SUMMARIES

1 WORKSHOP SUMMARY

J. WEI, BNL

During the two-day workshop, representatives from CERN, FNAL, KEK, BNL, and other institutions and universities met and discussed issues relevant to LHC interaction region correction schemes and plans. In this Section, we summarize the proposed IR corrector layout and correction plan. In Sections 2, 3, and 4, summaries of the three individual sessions, Field quality, Global correction, and Local correction, are given by the corresponding session chairmen.

1.1 Proposed IR corrector layout and plan

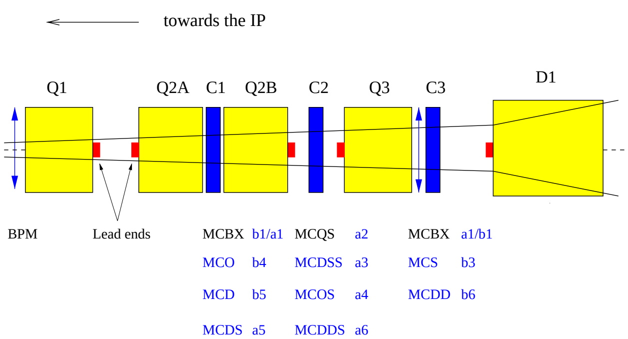

Figure 1: Schematic layout of the proposed LHC inner triplet region correction packages.

The proposed layout and content for the interaction region corrector packages is shown in Fig. 1.

1. The corrector layout for all the 8 inner triplets of the 4 interaction region are identical. This allows constructional and operational standardization as well as sorting.

2. Correctors at IP2 are mainly useful during the heavy ion operation when the β^* at IP2 is low. Correctors at IP2 and IP8 may also be used for global correction. Initially, one may choose not to power IP8 correctors until needed.

3. Each inner triplet contains 3 corrector packages: package C1 located between Q2A and Q2B contains five elements: b_1, a_1, b_4, b_5, and a_5; package C2 located between Q2B and Q3 contains four elements: a_2, a_3, a_4, and a_6; package C3 located between Q3 and D1 contains four elements: b_1, a_1, b_3, and b_6.

4. The strengths designed for each correction element is given in Table 1. Tentatively, the strengths for $n > 2$ multipoles are set here at twice the maximum strength used to locally compensate the lumped multipole errors of IR inner triplet quadrupoles built by FNAL (reference table version 2.0) and KEK (reference table version 3.0), cold D1 built by BNL (reference table version 1.0), and warm D1 (reference table version 1.0). (It was decided that these strength should be moderately chosen to maximize their effectiveness.)

5. The strength for $n = 1, 2$ elements are chosen to be as much as practically achievable.

6. Due to the strong b_6 correction needed, more space is reserved for its coil winding. Therefore, the package C3 that contains the b_6 correction element has only two nonlinear ($n > 2$) layers, while both C1 and C2 have three nonlinear layers.

7. The design strength will be finalized by the end of year 1999 after further measurements are made on the IR magnet prototypes and after further feasibility studies are performed on the corrector spool piece design.

Table 1: Proposed IR corrector package contents and strength. The strength is integrated over the length of the correction element normalized at the reference radius of 17mm. Each inner IR triplet contains one of each type of correction element. The magnetic length of each element is 0.5m.

n	b_n strength	a_n strength	unit
1	3.0	3.0	[T]
2	–	0.51	[T]
3	0.029	0.068	[T]
4	0.027	0.068	[T]
5	0.012	0.012	[T]
6	0.025	0.010	[T]

1.2 Other issues

Consensus is reached on other issues at the workshop pertaining to IR compensation and operation:

1. Updated error tables for IR inner triplet quadrupoles and warm D1 dipoles are needed before the end of September 1999 for the final determination of the IR corrector strength.

2. During the LHC operation, a “threshold” (e.g. 10% of the maximum strength) may be set for the powering of IR correctors below which correctors will not be activated.

