Session Summary:

FIELD QUALITY AND RELATED ACCELERATOR REQUIREMENTS

December 14, 1998
S. Peggs, BNL

1 Introduction

The workshop "Magnets for a Very Large Hadron Collider" was held in Port Jefferson NY, from November 16 – 18, 1998. This is the summary of the session entitled "Field Quality and Related Accelerator Requirements". Table 1 lists the presentations that were made in the session, and which form the basis for the discussion and comments, below.

Speaker	Topic
S. Peggs	Magnet Field Quality and Lattice Design Options
R. Gupta	Field Quality Aspects of the Different Magnet Designs
G. Sabbi	Magnetic Design of Small Aperture Dipoles: Shell & Block
V. Kashikhin	Iron Magnetic Design and Test for Low-Field Magnets
W. Foster	Aperture Budget for Low Field VLHC and Injector
R. Gupta	Common Coil Magnet System with a Large Dynamic Range

Table 1: Presentations: "Field quality and related accelerator requirements".

It was Hegel who first talked of an evolution of ideas beginning with "thesis", inevitably leading to contradictory ideas of "antithesis", which eventually are resolved through "synthesis". His perspective was quite abstract and spiritual. Marx later embraced this terminology, but turned into a perspective of pragmatic action.

It can be argued – although perhaps not persuasively – that the workshop went through this Hegelian evolution in discussing the relationship between the Magnet Physicists and Engineers (who dominated the workshop) and the Accelerator Physicists (the minority).

THESIS: "Strong interactions with Accelerator Physics are necessary".

This statement was casually made in plenary session at the beginning of the workshop.

ANTITHESIS: "Let's ask the Accelerator Physicists to make minimum requirements on magnet performance". "Accelerator Physics is easy – sit down for a weekend, read a book, and learn it".

Both of these (approximate) statements were made during the workshop.

SYNTHESIS: "Let's interact strongly on field quality, aperture, impedances, time dependent effects, et cetera".

It's not sufficient to merely "pass parameters" between Magnet Builders and Accelerator Physicists, as if they were software modules.

2 Discussion and comments

The discussions and comments, below, loosely follow the chronological sequence of the presentations. In some places related comments on common topics made by different speakers are drawn together, to aid pedagogy.

2.1 Trading systematic errors with cell length

Systematic field errors dominate random field errors in contemporary low temperature superconducting magnets. This is the RHIC experience. It is a hypothesis which may or may not be true for each of the many potential vlhc magnet technologies.

If true, the hypothesis greatly simplifies the Accelerator Physics analysis, since the emphasis shifts away from Dynamic Aperture calculations (which are notoriously slow and difficult) to linear aperture and tune shift calculations (which are relatively straightforward).

Calculations of tune shifts may be manipulated to give scaling rules for maximum allowable systematics . For a given magnet aperture, lattices with relatively long arc cells have cost saving advantages. The maximum arc cell length may be set by the maximum tolerable tune shifts. Thus, arc cell length may be traded off against systematic field quality, as shown for a typical parameter set in Figure 1.

The figure assumes that a tune shift as large as 0.1 is acceptable. Justifying this assertion is a major challenge to Accelerator Physicists, consistent with the charge to the workshop to "*explore and develop innovative concepts that will result in significant cost reductions*".

