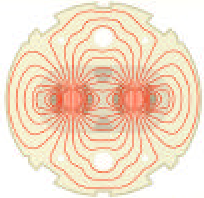

Workshop on LHC IR Correction Systems

Field Quality in FNAL Model Magnets

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6 May 1999

Outline

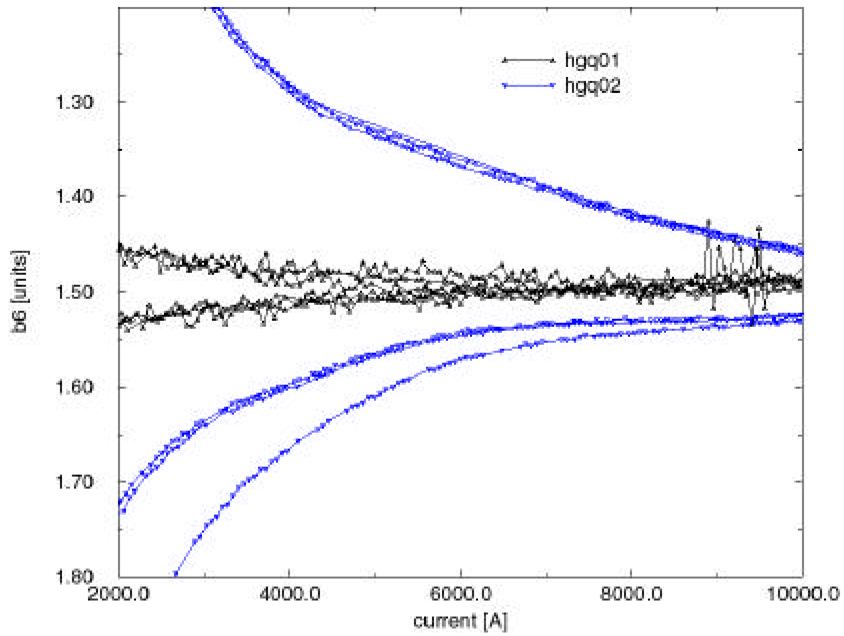
- **Field quality**
  - **apparatus and analysis**
  - **transfer function and field angle**
  - **evolution of the body harmonics**
  - **end field**
- **Studies of the ability to modify the design field with tuning shims**

Apparatus and Analysis

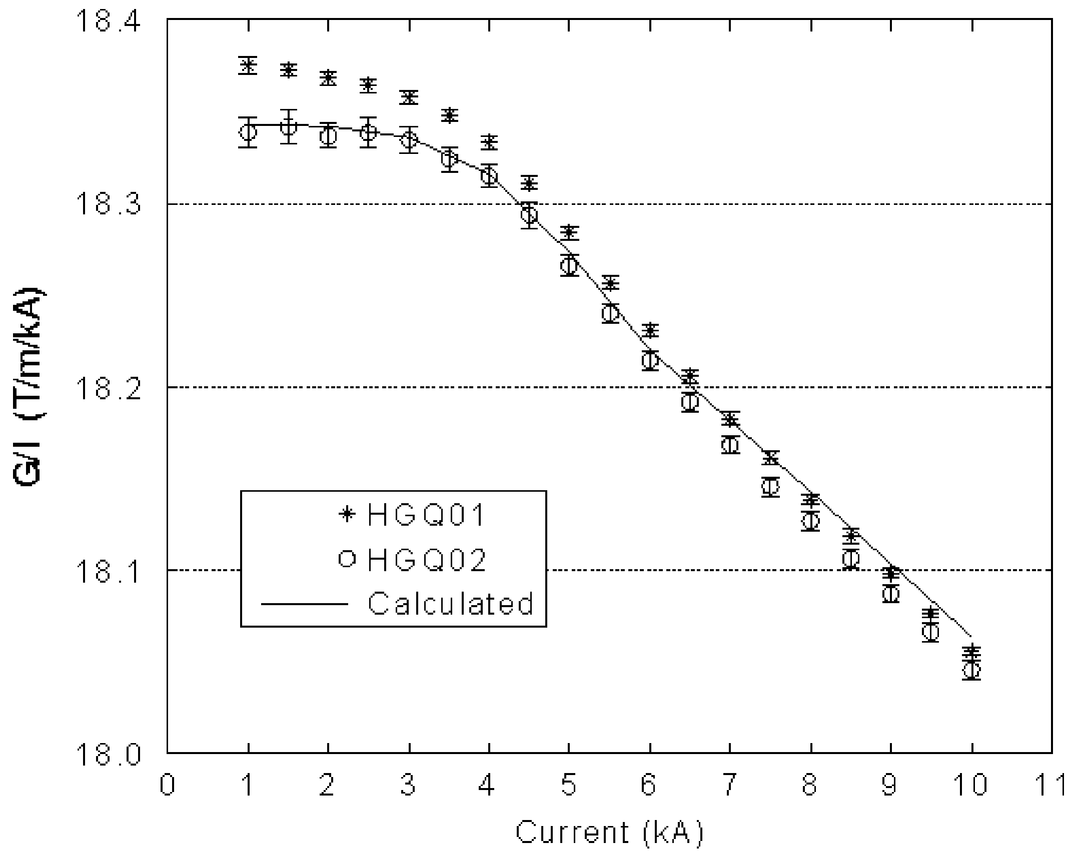
- measurements made in vertical dewar using rotating coil
  - probes
    - 0.25 m length, 2.5 cm OD (HGQ01)
    - 0.82 m length, 4.1 cm OD
    - 2 dipole, 2 quad bucking coils, tangential main coil
- probe signals, current read by 6 HP3458 DVMs simultaneously triggered by angular encoder
- probe centered using feed down of quadrupole to dipole
- 17 mm R_{ref}

