.4	85.3	25.0	310.9	278.4
5	66.8	72.9	72.8	67.9	63.5
6	68.5	72.1	65.6	44.7	70.0
7	5.7	352.8	338.3	312.5	270.6
8	215.8	214.3	207.2	255.6	240.5
9	298.8	302.1	300.3	278.3	269.4
10	13.0	15.2	14.1	334.2	318.9
11	6.2	4.7	337.9	280.0	275.5
12	36.9	46.4	54.4	205.5	197.6
13	205.6	199.9	189.6	311.7	305.6
14	245.2	203.1	175.4	150.9	161.2
15	23.8	27.7	22.5	1.8	351.4
16	31.5	28.7	22.9	307.3	207.7
17	138.5	124.9	136.4	180.7	192.8
18	226.4	249.4	229.8	257.8	236.1
19	52.2	36.9	52.0	359.9	339.9
20	157.8	153.3	151.8	308.6	276.4
21	333.2	332.0	328.3	273.5	264.2
22	254.0	249.7	251.8	238.8	260.4
23	31.5	34.0	38.5	54.6	67.3
24	190.1	195.4	180.8	187.4	207.2
25	341.0	340.2	334.8	291.0	286.5
26	241.5	240.0	246.5	284.0	279.7
27	338.4	338.3	341.2	304.1	289.6
28	152.2	137.5	127.8	51.4	218.9
29	34.6	19.7	26.5	1.2	2.5
30	172.7	180.3	179.9	188.7	208.6

TABLE A4 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	303.8	310.5	304.3	284.8	296.0
32	222.1	232.5	246.0	230.8	231.1
33	37.9	32.1	35.7	5.0	305.3
34	106.2	105.9	154.8	172.0	176.7
35	81.8	78.3	71.5	118.6	159.1
36	259.2	256.2	257.0	234.6	256.4
37	24.5	15.1	24.2	116.0	145.2
38	320.7	322.0	314.3	328.9	320.8
39	136.2	140.9	158.4	294.6	310.9
40	96.9	97.8	95.5	32.8	239.4
41	160.4	97.6	88.4	216.4	220.4
42	227.6	219.8	226.8	193.1	220.5
43	89.0	85.7	84.6	308.8	316.0
44	316.5	322.3	322.5	317.0	287.9
45	171.5	173.7	205.6	240.9	226.0
46	334.8	343.6	329.3	341.3	299.0
47	340.9	341.0	332.7	294.2	286.5
48	99.3	86.2	130.8	187.9	194.9
49	198.3	207.6	211.2	208.5	206.4
50	121.5	118.5	117.1	109.6	222.1
51	220.5	324.1	340.1	331.5	315.3
52	323.3	321.1	314.4	295.6	273.7
53	146.5	215.0	316.2	255.1	251.7
54	242.0	256.5	258.0	306.1	219.0
55	180.5	153.5	167.4	253.5	277.4
56	66.5	59.8	50.4	337.7	335.7
57	163.0	170.4	175.0	4.6	340.5
58	27.4	25.5	23.0	55.8	12.6
59	340.3	66.3	107.2	140.2	157.0
60	296.6	285.3	285.9	270.8	274.1

TABLE A5 - Octupole contribution at 30 mm from axis (units of 10^{-4})

Serial #	54.36A	130.65A	262.29A	401.76A	587.45A
1	0.793	0.796	0.724	0.492	0.587
2	0.605	0.525	0.684	0.600	0.614
3	1.637	1.077	0.539	0.380	1.000
4	0.417	0.141	0.235	0.110	0.296
5	0.272	0.043	0.046	0.103	0.082
6	0.439	0.126	0.279	0.164	0.233
7	0.289	0.414	0.212	0.153	0.065
8	0.391	0.292	0.379	0.222	0.148
9	0.993	1.159	1.155	1.024	1.277
10	0.306	0.246	0.257	0.239	0.105
11	0.700	0.643	0.468	0.346	0.453
12	0.520	0.513	0.463	0.550	0.780
13	0.179	0.303	0.279	0.393	0.593
14	0.749	0.523	0.443	0.294	0.403
15	0.364	0.234	0.316	0.264	0.354
16	0.238	0.201	0.144	0.179	0.287
17	0.453	0.257	0.323	0.294	0.494
18	0.605	0.653	0.651	0.859	0.801
19	0.463	0.366	0.641	0.374	0.398
20	0.196	0.246	0.220	0.115	0.315
21	0.569	0.611	0.568	0.813	0.861
22	1.574	1.924	1.803	2.004	2.217
23	1.358	1.331	1.130	0.962	1.037
24	0.680	0.753	0.817	0.746	0.664
25	0.806	0.882	0.921	0.643	0.672
26	1.170	1.001	0.998	0.963	0.822
27	0.907	0.853	0.634	0.776	0.851
28	0.421	0.421	0.347	0.396	0.391
29	0.555	0.408	0.488	0.354	0.388
30	0.356	0.621	0.661	0.262	0.639

