Magnets that Meet Tracking Requirements for AHF

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AHF Magnet Designs

- Dipole Magnet
  - B = 0.15 T at Injection (4 GeV)
  - B = 1.64 T at Extraction (50 GeV)
  - L_{eff} = 6.87 m
  - Gap = 5.0 cm
- Quadrupole Magnet
  - G = 1.81 T/m at Injection (4 GeV)
  - G = 18.5 T/m at Extraction (50 GeV)
  - L_{eff} = 1.29 m or 1.55 m
  - Pole tip radius = 5.0 cm

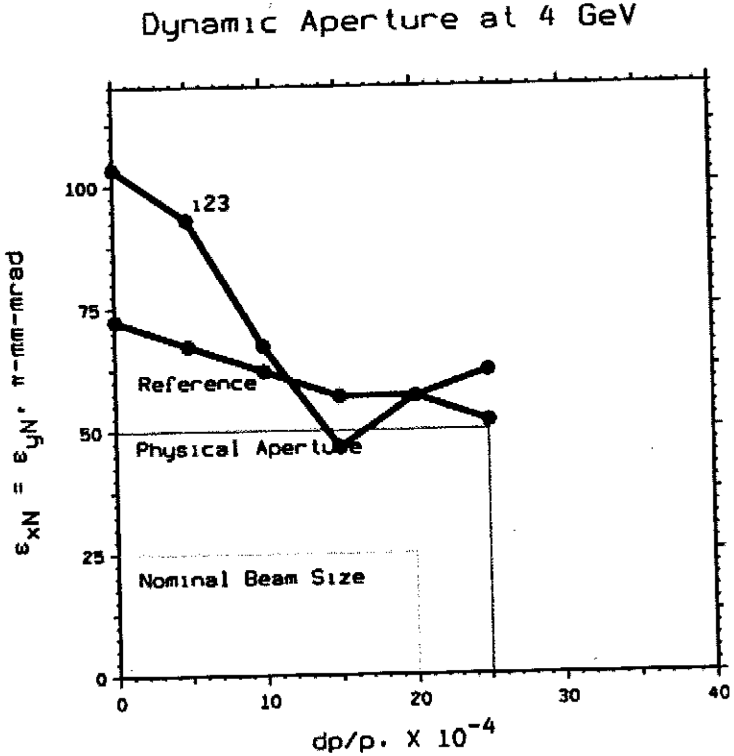
AHF Magnet Design Selections

- Dipole Magnet
  - FNAL MI or SSC MEB Design (longer with more sagitta)
  - Procurement, fabrication and assembly based on FNAL MI
  - Meets AHF requirements

- Quadrupole Magnet
  - Initial tracking studies based on harmonics in FNAL MI Handbook shows dynamic aperture problems at injection
  - Performed analysis to better understand source of harmonics
  - Studied different quadrupole designs and measurements to determine reasonable requirements
  - Verified dynamic aperture with new requirements

Initial Studies of Dynamic Aperture

original			
(based on values in FNAL MI Handbook)			
Multipole Order	Coefficient	systematic	random
quadrupole	b2		24
sextupole	b3	-0.51	2.73
octupole	b4	1	1.02
decapole	b5	0.03	1.12
duodecapole	b6	-1.49	0.63
14	b7	0.21	0.64
16	b8	1.14	0.64
18	b9	-0.19	0.12
20	b10	-0.77	0.06
skew sextupole	a3	1.08	1.85
skew octupole	a4	-2.05	2.38
skew decapole	a5	-0.75	0.47
skew duodecapole	a6	0.43	0.7
14	a7	0	0.44
16	a8	0	0
18	a9	-0.07	0.16
20	a10	-0.12	0.07



- Dynamic aperture smaller than physical aperture
- Dipole random and systematic harmonics based on FMI magnet measurements
- Quadrupole random and systematic harmonics based on "old" magnet measurements of FNAL main ring

HARMONICS CONVENTION

- Normal - B_n
- Skew - A_n
- Dipole - n=1
- Quadrupole - n=2
- Expressed in Units of 10^{-4} $\Delta B_n/B_2$ at a radius of 2.54 cm