Apparatus and Analysis

- Improvements in apparatus have been made
  - –longer, larger radius probe improves signal-noise
  - –better centering bearings
  - –larger radius, multi-sectioned driveshaft separated by flexible couplings
- Improved measurements

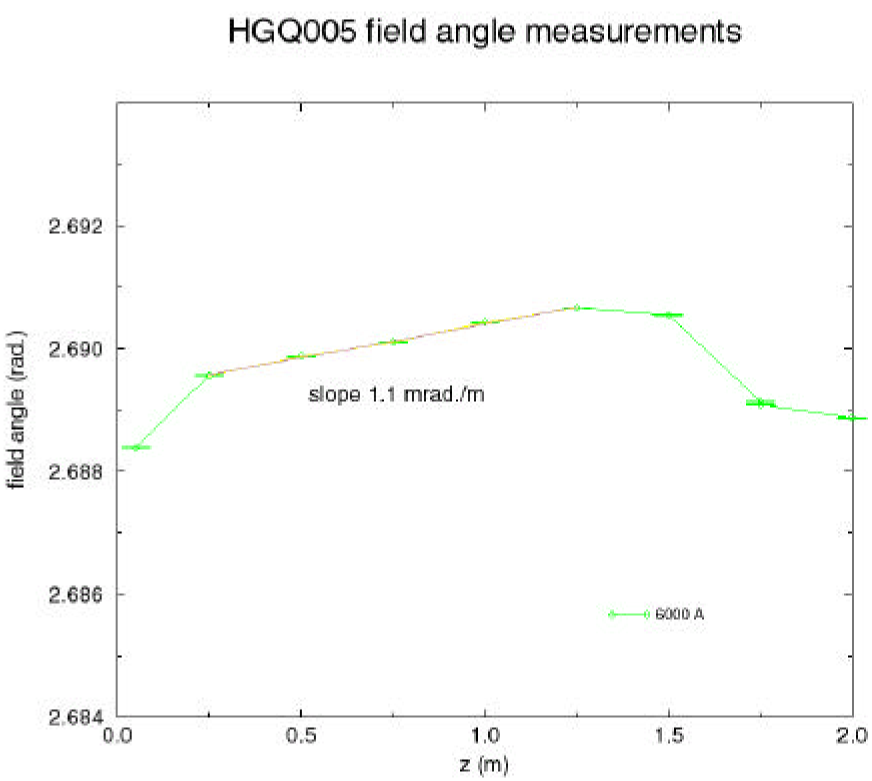


Transfer Function and Field Angle



- Transfer function
  - G/I=18.35 T/m/kA at low currents
  - Iron saturation effect reduces transfer function by 2% at nominal current