TABLE A5 (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	1.039	0.831	0.734	0.830	0.684
32	0.754	0.763	0.561	0.656	0.549
33	0.418	0.518	0.677	0.409	0.431
34	0.519	0.576	0.558	0.479	0.479
35	0.340	0.311	0.107	0.570	0.635
36	0.180	0.409	0.299	0.315	0.371
37	0.024	0.101	0.251	0.110	0.124
38	0.601	0.950	0.672	0.931	0.732
39	0.654	0.813	0.803	0.951	0.603
40	0.484	0.626	0.549	0.399	0.390
41	0.434	0.143	0.139	0.233	0.093
42	0.356	0.769	0.612	0.658	0.706
43	0.505	0.730	0.642	0.637	0.723
44	1.061	0.256	0.625	0.664	0.361
45	0.126	0.376	0.096	0.477	0.335
46	0.030	0.119	0.166	0.130	0.187
47	0.539	0.573	0.529	0.490	0.544
48	0.200	0.268	0.397	0.291	0.193
49	0.368	0.398	0.367	0.280	0.308
50	0.132	0.289	0.291	0.274	0.213
51	0.024	0.298	0.409	0.329	0.235
52	0.448	0.356	0.282	0.234	0.389
53	0.036	0.289	0.101	0.021	0.077
54	0.094	0.154	0.138	0.251	0.200
55	0.496	0.443	0.475	0.488	0.679
56	0.383	0.328	0.279	0.323	0.235
57	0.342	0.335	0.505	0.586	0.468
58	0.820	0.901	0.732	0.770	0.758
59	0.366	0.379	0.363	0.350	0.362
60	1.030	0.825	0.948	0.897	0.859

TABLE A6 - Decapole contribution at 30 mm (units of 10^{-4})

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	0.159	0.349	0.009	0.241	0.105
2	0.441	0.289	0.117	0.191	0.324
3	0.324	0.177	0.093	0.181	0.081
4	0.094	0.069	0.088	0.068	0.102
5	0.131	0.070	0.051	0.100	0.072
6	0.091	0.064	0.075	0.072	0.053
7	0.305	0.236	0.224	0.053	0.225
8	0.187	0.069	0.081	0.269	0.315
9	0.087	0.061	0.047	0.081	0.190
10	0.172	0.148	0.106	0.054	0.079
11	0.071	0.082	0.041	0.068	0.067
12	0.043	0.033	0.056	0.060	0.157
13	0.156	0.104	0.212	0.230	0.166
14	0.171	0.164	0.153	0.172	0.149
15	0.176	0.234	0.085	0.162	0.144
16	0.062	0.030	0.088	0.052	0.076
17	0.047	0.135	0.135	0.177	0.092
18	0.202	0.147	0.161	0.193	0.172
19	0.036	0.169	0.054	0.229	0.094
20	0.509	0.543	0.642	0.717	0.549
21	0.310	0.238	0.380	0.304	0.405
22	0.282	0.468	0.361	0.380	0.430
23	0.366	0.489	0.510	0.461	0.576
24	0.013	0.013	0.031	0.017	0.058
25	0.235	0.309	0.262	0.344	0.225
26	0.098	0.042	0.068	0.004	0.026
27	0.420	0.441	0.325	0.314	0.388
28	0.129	0.126	0.126	0.125	0.111
29	0.465	0.485	0.501	0.463	0.508
30	0.353	0.371	0.241	0.308	0.189

