An Update on US-LHC Accelerator Physics Activities at BNL

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RHIC/AP/149

1. Overview
2. Magnet Error Assessment & Compensation Strategy
3. Production Monitoring & Support
4. CERN Compatibility & Software Adaptation
5. Summary

Budget profiles:

WBS	LAB	Labor [fte-yrs]	Labor [k$]	Matl. [k$]	Total [k$]
1.4.1	BNL	14.0	1,983	0	1,983
1.4	Total	36.2	5,083	176	5,259

Year	FY97	FY98	FY99	FY00	FY01	FY02	FY03	FY04	Total
[fte-yrs]	0.5	2.0	1.6	1.9	2.0	2.0	2.0	2.0	14.0

Section	Title	BNL [fte-yr]
	Design Issues	
4.1.1	Dynamics analysis & simulation	4.3
4.1.2	High Gradient Quadrupoles	1.5
4.1.3	Beam splitting dipoles, D1	0.5
4.1.4	RF section magnets	1.0
4.1.5	Alignment	3.3
4.1.6	Quality review of production magnets	2.8
	Beam Physics Issues	
4.2.4	Software maintenance & development	0.6

- "Labor" and "Materials" are fully loaded with overhead and contingency.
- Travel costs are covered in the Project Management budget.

1. Overview

- Production oriented — support US-LHC magnets
  - * Design stage: (4.1.1, 4.1.2, 4.1.3, 4.1.4)
  - – Impact assessment of magnetic & alignment errors
  - – Magnet design optimization & compensation
    (end orientation; body-end compensation;
    tuning shim optimization; quench/thermal dependence)
  - – Triplet corrector layout & strategy
    (higher order correctors; beam-based; local decoupling)
  - * Production stage: (4.1.5, 4.1.6)
  - – Database to record field & alignment data
  - – Routine analysis & review of measurement data
  - – QA feedback to magnet builders and surveyors
  - – Installation preparation & Sorting
- Compatibility to CERN software and analysis (4.2.4)
  - – Benchmarking & occasional cross-check
  - – Standard eXchange File (SXF) shards by various codes and labs

- Scope
  - Integrated analysis of LHC collision performance
  - US-LHC magnets: HGQ (FNAL) & RF dipoles (BNL)
  - Relevant non US-LHC IR magnets: other HGQ (KEK), IR dipoles D1 (CERN?)
- Collaboration with other laboratories
  - Intimate relation with BNL & FNAL Magnet Groups, and with FNAL AP Group
  - In close contact with CERN AP Group and Magnet Groups (parameter verification; monthly reports; workshops; visits; MTA Group for magnet measurement database structure)
- The Team
  - J. Wei, F. Pilat, V. Ptitsin, S. Tepikian (RHIC AP); C.G.. Trahern (RHIC Controls)
- US Collaborators
  - R. Talman, N. Malitsky (Cornell); J. Shi (U. Kansas)
- A "Technology Transfer" — RHIC to US-LHC
  - Adaptation of analysis method, software tools, and database structure
  - Adaptation of compensation strategy & corrector layout

2. Magnet Error Assessment & Compensation Strategy

Figure of Merit: action-kick minimization

$$\left|\frac{\Delta J_{x,y}}{J_{x,y}}\right| = \frac{1}{4\pi\rho}\int \sum_n \beta_{x,y}\left[(2\beta_{x,y}J)^{1/2} + \frac{\Delta_{sep}}{2}\right]^{n-2} c_n \, ds < 0.005,$$

$$c_n = \begin{cases} \dfrac{10^{-4}b_n}{R_0^{n-1}}; & \text{or} \quad \dfrac{10^{-4}a_n}{R_0^{n-1}}, \qquad \text{(for dipoles)} \\[2ex] \left(\dfrac{G_0}{B_0}\right)\dfrac{10^{-4}b_n}{R_0^{n-2}}; & \text{or} \quad \left(\dfrac{G_0}{B_0}\right)\dfrac{10^{-4}a_n}{R_0^{n-2}}, \qquad \text{(for quadrupoles)} \end{cases}$$

Action-kick sensitivity to D1 errors at collision:

Multipole	b_2/a_2	b_3/a_3	b_4/a_4	b_5/a_5	b_6/a_6	b_7/a_7	b_8/a_8	b_9/a_9	b_{10}/a_{10}	b_{11}/a_{11}
$\lvert\Delta J/J\rvert$ ($\times 10^{-3}$)	4.08	2.48	1.51	0.93	0.57	0.35	0.21	0.13	0.08	0.05

- 1 unit multipole error; $\beta^* = 0.5$ m; 11σ amplitude
- reference radius defined at $R_0 = 25$ mm

Reference D1 Magnetic Errors at Collision ($R_0 = 2.5$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
2	0.1	0.8	0.3	0.6	3.5	1.6
3	−3.3	3.4	1.8	−0.3	0.6	0.2
4	0.0	0.3	0.1	0.0	1.1	0.4
5	0.5	0.8	0.4	−0.1	0.2	0.1
6	−0.1	0.1	0.0	−0.1	0.6	0.2
7	1.1	0.2	0.1	0.0	0.1	0.0
8	0.0	0.0	0.0	0.0	0.2	0.1
9	0.0	0.1	0.1	0.0	0.0	0.0
10	0.1	0.1	0.0	0.0	0.0	0.0
11	−0.6	0.0	0.0	0.0	0.0	0.0
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	−0.5	2.3	1.0	−1.4	4.3	1.8
3	22.4	2.9	1.1	−9.9	1.0	0.4
4	0.0	0.7	0.2	0.1	0.8	0.3
5	−0.4	0.7	0.2	2.2	0.3	0.1
7	0.9	0.1	0.1	−0.9	0.1	0.1
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	0.2	1.8	0.7	0.9	4.5	1.9
3	6.1	2.7	1.2	0.3	1.0	0.3
4	0.0	0.4	0.2	0.2	0.7	0.3
5	0.0	0.7	0.2	0.0	0.3	0.1
7	0.0	0.1	0.1	0.0	0.1	0.1

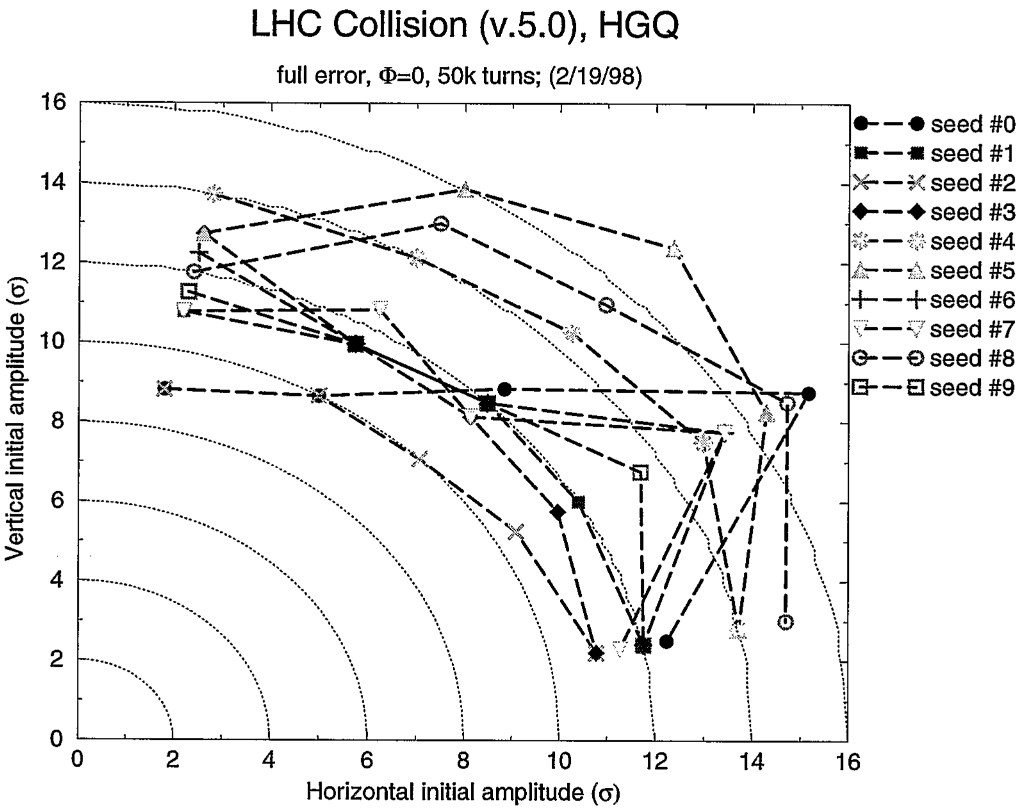
- Version 1.0 dated Feb. 4, 1998, based on RHIC arc dipole measurement data