Transfer Function and Field Angle



Field angle

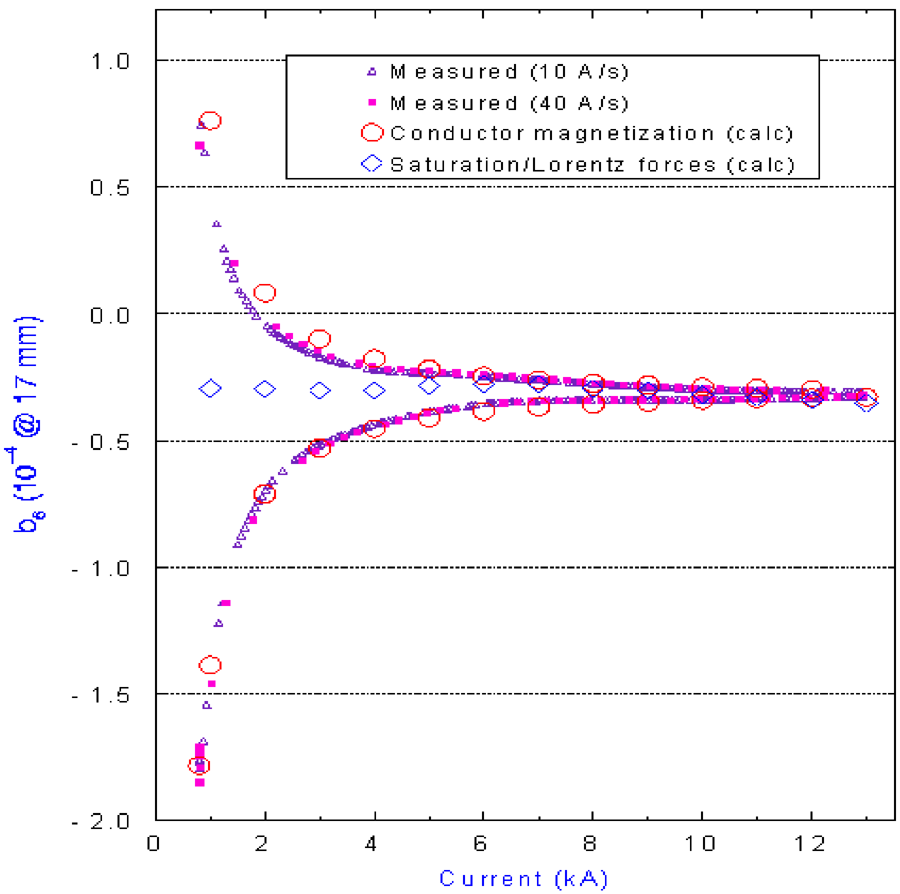
Magnet twist (mrad/m):

	mech.meas.	magn.meas.
HGQ01	6	7
HGQ02	0.6	<1
HGQ03	1.0	1
HGQ05	0.9	1.1

Next steps:

- twist reduction below 0.3 mrad/m → tooling optimization, yoke/skin welding procedure

Field Harmonics



- Iron saturation and Lorentz force effects on b_6 at high currents are small

Coil magnetization effect on b_6 at low currents is in a good agreement with calculations

- There is no noticeable effect of coil magnetization, iron saturation and Lorentz force on b_{10}

Measured Field Harmonics Summary

Field	Measured Field Harmonics (6kA)				Ref. Table v2.0	
Harm.	HGQ01	HGQ02	HGQ03	HGQ05	Uncert.	Random
b3	0.36	-0.70	1.04	0.72	0.3	0.8
a3	0.27	0.55	-0.30	0.12	0.3	0.8
b4	0.26	0.18	0.14	0.00	0.2	0.8
a4	2.00	0.53	0.32	0.19	0.2	0.8
b5	-0.29	0.09	-0.34	-0.04	0.2	0.3
a5	0.02	-0.17	0.26	0.05	0.2	0.3
b6	-3.91	-1.54	-1.02	-0.30	0.6	0.6
a6	-0.02	0.03	0.07	-0.03	0.05	0.1
b7	-0.08	-0.01	-0.06	0.01	0.05	0.06
a7	-0.05	0.00	-0.03	0.01	0.04	0.06
b8	0.06	0.01	0.00	0.00	0.03	0.05
a8	0.02	0.02	0.03	0.00	0.03	0.04
b9	0.04	0.00	0.00	0.00	0.02	0.03
a9	0.01	-0.01	0.01	0.00	0.02	0.02
b10	0.04	-0.01	0.00	0.00	0.02	0.03
a10	-0.12	-0.09	-0.05	0.01	0.02	0.03

- Harmonics measured at magnet center
- Steady improvement in field quality
  - improvements in coil fabrication procedure have produced coils closer to design values
- HGQ05 field harmonics smaller than reference table except for b_3

Predicted Field Based on As-Built Cross-Section

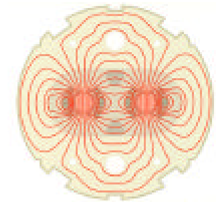
	HGQ01	HGQ02	HGQ03	HGQ05
a4	1.27	0.94		
b6	-4.24	-2.86	-1.39	-0.08
a8	0.02	0		
b10	-0.14	-0.09	-0.04	0.01

- adjustments made to
  - curing cavity size
  - curing pressure
  - cable insulation scheme
  - bare cable size
- coil shim thickness reduced by a factor of 2 from each magnet to the next
- more uniform coil size and modulus