TABLE A6 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	0.099	0.041	0.036	0.084	0.079
32	0.153	0.188	0.187	0.208	0.247
33	0.089	0.066	0.039	0.123	0.131
34	0.222	0.200	0.175	0.192	0.230
35	0.126	0.099	0.069	0.073	0.077
36	0.169	0.237	0.547	0.194	0.282
37	0.288	0.219	0.168	0.113	0.264
38	0.155	0.176	0.174	0.115	0.049
39	0.241	0.152	0.145	0.281	0.217
40	0.325	0.285	0.289	0.364	0.350
41	0.134	0.184	0.022	0.120	0.103
42	0.146	0.084	0.216	0.163	0.145
43	0.309	0.311	0.242	0.372	0.310
44	0.197	0.462	0.453	0.261	0.443
45	0.167	0.152	0.243	0.122	0.052
46	0.043	0.058	0.055	0.061	0.125
47	0.053	0.122	0.056	0.105	0.131
48	0.122	0.095	0.127	0.111	0.238
49	0.224	0.144	0.189	0.069	0.123
50	0.114	0.068	0.060	0.100	0.055
51	0.171	0.104	0.175	0.122	0.197
52	0.582	0.579	0.566	0.452	0.420
53	0.104	0.035	0.062	0.025	0.120
54	0.056	0.095	0.023	0.010	0.080
55	0.262	0.177	0.207	0.300	0.372
56	0.118	0.028	0.017	0.125	0.036
57	0.099	0.063	0.104	0.295	0.166
58	0.210	0.153	0.154	0.271	0.118
59	0.248	0.284	0.223	0.252	0.332
60	0.151	0.336	0.308	0.268	0.212

TABLE A7 - 12-pole contribution at 30 mm (units of 10^{-4})

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	0.075	0.140	0.273	1.020	2.658
2	0.103	0.084	0.238	1.002	2.623
3	0.215	0.137	0.240	0.988	2.534
4	0.094	0.155	0.356	1.114	2.728
5	0.185	0.256	0.457	1.177	2.802
6	0.177	0.147	0.430	1.139	2.746
7	0.142	0.166	0.491	1.131	2.791
8	0.122	0.132	0.121	0.953	2.609
9	0.073	0.148	0.313	1.024	2.745
10	0.155	0.184	0.164	0.905	2.636
11	0.180	0.192	0.181	0.902	2.625
12	0.195	0.208	0.087	0.813	2.475
13	0.264	0.192	0.055	0.764	2.481
14	0.060	0.124	0.193	0.882	2.634
15	0.179	0.063	0.122	0.870	2.573
16	0.292	0.239	0.161	0.983	2.536
17	0.077	0.147	0.181	0.953	2.671
18	0.121	0.141	0.167	1.007	2.799
19	0.303	0.216	0.172	0.927	2.705
20	0.279	0.304	0.172	0.733	2.503
21	0.172	0.102	0.193	0.908	2.648
22	0.360	0.345	0.089	0.682	2.467
23	0.090	0.164	0.195	1.032	2.817
24	0.011	0.029	0.266	1.103	2.930
25	0.148	0.148	0.314	1.188	2.907
26	0.078	0.108	0.345	1.140	2.970
27	0.154	0.154	0.437	1.222	3.064
28	0.135	0.201	0.408	1.202	3.026
29	0.169	0.211	0.211	1.027	2.852
30	0.145	0.100	0.293	1.172	2.917

TABLE A7 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	0.039	0.119	0.291	1.149	3.001
32	0.271	0.234	0.488	1.278	3.128
33	0.009	0.061	0.331	1.130	2.945
34	0.144	0.167	0.309	1.138	2.857
35	0.205	0.150	0.357	1.140	2.798
36	0.121	0.047	0.384	1.145	2.936
37	0.158	0.232	0.200	1.070	2.698
38	0.130	0.135	0.351	1.161	2.880
39	0.140	0.118	0.335	1.181	2.885
40	0.162	0.195	0.394	1.283	3.063
41	0.112	0.153	0.416	1.217	2.988
42	0.201	0.124	0.214	1.141	2.894
43	0.132	0.101	0.344	1.171	2.943
44	0.230	0.199	0.093	1.495	2.951
45	0.142	0.138	0.448	1.211	2.920
46	0.133	0.115	0.243	1.071	2.816
47	0.043	0.025	0.271	1.030	2.850
48	0.077	0.102	0.204	1.059	2.969
49	0.169	0.135	0.278	1.110	2.907
50	0.084	0.121	0.264	1.078	2.876
51	0.042	0.098	0.302	1.071	2.743
52	0.112	0.171	0.336	1.133	2.796
53	0.170	0.076	0.255	1.011	2.684
54	0.021	0.091	0.231	0.980	2.627
55	0.210	0.113	0.176	0.917	2.556
56	0.145	0.118	0.293	1.059	2.754
57	0.141	0.037	0.263	1.115	2.851
58	0.156	0.106	0.434	1.263	3.070
59	0.016	0.032	0.273	1.057	2.877
60	0.436	0.391	0.665	1.471	3.195