Analysis of Quadrupole Magnet Harmonics for AHF

- Analyze Quadruple Measurement Data for a variety of Magnets
  - Better understanding of random errors
  - Look at assembly tolerances and errors
    - Coil proximity to pole
    - Gaps/tilts between half cores and quadrants
  - Determine "reasonably achievable" systematic and random errors
  - Add 30% margin and use result as "requirement"

- Quadrupole Measurement Data
  - FNAL MI Quads
  - ANL ALS Quads
  - LER Quads (SLAC PEPII)
  - SQC Quads (FNAL Antiproton Accumulator)

Analysis of Quadrupole Magnet Harmonics for AHF (cont)

- Analyze Recently Built IQC and IQD MI Quadruples
  - Analyze Measurement Data
    - Correlation between measured harmonics
    - Magnitude of Random Errors
  - Analyze MI Quadrupole with POISSON
    - Look at assembly tolerances and errors in 2D
      - Coil placement errors
      - Gaps between iron quadrants and half cores
      - Tilts between iron quadrants and half cores
      - Translation between iron mating surfaces
      - Stacking factor asymmetries
  - Compare simulated fabrication errors with measured random errors
    - They will have a distribution and a standard deviation
    - Can we predict the random multipole errors on the basis of the POISSON 2D models?

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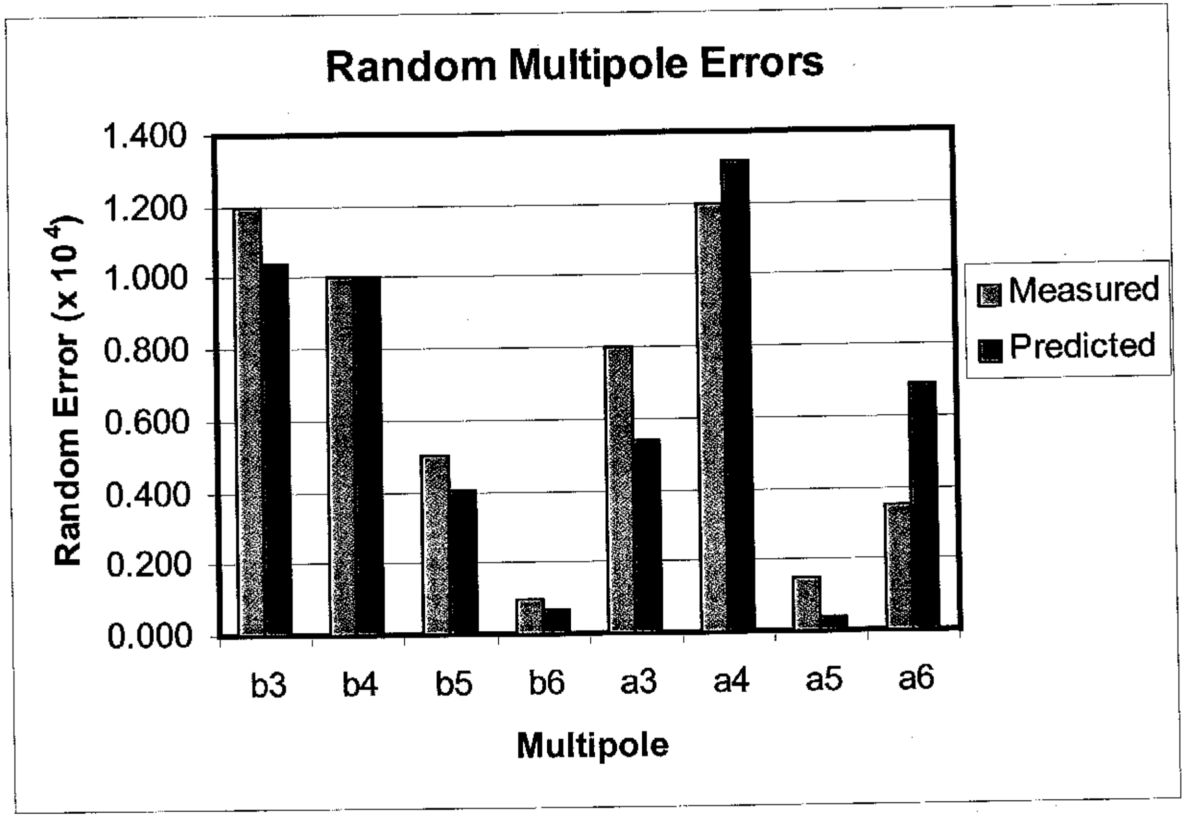
Good Agreement with Measured Random Errors