Summary of Body Field Harmonics of the 4 Models

field	Measured – Calculated Field Harmonics						Ref. Table v2.0	
harm.	HGQ01	HGQ02	HGQ03	HGQ05	Mean	RMS	Uncert.	Random
b3	0.36	-0.70	1.04	0.72	0.36	0.76	0.3	0.8
a3	0.27	0.55	-0.30	0.12	0.16	0.36	0.3	0.8
b4	0.26	0.18	0.14	0.00	0.15	0.11	0.2	0.8
a4	0.73	-0.41	0.32	0.19	0.21	0.47	0.2	0.8
b5	-0.29	0.09	-0.34	-0.04	-0.15	0.20	0.2	0.3
a5	0.02	-0.17	0.26	0.05	0.04	0.18	0.2	0.3
b6	0.33	1.32	0.37	-0.22	0.45	0.64	0.6	0.6
a6	-0.02	0.03	0.07	-0.03	0.01	0.05	0.05	0.1
b7	-0.08	-0.01	-0.06	0.01	-0.04	0.04	0.05	0.06
a7	-0.05	0.00	-0.03	0.01	-0.02	0.03	0.04	0.06
b8	0.06	0.01	0.00	0.00	0.02	0.03	0.03	0.05
a8	0.00	0.02	0.03	0.00	0.01	0.02	0.03	0.04
b9	0.04	0.00	0.00	0.00	0.01	0.02	0.02	0.03
a9	0.01	-0.01	0.01	0.00	0.00	0.01	0.02	0.02
b10	0.04	-0.01	0.00	0.00	0.01	0.02	0.02	0.03
a10	0.02	0.00	-0.01	0.00	0.00	0.01	0.02	0.03

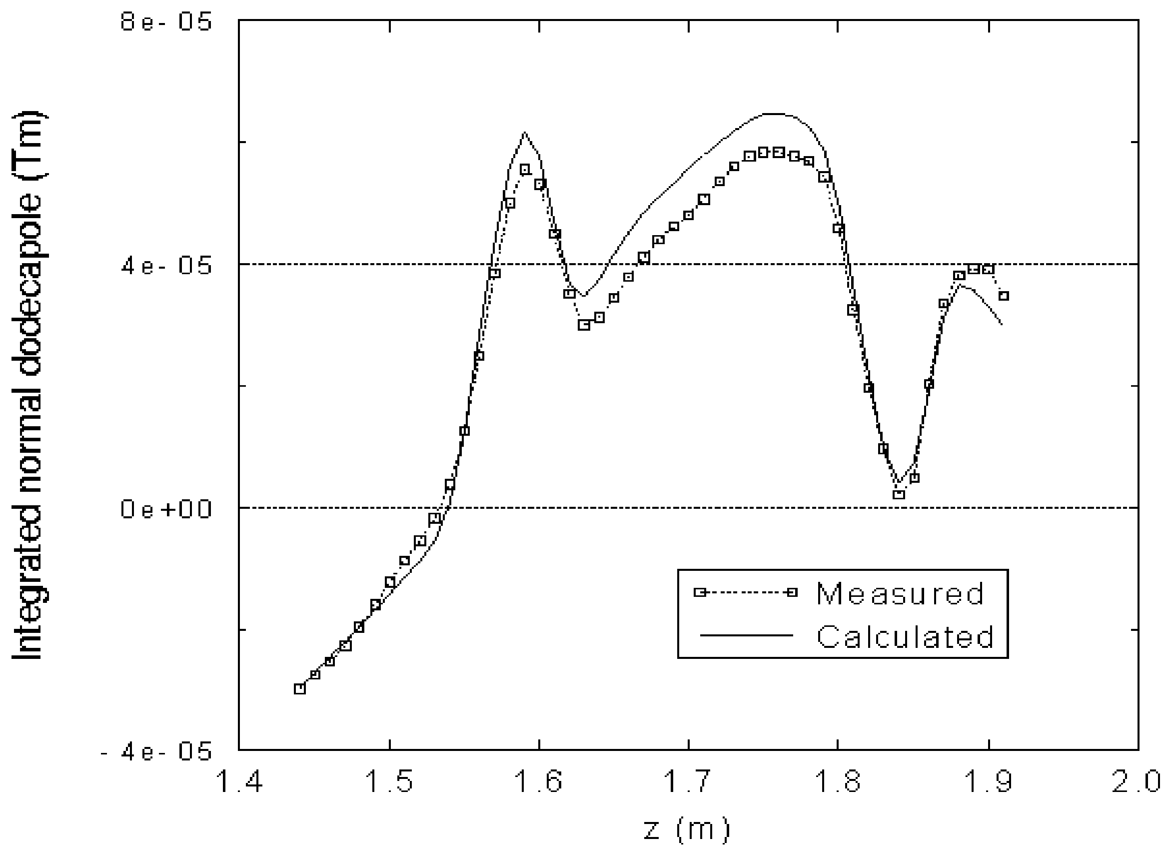
- Correct the measured field by the as-built calculations so we can use the ensemble of magnets to predict the behavior of the ensemble of production magnets
  - assumes coil size varations are controlled during production
- mean and RMS for 4 magnets are mostly at or below the values in the reference table



Summary of Body Field Harmonics of the 4 Models

- AP studies show reference harmonics yield required dynamic aperture
- HGQ05 as-built field corrections are very small
- HGQ05 field compares favorably with reference table
- After correction for production effects, the mean and RMS of the harmonics for the 4 models compares favorably with the reference table

