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FERMILAB-Pub-97/378

Summary Report of the LHC Mini-Workshop on Interaction Region Design

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May 1998

Proceedings of the *LHC Mini-Workshop on Interaction Region Design*,
Fermilab, Batavia, Illinois, October 7-8, 1997

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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November 1997

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The LHC Mini-Workshop on Interaction Region Design was held at Fermilab on October 7-8, 1997. Thirty five people from CERN, LBNL, BNL, University of Houston, University of Kansas and Fermilab attended the workshop. The following topics were discussed:

- Field quality requirements for the High Gradient Quadrupole (HGQ) magnets being built at Fermilab for the LHC inner triplets.
- Layout of the inner triplet in the interaction region (IR).

The discussions are summarized below.

1. HGQ field quality table:

   The HGQ field quality table provides a common reference for discussion of field quality issues from the viewpoint of magnet fabrication, machine performance and IR systems layout. The first version of the table was presented in [1]. Subsequent revisions are issued as new data from the magnet R&D program, the machine performance studies and the systems layout design become available. The criteria in setting the field quality requirements is that the long term dynamic aperture in collision (including both beam-beam effect and magnet errors) should be equal to or greater than 8σ, where σ is the rms beam size. It is known that the arc magnets have insignificant effect on the dynamic aperture in collision. Following workshop discussions, two tables have been adopted: Table 1 for the magnet body, Table 2 for the end regions. In Table 1, the $\pm$ sign in the systematic part represents uncertainties due to limitations of field quality correction schemes, errors in magnetic measurements and variations of material properties (such as magnetic permeability of the stainless steel collar and iron yoke). A more detailed discussion of the format of Table 1-2, the error sources which have been considered and the differences with respect to the previous version can be found in [2].

   Preliminary tracking results, using the LHC collision optics v5.0, fractional horizontal and vertical tunes of 0.307 and 0.302, 10^5 turns, horizontal crossing, and including both beam-beam interactions and magnet errors, give a dynamic aperture of 8.05σ for a crossing angle of 300 μrad when Table 1-2 are used. This means an increase of about 2σ when compared with the tracking results

Reference Table 1. HGQ Magnet Body (at $R_0 = 1$ cm)

	Systematic		Random	
n	b_n	a_n	b_n	a_n
3	0 ± 0.2	0 ± 0.2	0.5	0.5
4	0 ± 0.09	0 ± 0.09	0.3	0.3
5	0 ± 0.04	0 ± 0.04	0.07	0.07
6	0 ± 0.02	0 ± 0.02	0.03	0.03
7	0 ± 0.01	0 ± 0.01	0.008	0.008
8	0 ± 0.004	0 ± 0.004	0.003	0.003
9	0 ± 0.002	0 ± 0.002	0.0016	0.0016
10	0 ± 0.0009	0 ± 0.0009	0.0005	0.0005

Reference Table 2. HGQ End Regions (at $R_0 = 1$ cm)

	Return End	Lead End
L_{end} (m)	0.33	0.41
b_6	0.14	0.66
b_{10}	-0.004	-0.0032
a_2	0	38.5
a_6	0	0.02
a_{10}	0	-0.0011

Notes added to Table 2: (1) Systematic only; (2) In order to scale to equivalent errors "uniformly distributed" over the whole magnet, using the following expression: b_n (or a_n) $\times$ L_{end}/L_{magnet}; (3) $L_{magnet} = L_{lead-end} + L_{return-end} + L_{body}$.

(5.91σ) obtained from using the PAC97 table [1]. The principal reason of this increment is that the random b_3 is reduced from 1.3 to 0.5. Because the tunes are near the third integer, b_3 plays a big role in limiting the dynamic aperture.

The value of the systematic b_{10} in Table 1 (0.0009) is significantly smaller than that in Ref. [3] (0.005). This is regarded to be both possible and necessary (leading to an increase of about 20% in dynamic aperture).

In Table 1, the a_n's and b_n's are well balanced in the sense that no single term is dominant in determining the dynamic aperture.