TABLE A8 - 20-pole contribution at 30 mm (units of 10^{-4})

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
1	0.437	0.452	0.457	0.476	0.555
2	0.442	0.441	0.459	0.475	0.519
3	0.454	0.453	0.456	0.484	0.539
4	0.448	0.446	0.460	0.479	0.537
5	0.444	0.440	0.464	0.479	0.528
6	0.441	0.447	0.450	0.482	0.532
7	0.443	0.464	0.446	0.486	0.530
8	0.458	0.441	0.459	0.444	0.536
9	0.447	0.471	0.440	0.472	0.551
10	0.455	0.446	0.461	0.486	0.533
11	0.445	0.450	0.468	0.493	0.544
12	0.445	0.448	0.453	0.478	0.530
13	0.446	0.463	0.440	0.471	0.547
14	0.439	0.448	0.465	0.485	0.538
15	0.445	0.450	0.445	0.479	0.536
16	0.452	0.436	0.450	0.511	0.513
17	0.449	0.448	0.457	0.480	0.534
18	0.453	0.457	0.459	0.482	0.528
19	0.434	0.463	0.464	0.491	0.527
20	0.454	0.451	0.454	0.472	0.532
21	0.447	0.440	0.449	0.475	0.542
22	0.436	0.459	0.450	0.491	0.532
23	0.452	0.458	0.454	0.481	0.536
24	0.446	0.451	0.455	0.478	0.526
25	0.446	0.459	0.456	0.517	0.524
26	0.442	0.448	0.457	0.479	0.543
27	0.445	0.451	0.454	0.484	0.543
28	0.445	0.457	0.454	0.488	0.547
29	0.446	0.465	0.457	0.477	0.546
30	0.446	0.458	0.459	0.472	0.546

TABLE A8 - (continued)

Serial #	65.36A	130.65A	262.29A	401.76A	587.45A
31	0.457	0.446	0.459	0.485	0.528
32	0.449	0.463	0.452	0.494	0.554
33	0.461	0.444	0.454	0.480	0.548
34	0.451	0.447	0.447	0.485	0.546
35	0.451	0.448	0.462	0.485	0.550
36	0.433	0.414	0.499	0.489	0.531
37	0.451	0.453	0.479	0.459	0.562
38	0.440	0.456	0.452	0.477	0.545
39	0.452	0.437	0.439	0.506	0.525
40	0.449	0.449	0.450	0.483	0.533
41	0.456	0.450	0.458	0.481	0.516
42	0.449	0.456	0.491	0.484	0.531
43	0.467	0.458	0.460	0.470	0.525
44	0.426	0.473	0.477	0.498	0.534
45	0.412	0.441	0.420	0.482	0.522
46	0.459	0.458	0.467	0.485	0.538
47	0.457	0.461	0.455	0.483	0.530
48	0.431	0.454	0.441	0.469	0.517
49	0.457	0.463	0.448	0.506	0.537
50	0.454	0.456	0.455	0.485	0.533
51	0.452	0.447	0.452	0.483	0.525
52	0.456	0.449	0.461	0.478	0.529
53	0.437	0.452	0.467	0.479	0.526
54	0.450	0.452	0.443	0.465	0.528
55	0.440	0.455	0.453	0.474	0.552
56	0.448	0.451	0.449	0.486	0.534
57	0.442	0.456	0.460	0.487	0.526
58	0.455	0.447	0.453	0.473	0.531
59	0.453	0.448	0.454	0.483	0.536
60	0.454	0.448	0.457	0.489	0.531