End Field Measurement



End Harmonics Optimization

	End Design Field				Ref. Table v2.0					
Field	Lead end		Return end		Lead end			Return end		
harm	v1.1	v2.0	v1.1	v2.0	mean	uncert	sigma	mean	uncert	sigma
b_6	6.6	4.6	1.2	0.1	2.0	2.0	0.75	0.0	1.0	0.75
b_{10}	-0.3	-0.1	-0.2	-0.1	-0.2	0.2	0.1	-0.2	0.2	0.1
a_6	-0.5	-0.1			0.0	0.5	0.15	-	-	-
a_{10}	-0.1	0.0			0.0	0.1	0.1	-	-	-
	[1.31, 2.03]		[-0.57, 0.25]		reference integration interval					
v1.1	*HGQ02, HGQ03*									
v2.0	*optimized end design*									

- end field quite sensitive to shimming of magnet end regions during production
- optimized end design in HGQ06

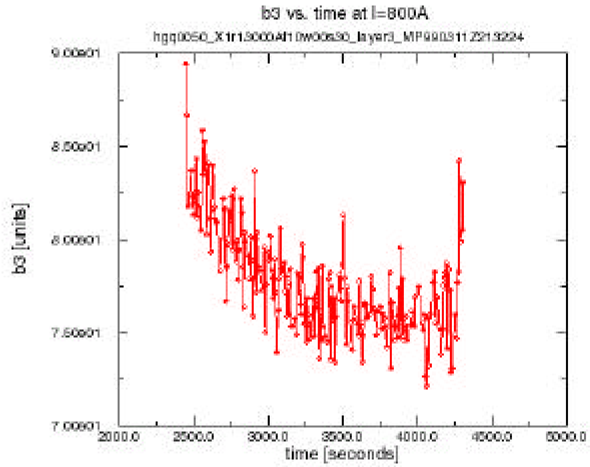
800 kA		
n	up/down ramp average	up-down ramp
b 3	0.804	0.047
b 4	0.056	0.031
b 5	-0.054	-0.033
b 6	-0.488	-2.825
b 7	0.007	0.005
b 8	-0.009	0.000
b 9	0.000	-0.004
b10	0.012	0.047
b11	0.001	0.000
b12	0.000	0.000
b13	-0.002	-0.001
a 3	0.129	-0.001
a 4	0.251	0.209
a 5	0.079	-0.008
a 6	0.000	0.084
a 7	0.017	-0.007
a 8	-0.005	0.008
a 9	0.001	-0.001
a10	-0.005	0.004
a11	0.000	0.002
a12	0.000	0.000
a13	-0.004	-0.002

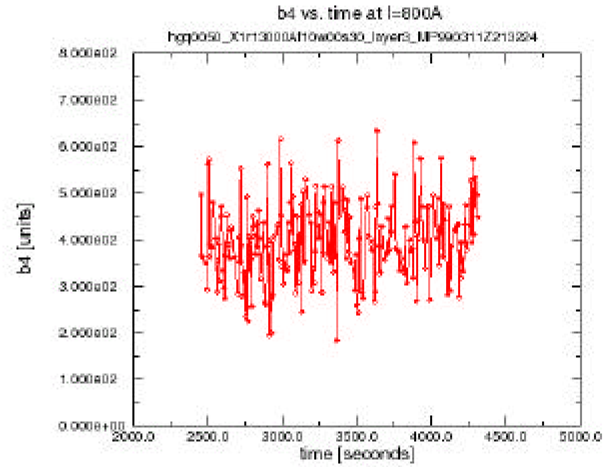
Injection Field

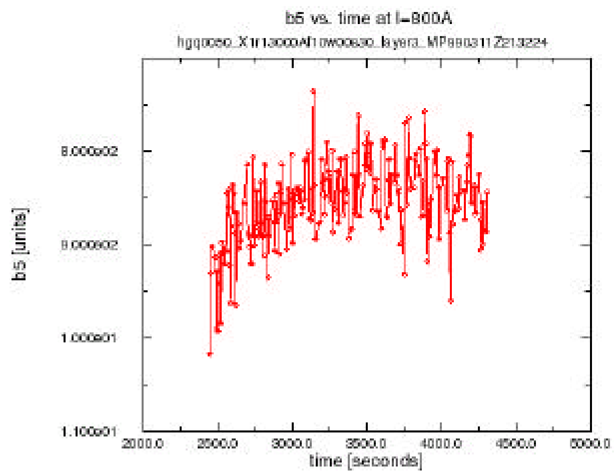
- conventional wisdom is that the IR quads “don’t matter” at injection
- should they matter these are the harmonics
- there are also changes (“drift”) in various harmonic components while sitting at injection