Also see http://www.rhichome.bnl.gov/AP/ap_notes/RHIC_AP_114_4.ps

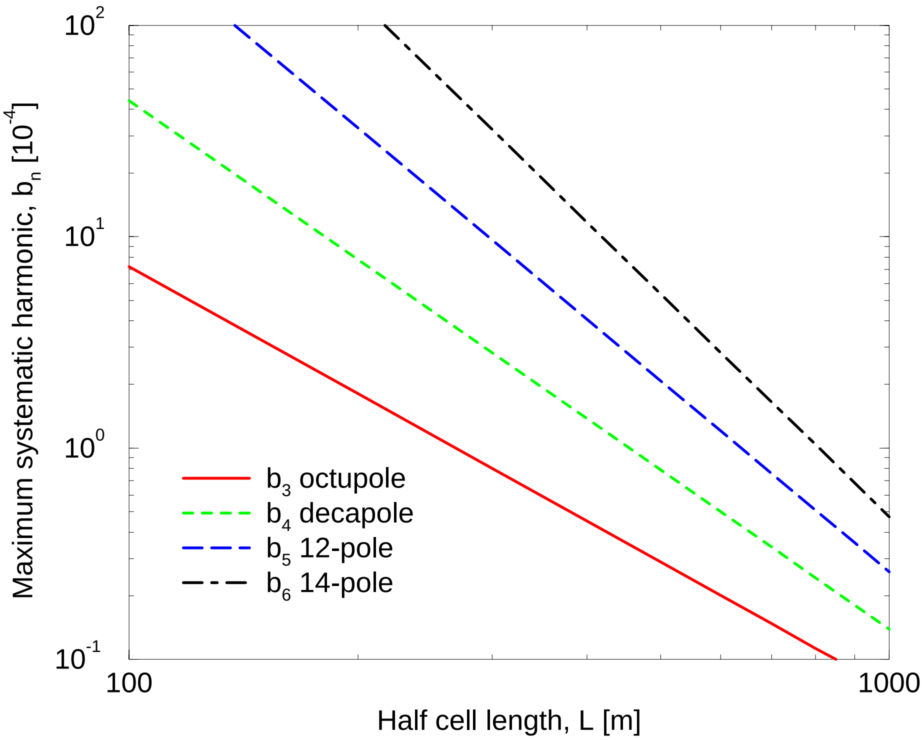

Figure 1: Maximum allowable systematic harmonics versus half cell length, when $\widehat{\Delta Q_x} = 0.1$, $\phi_c = 90$ degrees, $\epsilon_x = 1\mu$m, and $m = 3$, at an energy of 1 TeV, with a reference radius of $r_0 = 16$ mm.

2.2 Random field errors estimations

R. Gupta showed data that compared measured random harmonic field errors in arc dipoles in the Tevatron, HERA, and RHIC. Random harmonics are reduced in the later magnets, sometimes by almost two orders of magnitude. Further, it was shown that the random harmonics predicted for SSC dipoles are in general far larger than the values actually measured.

The exaggerated random harmonic predictions are said to be due to the conservative assumption that is often made, in which the misalignments of all components – collars, wedges, and coils – are all completely random. In fact there are many internal constraints that limit the net random field error. Further, some of these random misalignments are averaged out along the length of the magnet.

Others, including *G. Sabbi* in his presentation, took issue with the severity of this over-estimation, although not with the general principle that internal constraints have yet to be properly handled. *Sabbi* showed a comparison between predicted random field errors for cos(θ) "shell" and rectangular "block" coil magnets. With the same misalignment assumptions, and the same coil aperture, the block coil magnet consistently achieves random errors which are a factor of 2 or 3 smaller than the shell coil magnet.

Also see http://www.fnal.gov/projects/hgq/hfm/ws_bnl/viewgraphs.html

2.3 Shell coil and block coil magnets

It is easier to construct brittle superconductors – Nb_3Sn or contemporary High Temperature Superconductors – into rectangular "block" coils, rather than the conventional cos(θ) "shell" coils. Following on from preliminary descriptions by the plenary speakers, *G. Sabbi* presented work in progress on a detailed design comparison of small aperture shell and block dipoles, as listed in Table 2.3.

Sabbi also noted the charge to *explore and develop innovative concepts that will result in significant cost reductions.* Therefore, despite the fact that the SSC arc dipole coil diameter increased from 40 to 50 mm, and the LHC arc dipole from 50 mm to 56 mm, we can consider the reducing the vlhc aperture from 50 mm to (say) 30 mm.

Coil type	Aperture [mm]	Layers	Current blocks
Block	30	3	6
Shell	30	3	6
Shell	50	2	6

Table 2: Shell and block dipoles discussed by Sabbi.

It is concluded that:

1. A 30 mm bore dipole with a design field of 12 – 13 T using Nb_3Sn conductor at 4.2 K allows substantial savings in superconductor with respect to a 50 mm bore magnet with same design parameters.
2. For these design parameters, shell and block designs are substantially equivalent in terms of conductor efficiency and field quality.
3. In order to achieve same transfer function, a vertical arrangement of two apertures requires a yoke radius that is 50% larger than the equivalent horizontal arrangement.

Also see http://www.fnal.gov/projects/hgq/hfm/ws_bnl/viewgraphs.html

2.4 Superferric magnets

W. Foster pointed out a "Fundamental difference between superferric magnets and conventional superconducting magnets: In iron-dominated magnets the good-field aperture goes all of the way to the pole tips. Circulating aperture is limited by physical aperture and magnet can be scaled as beam size decreases with energy. In conductor-dominated magnets the superconductor is 'lumpy' and the good-field region does not exist within $\sim$0.5 inches of conductor. Minimum reasonable coil aperture is $\sim$1.5 inches and usually $>$2 inches".