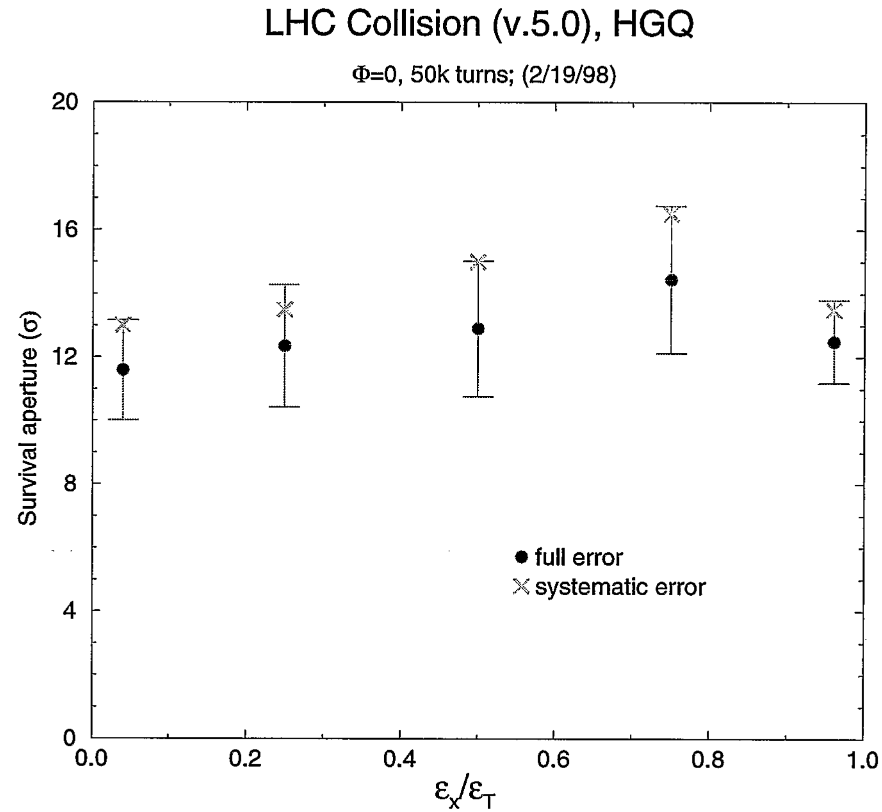
Reference HGQ Magnetic Errors at Collision ($R_0 = 1.0$ cm):

Order, n	Normal			Skew		
BODY [unit]	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
3	0.	0.2	0.5	0.	0.2	0.5
4	0.	0.09	0.3	0.	0.09	0.3
5	0.	0.04	0.07	0.	0.04	0.07
6	0.	0.02	0.03	0.	0.02	0.03
7	0.	0.01	0.008	0.	0.01	0.008
8	0.	0.004	0.003	0.	0.004	0.003
9	0.	0.002	0.0016	0.	0.002	0.0016
10	0.0003	0.0009	0.0005	0.	0.0009	0.0005
LEAD END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	0.			16.		
6	0.27			0.0083		
10	−0.0013			−0.00046		
RETURN END [unit-m]	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
6	0.046					
10	−0.0013					