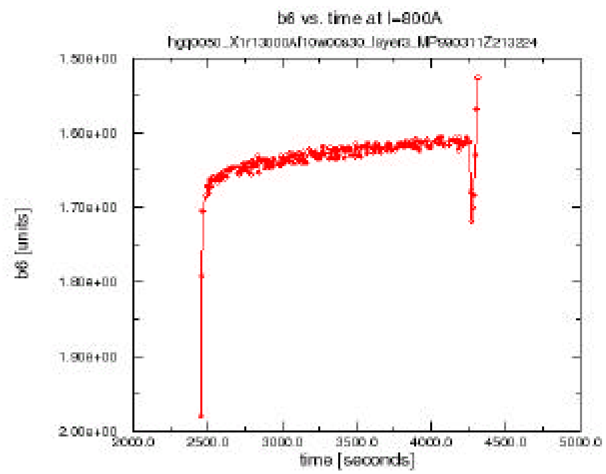
the Magnet Test Facility

fermilab



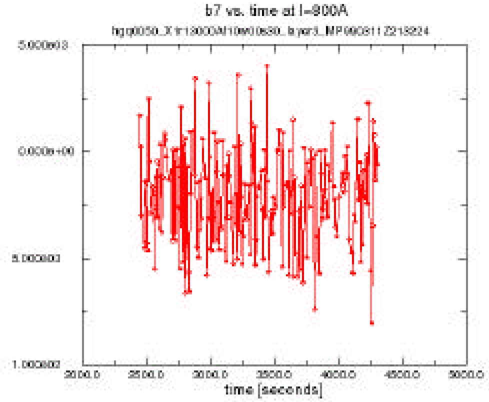


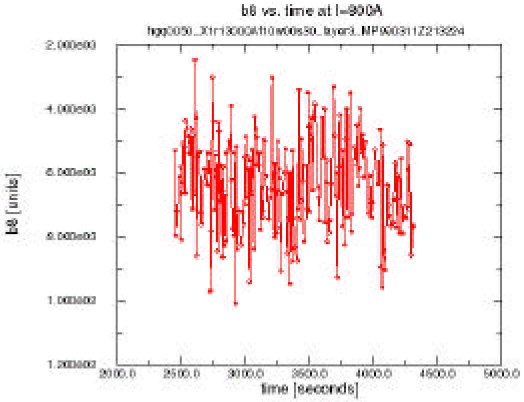


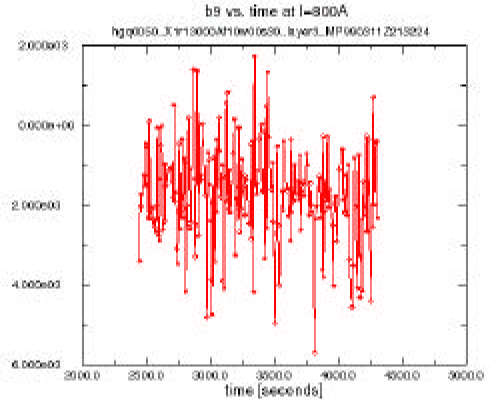


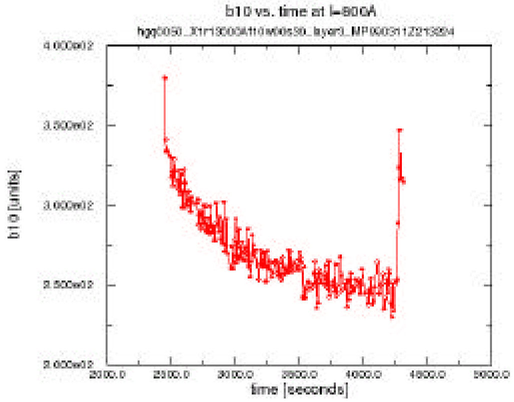
the Magnet Test Facility

fermilab