- Three main sources of random errors identified
  - Coil placement errors (σ = .018")
  - Gaps between half cores (σ = .0011")
  - Tilts between half cores (σ = .05 mrad)

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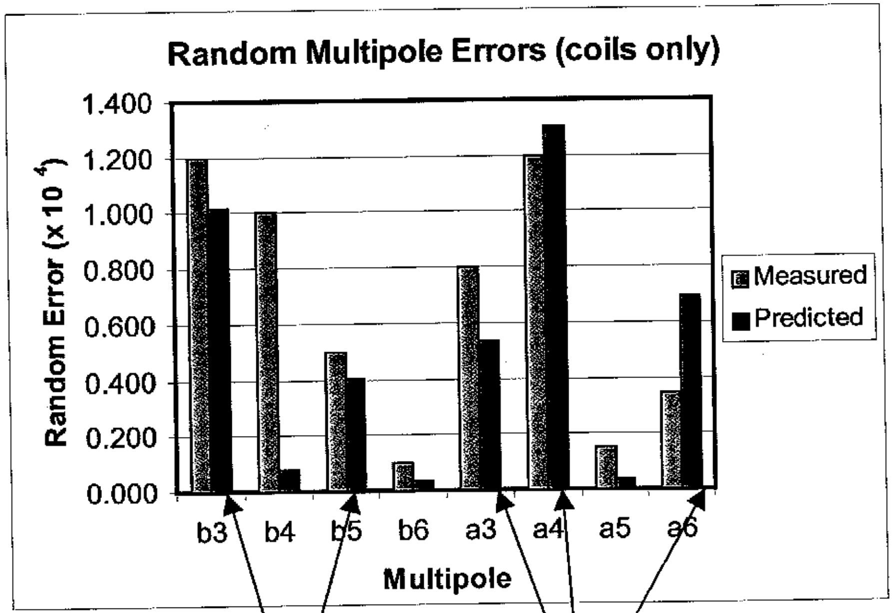
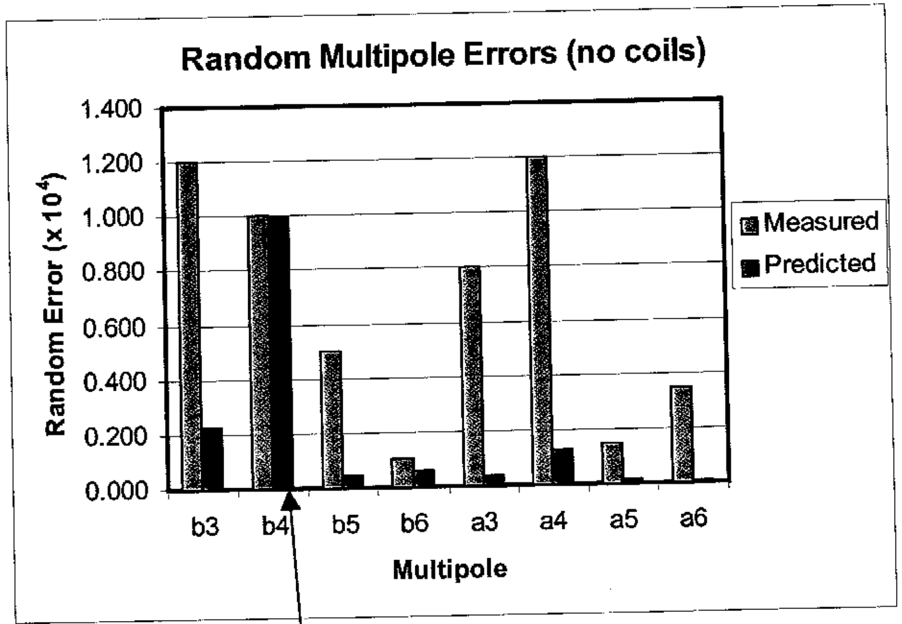
Random errors are dominated by coil placement errors