3. The orientation of the IR inner triplet quadrupoles and cold D1 is shown in Fig. 1. This arrangement reduces the requirements on the IR corrector power supply strengths.

4. Magnetic tuning shims are not planned to be used for any LHC IR magnets due to mechanical difficulties and uncertainty in magnetic multipole errors.

5. In general, sorting on IR magnets, correctors, and assemblies is encouraged during all stages of the construction to optimize the performance and to minimize the corrector power supply requirements. The decision on the IR corrector layout, however, is made independent of sorting consideration, since sorting is often constraint by real world issues like planning, assembly and installation schedules.

6. Options for global correction will be evaluated in the future to determine the corrector candidates and their locations, preferably in regions where the counter-rotating beams are separated.

7. Impacts from magnetic errors of multipole order higher than $n = 10$ appear to influence the dynamic aperture when the betatron amplitude is larger than 10σ in the presence of the design crossing angle. In practical operation, however, these higher order impacts are likely to be negligible due to their strong amplitude dependence, when the actual dynamic aperture is below 10σ.

8. Alignment of IR magnet cold masses and assemblies is crucial to the collision performance. Reference misalignment tables will be established for the IR magnets and correctors.

2 SUMMARY OF FIELD QUALITY SESSION

J. STRAIT, FNAL

This session reviewed the expected field quality of the Fermilab and KEK IR quadrupoles and calculations of the impact of the field errors on the LHC performance. Data from the existing model magnets were presented and the relation between them and the reference harmonics tables were discussed. A number of recommendations were developed concerning which harmonics are the most dangerous and how the current versions of the reference harmonics tables could be improved.

2.1 Questions for the workshop

A number of questions were posed to the workshop, which are listed below, together with the answers developed during the discussions.

1. What is the optimal choice of corrector layers? This is addressed in Jie Wei's summary presentation.

2. Are corrector positions optimal? The corrector positions will remain as in the original layout: MCBX between Q2a and Q2b, MCQS between Q2b and Q3, and MCBX between Q3 and D1.

3. What should be the lead end orientation for Q3? The lead end should remain facing the IP.

4. Can MCBX.Q3 contain only a horizontal dipole? Both horizontal and vertical layers should be included in this magnet.

5. Should the same correctors be used in IR2 and IR8 as in IR1 and IR5? The same correctors should be installed in all locations and leads for all should be brought through the DFBX, but it is left as an option that some layers might not be powered at the low luminosity IRs.

6. The corrector strength should be set to cover the systematic errors plus how many sigma? This will be discussed in Jie Wei's summary presentation.

7. Do we need a reference misalignment table? This table should be developed in the coming months.

8. Can FNAL eliminate tuning shims? Yes.

2.2 Error contribution in order of importance

Tracking and other beam studies indicate that the errors contributing to machine performance, in order of importance, are

1. b_{10} if it is above about 0.06 units.

2. Random b_6, which is currently 0.6 units in both FNAL and KEK quadrupoles.

3. Multipoles of order 3 and 4 in both lab's magnets.

4. Lead end b_6 in both lab's magnets.

2.3 Reference error tables

Continued discussion is required to ensure that there is a common understanding concerning the use and meaning of the reference harmonics tables. At least two types of meaning are attached to the values in the tables:

1. They are statistical estimates of the errors expected for the magnets to be installed in LHC. This is the usage assumed by those doing tracking studies.

2. They are specifications for magnet manufacturers, with the sum of systematic plus uncertainty plus rms errors taken essentially to be limits. The table entries are treated this way by some magnet builder.

The lack of common understanding results in the tables being perceived as "pessimistic" by the accelerator physicists on the one hand and as justifiably "conservative" by

Table 2: Measured harmonics for FNAL models compared with the reference table.