the Magnet Test Facility

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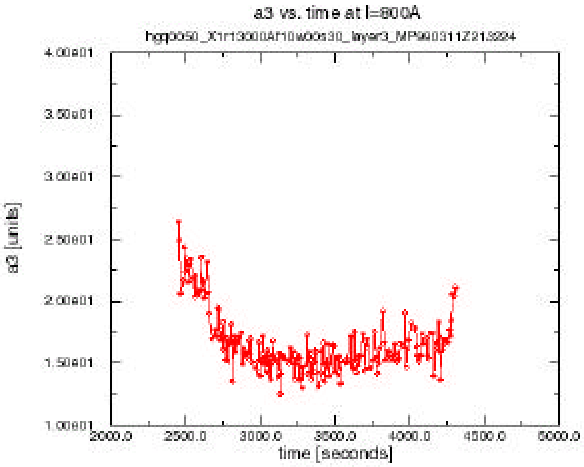
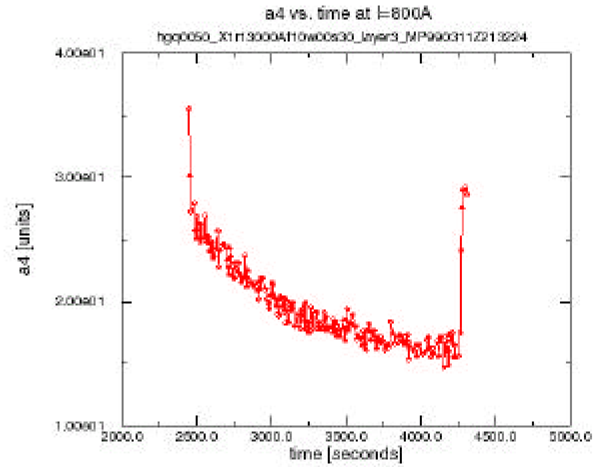
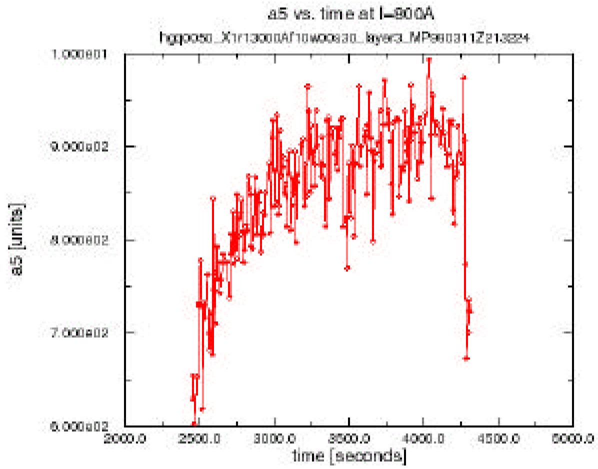
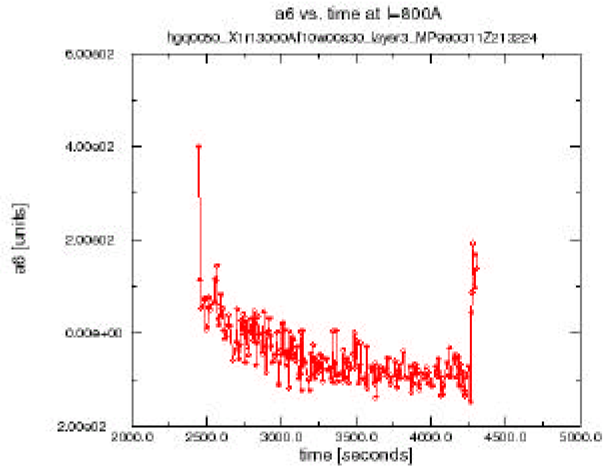
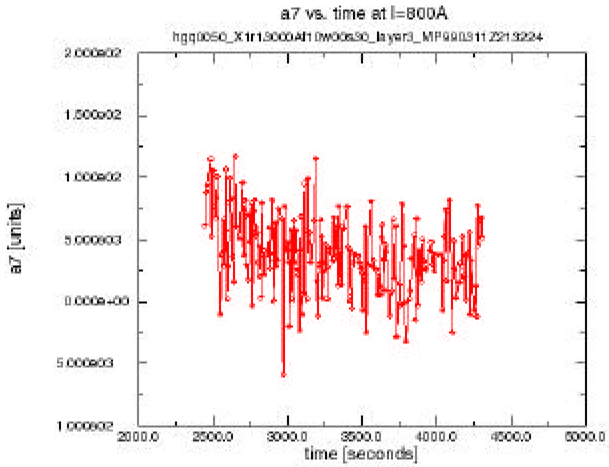