- Version 1.0, based on TD-97-050, G. Sabbi, November 1997

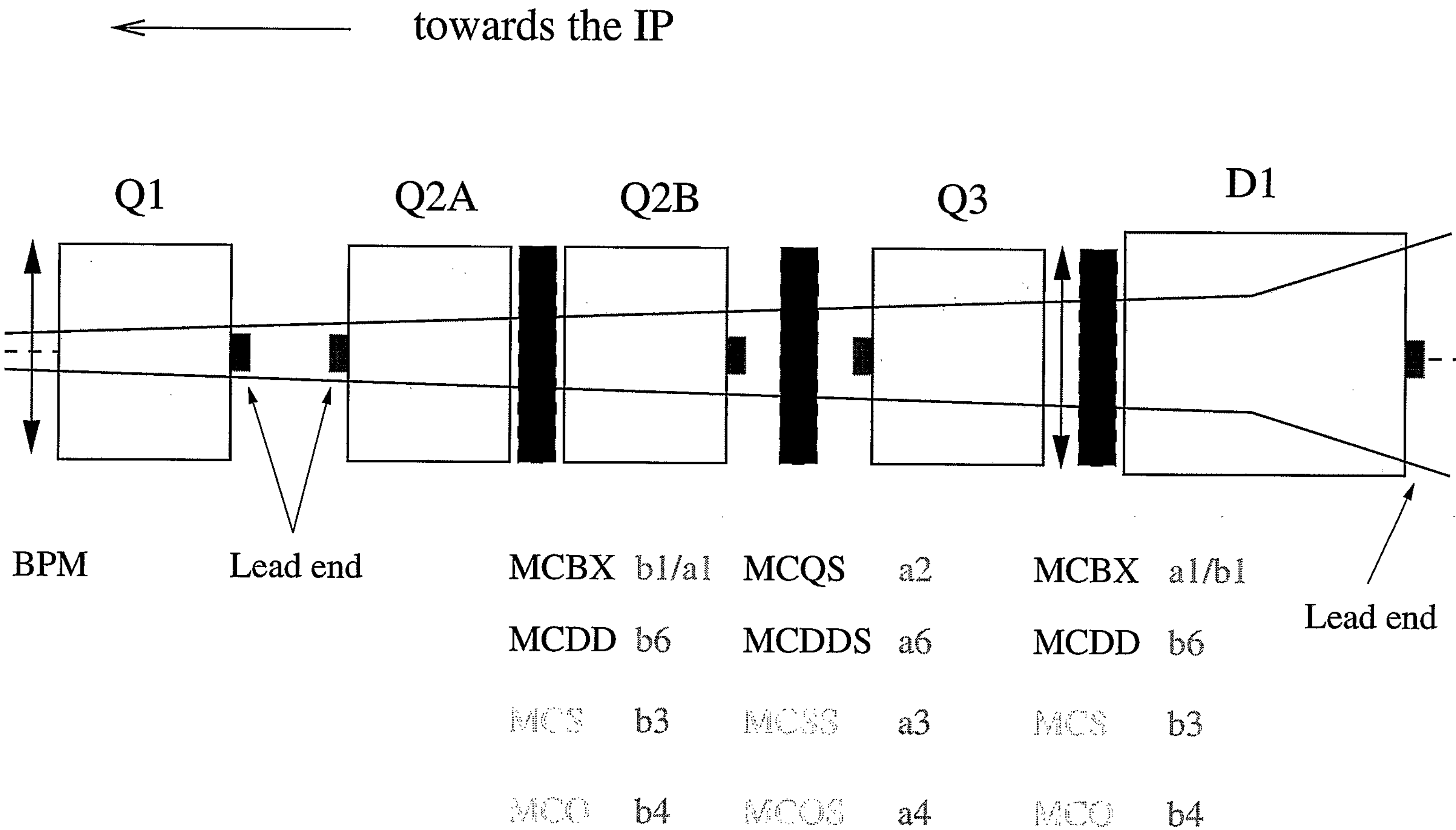
6-Dimensional Tracking of HGQ Errors at Collision:



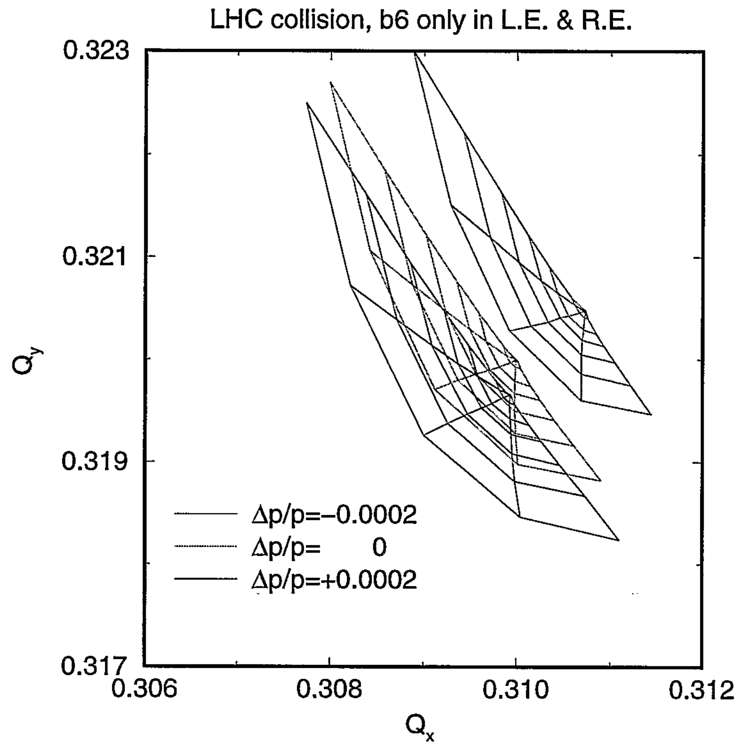


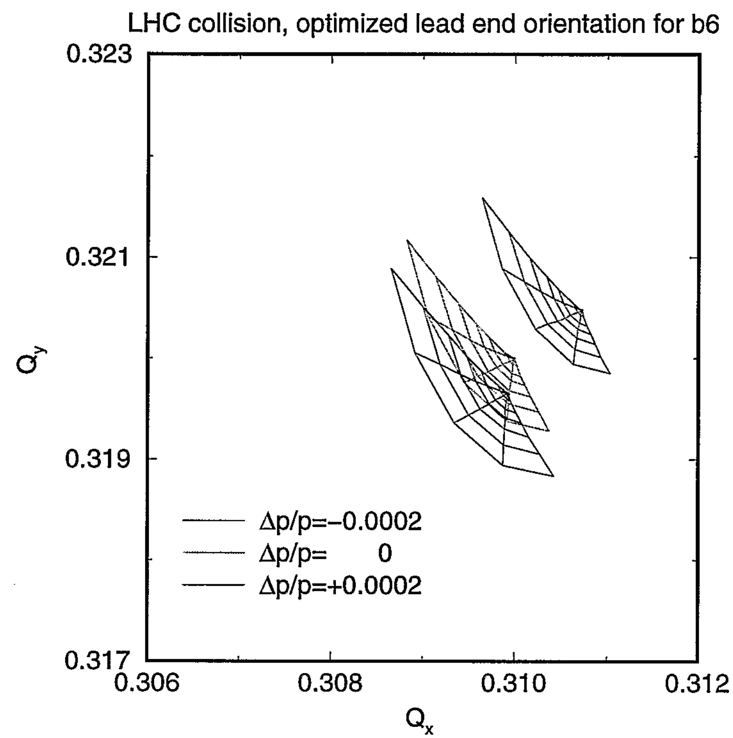
- 50k turn tracking using TEAPOT; zero crossing angle assumed
- mostly caused by random a_3/b_3 and a_4/b_4 error
- $\Longrightarrow$ Need IR correction