Strong correlation with coil placement error

Strong correlation with iron mating surface gaps

- **Investigate correlation between measured harmonics to support analysis**
- **Look for correlation between B_3, A_3, A_4, B_5, A_6**

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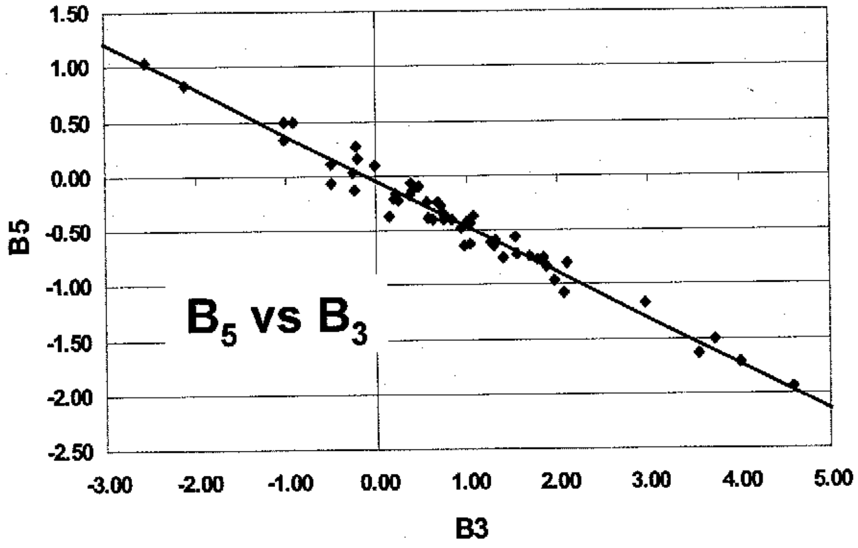
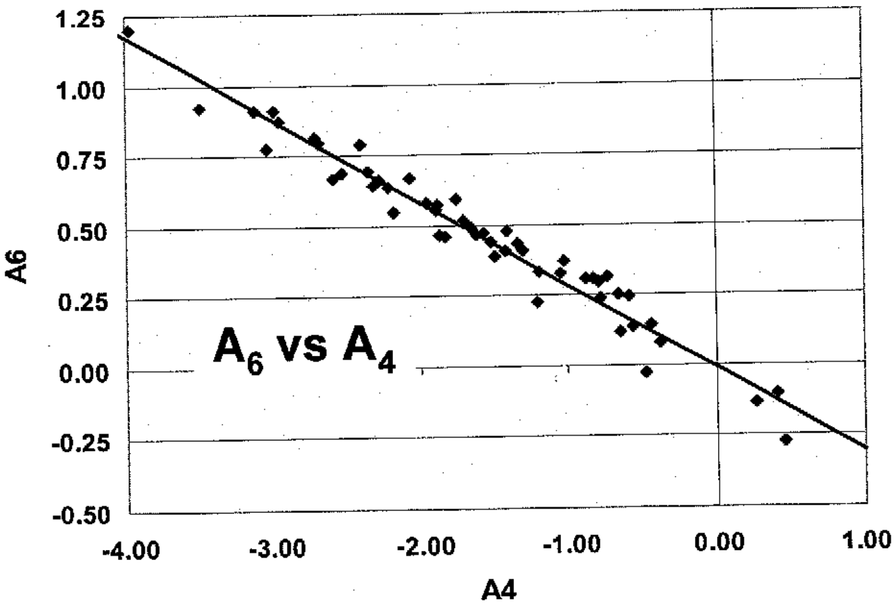
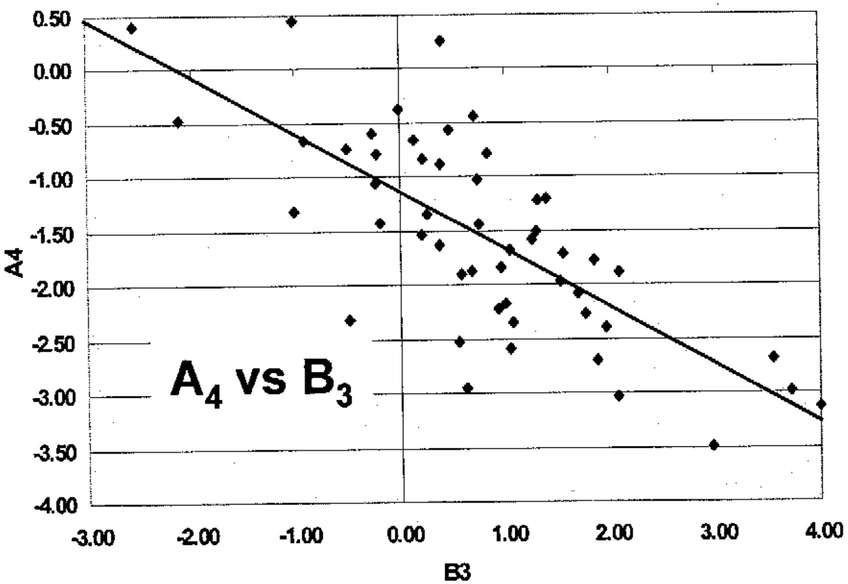
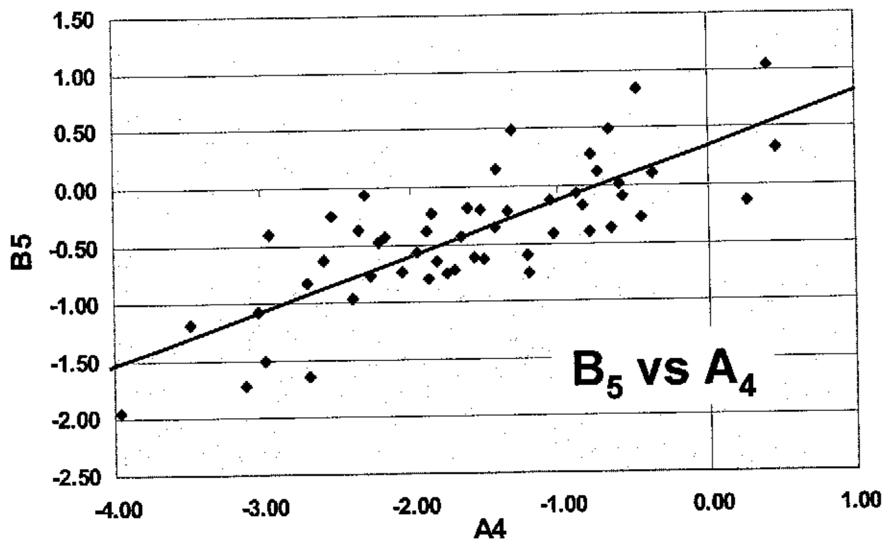
Strong correlation observed for harmonics excited by coil placement errors (except A_3)