Field harmonic	Measured field harmonics						reference table V2.0	
	HGQ01	HGQ02	HGQ03	HGQ05	mean	rms	uncertainty	random
b_3	0.36	-0.70	1.04	0.72	0.36	0.76	0.30	0.80
a_3	0.27	0.55	-0.30	0.12	0.16	0.36	0.30	0.80
b_4	0.26	0.18	0.14	–	0.15	0.11	0.20	0.80
a_4	0.73	-0.41	0.32	0.19	0.21	0.47	0.20	0.80
b_5	-0.29	0.09	-0.34	-0.04	-0.15	0.20	0.20	0.30
a_5	0.02	-0.17	0.26	0.05	0.04	0.18	0.20	0.30
b_6	0.33	1.32	0.37	-0.22	0.45	0.64	0.60	0.60
a_6	-0.02	0.03	0.07	-0.03	0.01	0.05	0.05	0.10
b_7	-0.08	-0.01	-0.06	0.01	-0.04	0.04	0.05	0.06
a_7	-0.05	–	-0.03	0.01	-0.02	0.03	0.04	0.06
b_8	0.06	0.01	–	–	0.02	0.03	0.03	0.05
a_8	–	0.02	0.03	–	0.01	0.02	0.03	0.04
b_9	0.04	–	–	–	0.01	0.02	0.02	0.03
a_9	0.01	-0.01	0.01	–	–	0.01	0.02	0.02
b_{10}	0.04	-0.01	–	–	0.01	0.02	0.02	0.03
a_{10}	0.02	–	-0.01	–	–	0.01	0.02	0.03

magnet builders on the other. The definition of the uncertainty $d(b_n)$ does not always appear to be clear. It must be remembered that this is not the same as the mean of the distribution of a finite number of magnets. It is clear that care must be used in treating the statistics of small numbers of magnets.

There was some discussion as to how data from the models and prototypes should be used to revise the tables. How closely should the error table follow from the mean and rms over the models? Should the table be based on all the model data, corrected for known manufacturing deviations, or just on the most recent models? Should the table be revised each time a new model is measured? Should the data be used to set table values directly, or only to adjust the table when the table is inconsistent with the data by a statistically significant amount? Should the data be treated as the best estimate of the field quality of production magnets, or just to set bounds (for example at a 90% confidence level) on the reference table values? No consensus conclusions were drawn.

2.4 Field quality of FNAL quadrupoles

The Fermilab reference harmonics table appears conservative relative to the data. Tab. 2 compares the measured harmonics for the first 4 models, corrected for the non-standard pole shims used in the first three models, with the reference table. The comparison reveals:

1. The measured rms $<$ random (b_n/a_n) for all b_n, a_n except b_3 and b_6, for which the measured rms is approximately the random error in the table. Were the reference table a realistic estimate of the expected rms for a production series, perhaps one-third of the measured values would be larger than the entries in the reference table.
2. The measured rms $\ll$ random (b_n/a_n) for a_3, b_4, a_4, by 2-3 times the estimated uncertainty in the measured rms. These are among the most important harmonics noted in Sec. 2.2 above.
3. The measured $\langle b_n \rangle$ and $\langle a_n \rangle$ are all consistent with 0 except $\langle b_4 \rangle = 0.15 \pm 0.05$. This apparently systematic value of b_4 may be small enough to be unimportant, but should be understood by the magnet builders.

It should be noted that this good field quality has been achieved without using the tuning shims.

2.5 Field quality of KEK quadrupoles

The draft KEK reference harmonics table V3.0 (Tab. 3) is explicitly conservative at this point. This conservatism is driven by the fact that the body and end designs have been recently changed, but no models of the new design have been built yet. Notable features of the table include:

1. $b_{3,4}/a_{3,4}$ values are larger than in the FNAL table.
2. $d(b_{10})$, $\sigma(b_{10})$ are together larger than the 0.06 "limit."
3. The two-piece stressed yoke can generate a systematic b_4 of approximately 0.7 units according to calculations, but this is not observed in the first two models.
4. Systematic differences exist in the first two models between measurement and calculation for the allowed harmonics: $\Delta b_6 \approx -1.0$ unit and $\Delta b_{10} \approx -0.1$ unit. If the cause of this can be understood, then $d(b_6)$ and $d(b_{10})$ can be reduced.
5. High order entries (except for b_{10}) are essentially the same as in the FNAL table.