2. End effects:

   There are two issues associated with the end effects:

   (a) The end fields are intrinsically 3-D. The field harmonics used in 2-D analysis (*i.e.,* the b_n's and a_n's) should be replaced by pseudo-harmonics or by their integrated values (integration from $B_z = 0$ somewhere inside the magnet to $B_z = 0$ somewhere outside the magnet). The values listed in

Table 2 are the integrated ones. However, some of the multipoles (*e.g.,* b_6) have a quick sign flip along the magnet axis near the ends (that is, it varies from a large positive amplitude to a negative one while giving a relatively small integrated value). How to justify that the integrated values are a faithful representation of the end effects?

Although there has been no detailed quantitative work on this problem, it is believed that the approach using the integrated value is appropriate. This is because the changes of the phases and β-functions are small within this region, which is less than half meter in length. However, it is recommended to carry out a calculation of the β-function weighted integral value of b_6 as a justification of the present approach.

(b) Cancellation of errors by ends arrangement.

It is posible to arrange the ends of neighboring magnets in such a way that the errors can be cancelled by each other. This has been successfully done at the RHIC IRs. It is shown that the footprints due to the end errors are reduced significantly when the arrangement is properly made. There are, of course, engineering constraints that one has to keep in mind when positioning the lead and return ends of each magnet.

3. Field measurement errors:

Field measurement accuracy has significant impact on the systematic error uncertainty and on the random errors, especially for the higher order multipoles [1]. In order to provide more accurate estimates, the systematic and random measurement errors are under study at Fermilab, using a simulation code written for the SSC magnets.

4. Closed orbit error:

The radial space in the HGQ is precious. The half-aperture is 35 mm. A space budget, which includes crossing separation, radiation shielding, helium flow channel, mechanical tolerance, closed orbit error and beam oscillation amplitude, has been established. In this budget, the allocation to the closed orbit error is 4 mm. It is pointed out that this number is too big. At collision, the closed orbit error at the IR should be and can be controlled to below 1 mm. It is, however, also strongly suggested that the extra 3 mm should be used as a reserve rather than to be allocated for any other purposes (such as to increase the thickness of the shielding).

5. Beam position monitor (BPM):

Presently there are three BPMs in the layout of the inner triplet region. There is a proposal to install only two because the other one is redundant. The reason is to reduce the cost. However, the workshop considered the redundancy to be necessary in this important region. The 3rd BPM can be used as a reserve in case any one of the other two BPMs fails.

The beam-based K-modulation technique is valuable in the alignment of the BPMs and HGQs. It is recommended to have a trim power supply (or other means for K-modulation) on each HGQ so that the alignment can be done with high accuracy and in a straightforward manner.

6. Correctors:

   There are several multipole correctors in the the inner triplet layout. The discussion is focused on the corrector between Q2a and Q2b. From beam physics point of view, this is an ideal location for a corrector because the β-function is the largest. However, this creates a substantial amount of engineering problems, such as the interconnections between the correctors and Q2a/Q2b, a long cryostat that will contain three magnets (Q2a, Q2b and the corrector), which makes field measurement and alignment difficult, *etc.*. Relocating the corrector would reduce its efficiency due to decrease of the β-function. For example, the efficiency of a b_6 corrector will be reduced by 32% if it is to be moved to the other side of Q2a. A b_{10} corrector (which may not be needed) would become virtually ineffective. These analytical estimates need to be checked by tracking.

   If, on the other hand, one decides to keep this corrector at where it is now, then the 1-meter space between Q2a and Q2b may not be enough and need to be increased to, say, 1.5 meters. The impact on the optics will have to be studied.

   In any of these correctors, one should consider to install multiple layers of coils so that each corrector can be used for correcting several types of multipoles. It is also pointed out that the correction should be *in-situ*. In other words, the correctors need to be close to the error sources. For instance, the lead ends give large systematic b_6. By locating the lead ends of Q2b towards Q3, one could put the b_6 corrector at the MCQS.

References

[1] G. Sabbi *et al.*, "Magnetic design of a high gradient quadrupole for the LHC low-β insertions," 1997 Particle Accelerator Conference, Vancouver, Canada, May 12-16, 1997.

[2] G. Sabbi, "HGQ_9711 Field Quality Table", Fermilab TD-97-050, November 1997.

[3] A. Faus-Golfe and A. Verdier, "Dynamic aperture limitations of the LHC in physics conditions due to low-beta insertions," 1996 European Particle Accelerator Conference, Sitges, Spain, June 10-14, 1996.