Summary of Harmonics Analysis

- Most Random Errors can be Modeled as 2D Assembly Tolerances
  - Coil placement errors and proximity to pole tip can dominate errors
  - Random octupole (B_4) caused by gaps and tilts between half cores
    - Systematic octupole is generally present
  - End effects not considered (A_3)
    - IQC and IQD have different lengths
    - Look at length and current dependence

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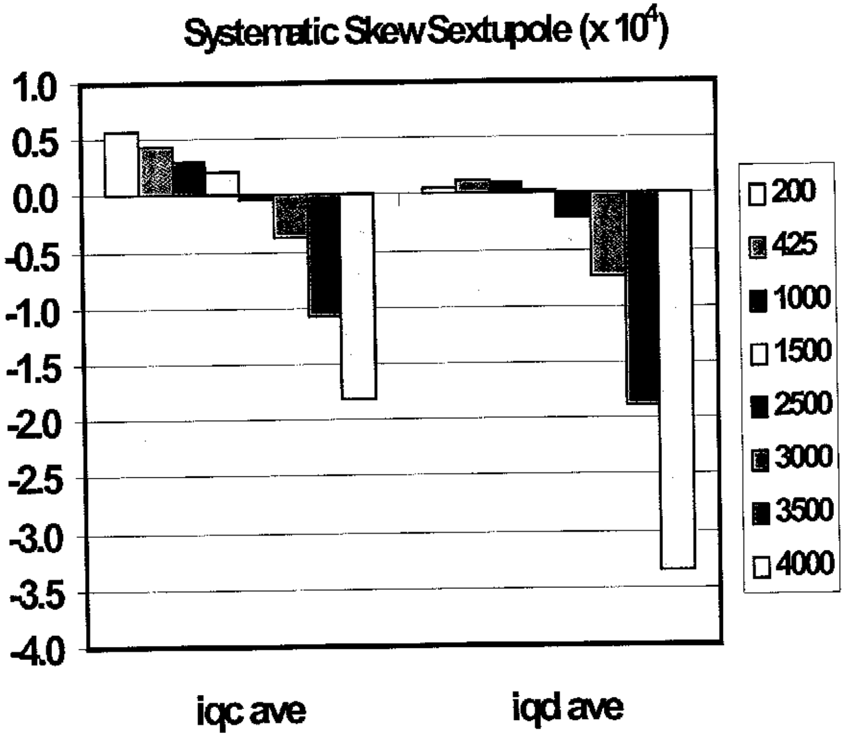
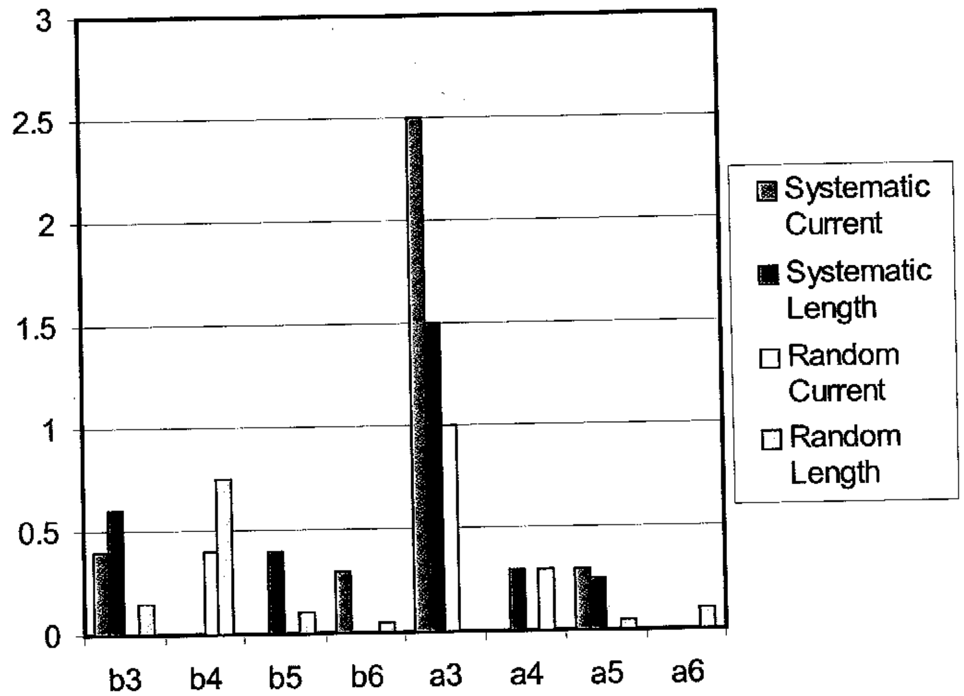
Skew Sextupole (A_3) shows Significant Length and Current Sensitivity





Skew sextupole field is dominated by end effects

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Compare Quadrupole Magnet Harmonics for SQC and LER