Insertion Region Proposed Layout



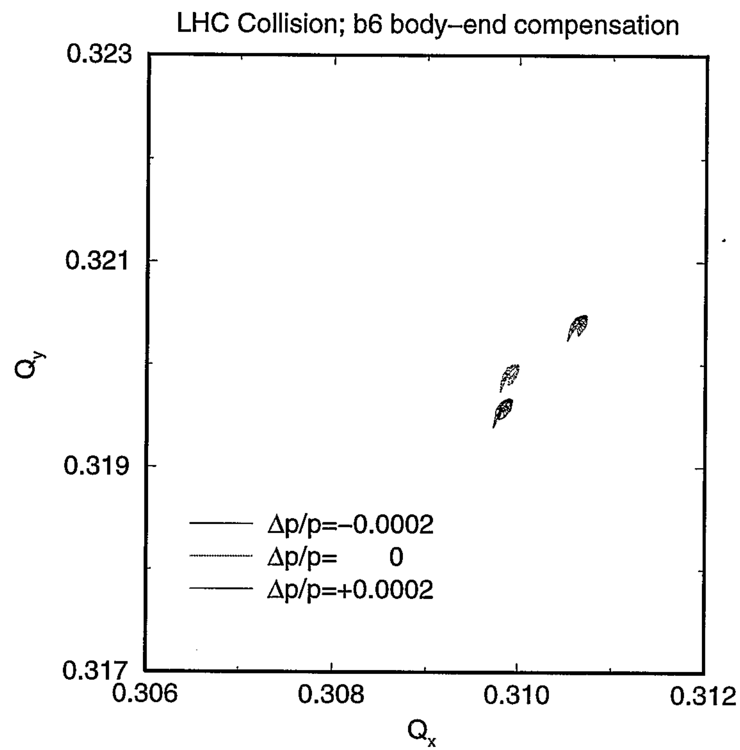
Tune Footprint Optimization with Magnet Orientation:





- impact of b_6 in HGQ lead ends minimized by F vs. D cancellation
- impact of b_3 in D1 dipole lead end reduced
- works for both beams at low β^*

Body-End Compensation



HGQ:

$$b_6(\text{body}) = -0.10\ B_{6L} - 0.23\ B_{6R} = -0.6\ (\text{unit}).$$

- weighted by β function to $(n/2)$th power; integrated b_6 compensation over each triplet
- coefficients show proper magnet orientation; optimum for $\beta^* = 0.5$ m (IP1, IP5)

D1:

$$b_3(\text{body}) = -0.095\ B_{3L} - 0.116\ B_{3R} = -2.8\ (\text{unit}).$$

Tuning Shims

- individually correct each HGQ and D1 after it is constructed and measured
- with 8 slots for shimming, can correct at least 4 body harmonics
- limited by measurement uncertainty
- limited by field variation with quench & thermal cycles

IR Correctors

- valuable "knobs" for beam-based correction
- useful for large measurement error & quench/thermal dependence
- for each multipole, need 2 correctors per triplet

RF Section Issues

- persistent b_3 at injection; saturation b_3 at maximum energy
- lack of local correction in RF Section

Compensation Strategy for HGQ and D1:

Order, n	Normal, b_n	Skew, a_n
1	MCBX	MCBX
2	trim	MCQS
3	S, (MCS [2])	S, (MCSS)
4	B, S, (MCO [2])	S, (MCOS)
5		
6	B+, MCDD [2]	B+, MCDDS
8	B	
10	B	

B: coil cross-section iteration

+: body-ends compensation

S: using tuning shims

MCBX: normal/skew dipole corrector for closed orbit

MCQS: skew quadrupole for decoupling

MCDD, MCDDS: local b_6/a_6 correctors

MCS, MCSS: local b_3/a_3 correctors

MCO, MCOS: local b_4/a_4 correctors

3. Production Monitoring & Support

- Review of magnetic field measurement data
  statistics and trends;
  quick feedback to magnet groups
- Review of alignment measurement data
  magnetic field w.r.t. coldmass fiducials;
  quadrupole w.r.t. multi-layer correctors
- Installation support
  magnetic field w.r.t. cryostat fiducials
  sorting