Table 3: KEK reference harmonics table V3.0 (draft), body multipoles in units of 10^{-4}, $R_{ref} = 17$ mm).

n	Normal			Skew		
	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
3	–	0.50	1.00	–	0.50	1.00
4	–	0.70	0.80	–	0.30	0.80
5	–	0.20	0.40	–	0.20	0.40
6	0.1	0.50	0.60	–	0.10	0.20
7	–	0.05	0.06	–	0.04	0.06
8	–	0.03	0.05	–	0.02	0.04
9	–	0.02	0.03	–	0.02	0.02
10	–	0.10	0.05	–	0.02	0.03

2.6 Highest order harmonics in tables

Currently the error tables include harmonics up to b_{10} and a_{10}, but this may not be a high enough order. If b_{10} is important, why not b_{14}, b_{18}, ...? Calculations done by Norm Gelfand, using the $d(b_{14})$ error from the original FNAL table which included harmonics up to order 14, are said to show a limit on the dynamic aperture of 11-12σ from this harmonic alone. The estimated accuracy of harmonics measurements ranges from $<$ 1% for $n \leq 3$ to (conservatively) $<$ 6% for $n \leq 15$, supporting the inclusion of higher order harmonics. Thus both FNAL and KEK need to estimate the higher order harmonics, especially the allowed moments which have the possibility to be more significant, and the effect of these on the beam needs to be evaluated.

2.7 Reproducibility of harmonic errors

The limit on the accuracy of the field quality and of the ability to correct the measured field errors may be set by the reproducibility of the field in an individual magnet. FNAL has seen changes in the transfer function and harmonics with thermal cycles (see Sec. 2.4), but has not yet looked for changes with quenching. KEK has observed changes at low field with quenching, but has not presented data on changes with thermal cycles. It remains to be verified that the field errors settle ("train") to constant values after a tolerable number of cycles. The source of the larger variations should be understood in order to try to minimize the changes.

2.8 Summary, conclusions and recommendations

1. The new KEK design eliminates the b_{10} problem, but the current values of $d(b_{10})$ and $\sigma(b_{10})$ in the draft V3.0 reference table are conservative at a level that may affect machine performance.

2. Both FNAL and KEK tables appear to have built in margin. That is, it seems likely that the production magnets will have better field quality than that implied by the tables.

3. We need to continue to develop a better common understanding of how to use tables and of the definitions of error types: statistical estimates vs. specifications and limits.

4. Both FNAL and KEK need to review their tables by September. The tables should be the best estimates of the distribution of errors in production series. If margin is included in table, this should be explicitly acknowledged along with the magnitude of the margin. The tables may need to account for changes with thermal cycle or quench. Higher order harmonics, especially the allowed moments, should be examined and included if they are important (10^{-4} at ≈20 mm). Both error tables should be entered into the CERN database used by the Field Component & Machine Performance Working Group, chaired by L. Walckiers.

5. The reference harmonics table for the Novosibirsk-built D1 dipoles needs to be updated.

6. The effect on the beam of time dependent field variations at injection should be evaluated.

7. Variation of the transfer function with thermal cycles must be understood, in particular to reduce the effect and to ensure that it "trains" to a stable value after a finite number of cycles.

8. Despite the conservatism, the existing tables seem to be good enough to be correctable with a reasonable set of correction coils. On this basis, FNAL plans not to use tuning shims. KEK has no provision for tuning shims.

9. A reference misalignment table should be developed jointly by the magnet builders and the accelerator physics group.

3 SUMMARY OF GLOBAL CORRECTION SESSION

J.-P. KOUTCHOUK, CERN

This session reviewed the means to minimize or suppress the requirement to locally correct the triplet multipoles. They are based on minimizing a measure of the non-linearity by sorting or correcting. This approach is confronted to the constraints of the real-world, such as those encountered in the RHIC construction. In this session the LEP experience was reviewed and the latest calculations on the beam-beam effect in LHC were presented as well.