SQC Quadrupoles				
n	normal	normal	skew	skew
	systematic	random	systematic	random
3	-0.015	0.450	0.109	1.210
4	-1.090	0.520	-0.130	0.108
5	-0.006	0.043	-0.007	0.110
6	-0.170	0.089		0.020
9	0.001	0.003	0.001	0.004
10	0.030	0.012	-0.001	0.002
12	-0.003			
LER Quadrupoles				
	normal	normal	skew	skew
n	systematic	random	systematic	random
3	-0.034	0.273	-0.029	0.307
4	0.184	0.380	-0.005	0.091
5	0.004	0.022	0.006	0.025
6	0.339	0.013	-0.006	0.011
7		0.003		0.003
8		0.001		0.002
9		0.001		
10	-0.013			

- Harmonics above n=6 are very small
- Consider only sextupole through duodecapole harmonics

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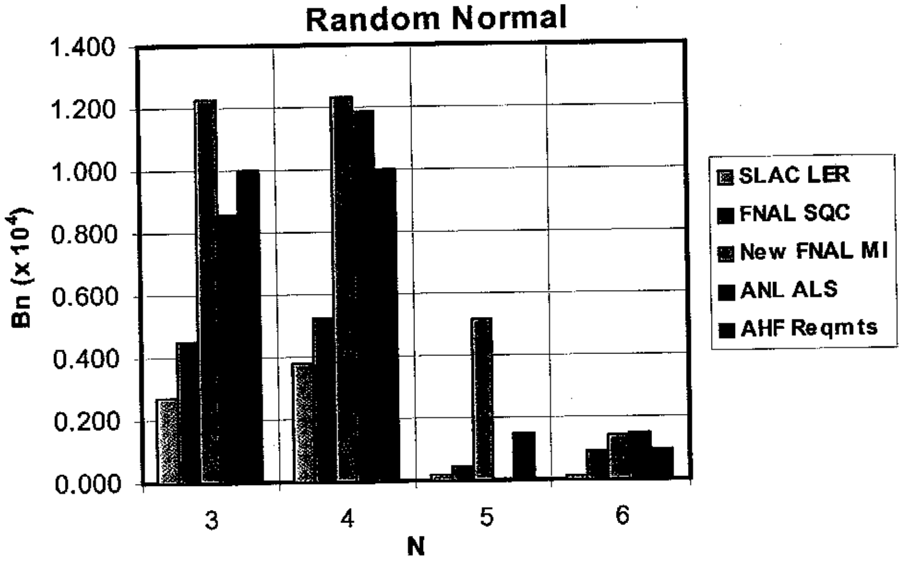
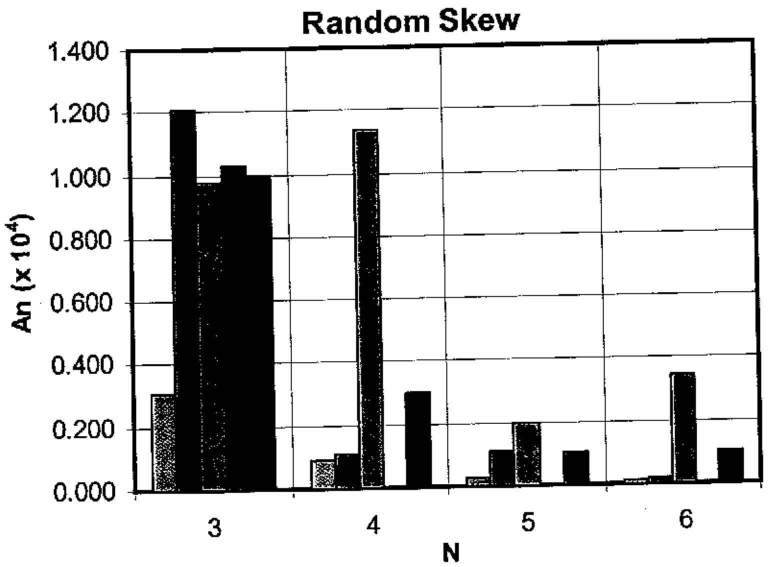
Quadrupole Magnet Random Harmonics