Foster also showed a misalignment and aperture budget table that included the effects of closed orbit distortion, injection steering errors, beam position monitor offsets, magnet straightness, and magnet settling (between realignments). He concluded that the required aperture at 150 GeV injection into a 3 TeV booster using low-field superferric magnets is $\pm$7.5 mm in the horizontal, and $\pm$6.9 mm in the vertical.

V. Kashikhin reported on a method to partially correct saturation effects in superferric combined function magnets. Saturation in the pole tips of the iron laminations leads to quadrupole gradient shifts and unwanted systematic sextupole harmonic errors. The method is to remove material from the center of the pole tip of every 10th lamination. Preliminary encouraging results were presented.

2.5 Hybrid block and common coil magnets

In his second presentation, *R. Gupta* pointed out that there are (at least) 10 – 15 years before the vlhc becomes a realistic design proposal. This gives us a rare opportunity to explore alternative magnet technologies.

High Temperature Superconductors have made rapid recent progress. However, it still remains to be shown that HTS materials are practical for large scale production, in both cost and technological performance. *Gupta* showed BNL drawings of a "hybrid block" magnet in which the outer coils are conventional low temperature conductors, while the inner coil is made of an HTS material under test. The HTS coil is subjected to forces similar to those that would be present in an all-HTS magnet. Designed to be easily broken down and reconstructed, the hybrid block magnet allows fast turn-around to explore and develop innovative magnet technologies such as HTS, Nb_3Sn, Nb_3Al, et cetera.

Also presented was the conceptual design of a "common coil" block magnet with four apertures, shown in Figure 2. The two outer low field iron-dominated apertures are used to accelerate the beam in a "booster" phase. The beams are then transferred to the two inner high field current-dominated apertures, for the final phase of acceleration to storage energies. This assumes that the same four bore magnet is installed around the entire circumference of a "high-field" vlhc tunnel.

Advantages claimed for this magnet include good field quality throughout

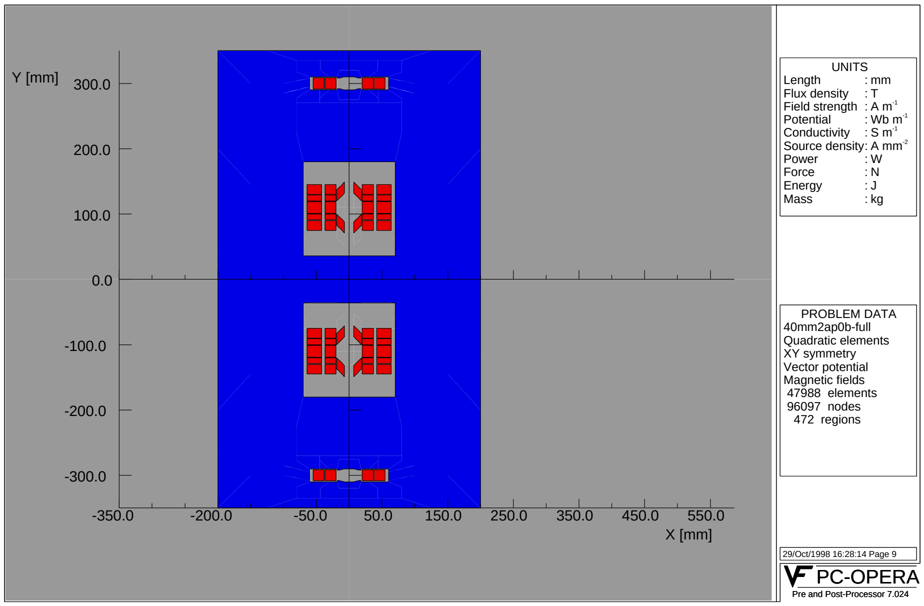

Figure 2: Common coil block magnet, with two outer iron dominated low field apertures, and two inner conductor dominated high field apertures.

an acceleration process with a total dynamic range of $\sim$150, using only a single power supply. Installation around the entire circumference has the advantage of a requiring only a single booster cycle, at the financial cost of providing a full length "booster". It may be possible to reduce the high field aperture, to (say) 25 mm, since the beam is transferred at $\sim$1.5 T, instead of at $\sim$0.5 T.

2.6 Time dependent effects – snap-back

Another advantage of the common coil magnet is that beam can be transferred from low-field to high-field apertures "on the fly" – while the magnet is ramping. This avoids the "snap-back" phenomenon, in which magnetic field harmonics change very rapidly when conductor-dominated magnets that have been sitting at a constant injection field for a significant time begin ramping.