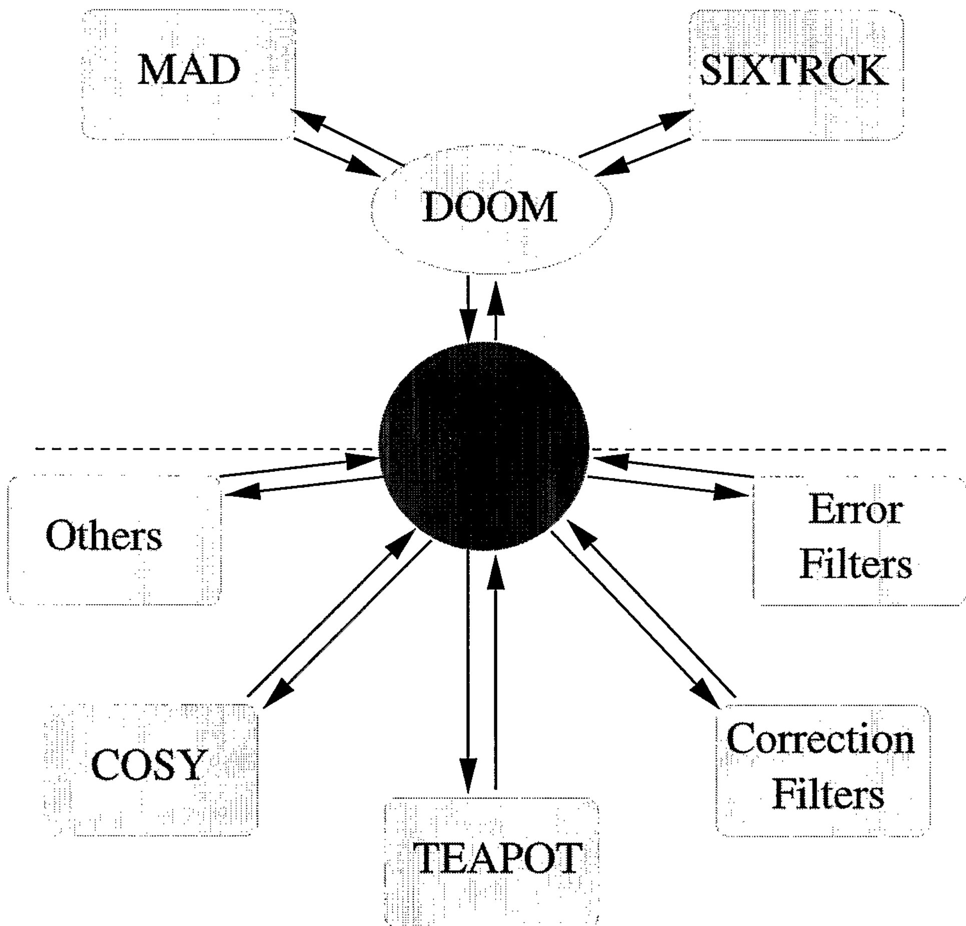
- database structures completed by BNL
- in contact with FNAL measurement group
- in contact with CERN magnet groups
- database/dataflow mini-workshop in June 1998

Summary of Database Tables for Measurement Data:

Table	Page	
Magnets	1	Magnet name table. Each magnet will have one row in this table.
Integral	2	Integral geometric multipoles table.
BodyHarm	4	The Dipoles and Quadrupoles will have multipoles measured at the ends and at the center. If so the center(body) data will be stored in this table
Endsharm	6	This table will store the multipole data from the ends. There should be twice as many rows here as in the BodyHarm table. Typically, higher order end harmonics are negligible and hard to measure. Therefore harmonics above a11 and b11 will not be recorded.
IntField	7	Integral field table. Only dipole magnets will have entries in this table
Magz	8	Magnetization multipoles
Eddy	10	Eddy current multipoles.
TDecay	12	Time decay multipoles - up ramp only
Centers	14	This table will conatin the centering offsets from the magnetic measurements
WarmCold	15	This table will hold the warm/cold transfer function and harmonics conversion values. The Delta_a1 --> Delta_b15 values are in Units*m for the lead and return regions and in Units otherwise.

4. CERN Compatibility & Software Adaptation

- Benchmarking & occasional cross-check
- Standard eXchange Format (SXF) shared by various codes and labs
- UAL-LHC mini-workshop held in February 1998



5. Summary

- 2.0 fte/year, to support US-LHC magnet design & construction at all stages
- Work as an integrated part of the program, closely collaborating with magnet groups at BNL & FNAL, AP groups at FNAL a& CERN, and later survey groups at various labs
- Jointly maintain *Reference* field error & misalignment tables (BNL & FNAL)
- Share benchmarked software and a Standard eXchange Format (SXF) as a base for both routine analysis and specialized error compensation (BNL, CERN, FNAL)
- Software workshop (for SXF development) held in February 98; database/dataflow workshop in June 98; joint workshop in 99
- To meet the demand and milestones of the Program