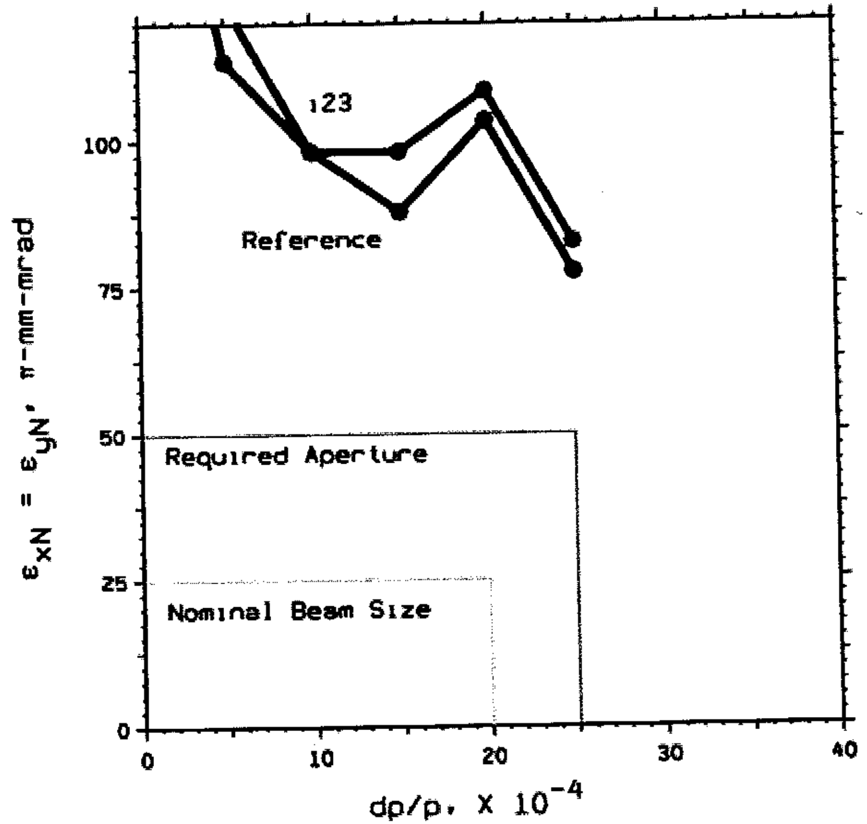




- All above magnets provide a dynamic aperture larger than the physical aperture for AHF
- Sextupole and octupole random errors are the most significant
- Expect random errors to be factor of two worse than best magnets
- Add ~30% margin to define requirements
- FNAL MI magnets are almost twice as long as AHF quads

AHF Quadrupole Magnet Harmonics Requirements and Tracking Results

AHF Quadrupole Magnet Harmonics Requirements			
Multipole Order	Coefficient	Systematic	Random
quadrupole	b2		12
sextupole	b3	0.2	1
octupole	b4	-0.5	1
decapole	b5	-0.1	0.15
duodecapole	b6	0.4	0.1
skew sextupole	a3	0.3	1
skew octupole	a4	0.1	0.3
skew decapole	a5	-0.1	0.1
skew duodecapole	a6	-0.1	0.1



Dynamic aperture is significantly larger than physical aperture

AHF Quadrupole Magnet Design Considerations

- Avoid Sensitivity of Harmonics to Coil Placement Errors
  - Move coils away from pole tip
  - Even number of coil layers - be careful with coil leads
- Half Core vs Four Quadrant Construction
  - Half core construction reduces sources of fabrication errors
  - Half core construction can restrict coil envelope
- Presently Considering Two Designs
  - SSC MEB scaled to 5.0 cm radius (quadrants)
  - SLAC LER (half core)
  - Both designs require modified coil package
  - Both designs can meet AHF requirements
- Design Selection and Optimization in progress

Summary

- FMI or MEB dipoles adequate to maintain dynamic aperture
- Quadrupoles can be built to maintain dynamic aperture
  - Avoid coil placement problems
  - Considering SSC MEB or SLAC LER designs
- Tracking results based on new requirements show substantial margin for dynamic aperture