3.1 Sorting

The sorting of the quadrupoles, including the effect on the two LHC rings, was shown by J. Shi to be definitely effective in terms of dynamic aperture, assuming the official error tables 2.0. J.P. Koutchouk pointed out the large randoms in this tables, which explain the success of sorting, but do not seem to be observed on the FNAL quadrupole models measured so far. S. Peggs analyzed how the sorting was conducted for RHIC. It appears that for all kinds of magnets, the sorting was used to fix more ‘fundamental’ quantities than the higher-order multipoles. It was further constrained by real world issues like planning and capability of measuring all magnets cold.

The consensus is that sorting should be kept to fix ‘pathologies’, i.e. unexpected problems rather than predictable dispersion of characteristics. If this turns out not to be necessary and if the random multipole errors turn out to be as expected in table 2.0, sorting for dynamic aperture remains attractive and should be feasible if planned (magnet storage, ...). Indeed, if sorting can prevent using the multipole correctors, operation will gain in simplicity and efficiency.

3.2 Global correction

These methods require making several hypotheses:

- What are the most important non-linearities?
- What should be the ‘measure’ for the non-linearity?
- What should be the layout of the correctors?

J. Shi chose to minimize a norm of the one-turn map coefficients order by order. T. Sen rather minimized excitations terms of 3^{rd} order resonances evaluated at the dynamic aperture. The corrector layout obeys no special rule in the first case while the sextupoles in the triplets were used in the second case. The map minimization appears effective and the very first results of the second method show some improvement in spite of an unfavorable sextupole arrangement.

It is not proposed to replace the local correctors by a global correction scheme. The unknowns are still too many: robustness versus optics errors, efficiency in case of an optics change between the non-linear source and the correctors or a tune change, effect of the global minimization of the non-linearity on the beam lifetime.

The advantage of the global scheme is its generality which allows to act even if the exact source is unknown by means of a small number of non-linear ‘knobs’. The consensus is to encourage an evaluation of what non-linear knobs could be implemented with the available LHC non-linear correctors and to identify which one would be worth adding.

3.3 Crossing angle

The latest results obtained by T. Sen show that the dynamic aperture due to the beam-beam only is limited at 8.5σ for the nominal crossing angle. The latter appears to be the very minimum for a decent dynamic aperture. Increasing it to $\pm$175 μrad gives a very significant decrease of amplitude growth in 4D tracking, especially in the range from 8 to 11σ.

The field quality requirements on the quadrupoles should not be relaxed, since the crossing angle cannot be decreased, and in fact may likely to be increased in the future.

3.4 LEP experience

Although the electron beam dynamics in LEP is very different, the review of the LEP experience shows the importance of a good and versatile instrumentation, and the requirement to take into account the complexity of operation and machine studies (13000 vertical orbit corrections in one year!). The beam based alignment using K-modulation turned out to be very useful and allowed the detection of PU misalignments far above expectations (up to 2 mm).

4 SUMMARY OF LOCAL CORRECTION SESSION

T. TAYLOR, CERN

The desired correction strengths of the local correction windings appear to be well within the range which can be obtained using the CERN techniques for making spool pieces. The distribution of the seven windings, with two windings in the dipoles and three in the skew quadrupole, is also acceptable. Using the baseline values, a check of the true engineering feasibility of the windings will be made at CERN.

The baseline strengths include a safety factor of at least two. If the multipoles come out to be much weaker than presently estimated, this could lead to having windings running at a very small fraction of their maximum value, which is operationally undesirable. It was suggested that the level below which a multipole would be considered to be acceptable without correction should be determined, and that this information should also be taken into account in the final determination of spool corrector strengths.

The final design of the spool pieces will be made after the next update of the expected multipole errors in the magnets, which is targeted for next September.