The snap-back effect is (arguably) the most difficult Accelerator Physics problem that the LHC will face in its commissioning. This may well also be true of the vlhc.

Despite the importance of snap-back and other time dependent effects, very little attention was paid to these effects at the workshop; persistent current induced harmonics measured in the LBL D20 magnet were briefly presented, and the dependence on "effective filament diameter" was briefly discussed.

3 Conclusions

One of the charges to the workshop was to "explore and develop innovative concepts that will result in significant cost reductions". This is a challenge to both Magnet Builders and to Accelerator Physicists.

1. If systematic field errors continue to dominate random field errors, it is straightforward to trade off field quality with arc cell length. Accelerator Physicists are challenged to show that tune shifts as large as 0.1 are tolerable.

2. Simple models of random component misalignments are found to overestimate random field errors, when predictions are compared with measurements. Block coil magnets are expected to have random errors that are significantly smaller than shell magnets.

3. Smaller aperture dipoles allow substantial savings over large bore magnets with the same design parameters. Shell and block magnet designs are substantially equivalent in conductor efficiency and systematic field quality. A vertical arrangement of two apertures requires a 50% larger yoke radius when compared to the equivalent horizontal arrangement.

4. The good field aperture approaches closer to the iron poles in an iron-dominated magnet than it does to the coils in a conductor-dominated magnet. Saturation effects in the pole tips of an iron-dominated magnet may be ameliorated by removing some material from the center of every Nth lamination.

5. Hybrid block magnets – with low temperature superconducting outer coils, and a high temperature superconductor inner coil – allow fast turn-around to explore and develop innovative magnet technologies such as HTS, Nb_3Sn, Nb_3Al, et cetera.

6. A common coil block magnet with four apertures potentially allows acceleration over a dynamic range of $\sim$150, using only a single power supply. Beam is transferred from the outer iron-dominated apertures to the inner current-dominated apertures "on the fly".

7. "Snap-back" is (arguably) the most difficult beam dynamics problem faced by the LHC. This and other time dependent effects in the emerging vlhc magnet technologies need to be closely monitored and evaluated.

4 Appendix: Expected harmonics

The following sets of expected harmonics were presented by various authors. They are gathered here for convenience.

Harmonic	b_n
a2	-1.30
b2	-.77
a3	-.18
b3	.92
a4	.06
b4	-.05

Table 3: The LBL D20 Nb_3Sn magnet (Gupta, Scanlan). Measured integrated harmonics at a field of 9.4 T, over a length of 1.4 meter, including ends. Units: 10^{-4} at a reference radius of 10 mm.

Component	Block 30 mm	Shell 30 mm	Shell 50 mm
b3	-.1	.1	.0
b5	.3	.3	-.1
b7	.6	.7	.0
b9	-.8	.6	.1
b11	1.2	2.9	.0
b13	.2	-.5	.0

Table 4: Block and shell magnets (Sabbi). Calculated geometric harmonics in the body. Units: 10^{-4} at a reference radius of 10 mm.

Field (T)	Transfer Func. (T/kA)	a_1	b_2	a_3	b_4	a_5	b_6	a_7	b_8
1.56	1.056	3.95	-3.83	.16	.26	-.06	2.15	.00	.01
3.11	1.055	3.95	-3.55	.16	.26	-.06	2.15	.00	.01
4.60	1.041	-.53	-.46	.16	.27	-.06	2.18	.00	.01
5.99	1.017	1.00	3.39	.04	.24	-.06	2.23	.00	.01
7.28	.988	-1.70	3.90	-.12	.19	-.07	2.30	.00	.01
8.51	.963	-3.36	2.99	-.20	.13	-.07	2.36	.00	.01
9.71	.942	-3.73	1.80	-.24	.08	-.07	2.41	.00	.01
10.89	.924	-3.18	.59	-.25	.03	-.07	2.45	.00	.01
12.06	.910	-2.24	-.47	-.25	.00	-.07	2.49	.01	.01
13.22	.898	-1.19	-1.34	-.25	-.03	-.07	2.53	.01	.01
14.38	.888	-.14	-2.08	-.24	-.05	-.07	2.55	.01	.01
15.53	.879	.86	-2.70	-.24	-.07	-.07	2.58	.01	.01
16.69	.872	1.81	-3.22	-.24	-.09	-.07	2.60	.01	.01

Table 5: Common coil magnet with four apertures (Gupta). Calculated harmonics in the body of a very preliminary design. Note that columns with normal (b_n) and skew (a_n) harmonics are interleaved. Units: 10^{-4} at a reference radius of 10 mm.