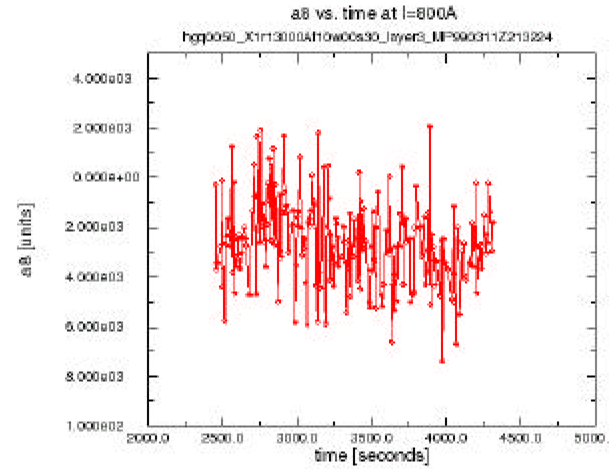




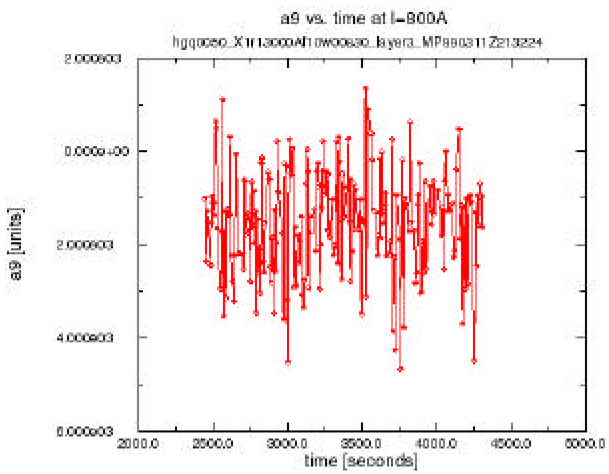




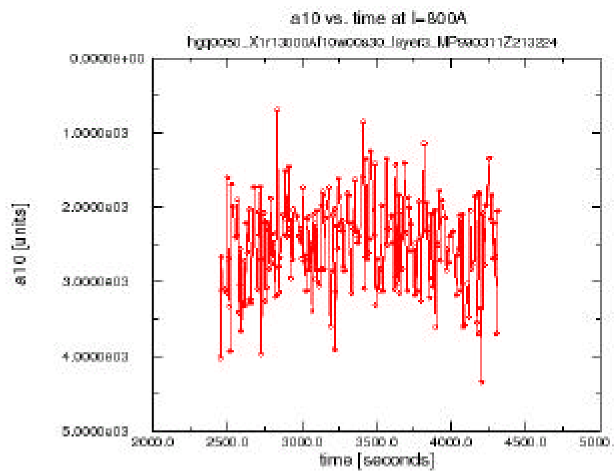
a7 vs. time at I=800A
a7 [units]
time [seconds]



a8 vs. time at I=800A
a8 [units]
time [seconds]



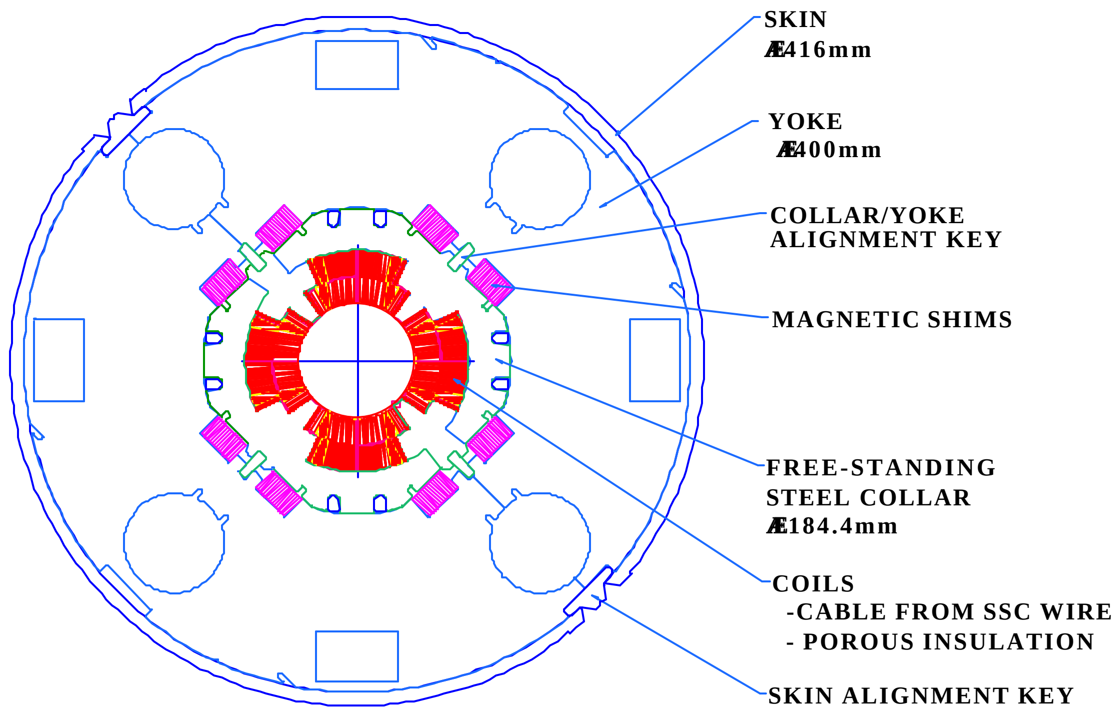
a9 vs. time at I=800A
a9 [units]
time [seconds]

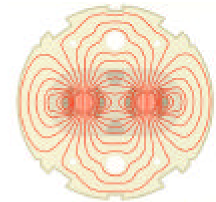


a10 vs. time at I=800A
a10 [units]
time [seconds]

Field Tuning Using Shims

- magnet cross section contains 20 mm holes for insertion of field tuning shims
- nominal design has each half filled by iron half by non-magnetic material
- changing the thickness of magnetic relative to non-magnetic material “tunes” the field
- the various shim positions tune different harmonic components



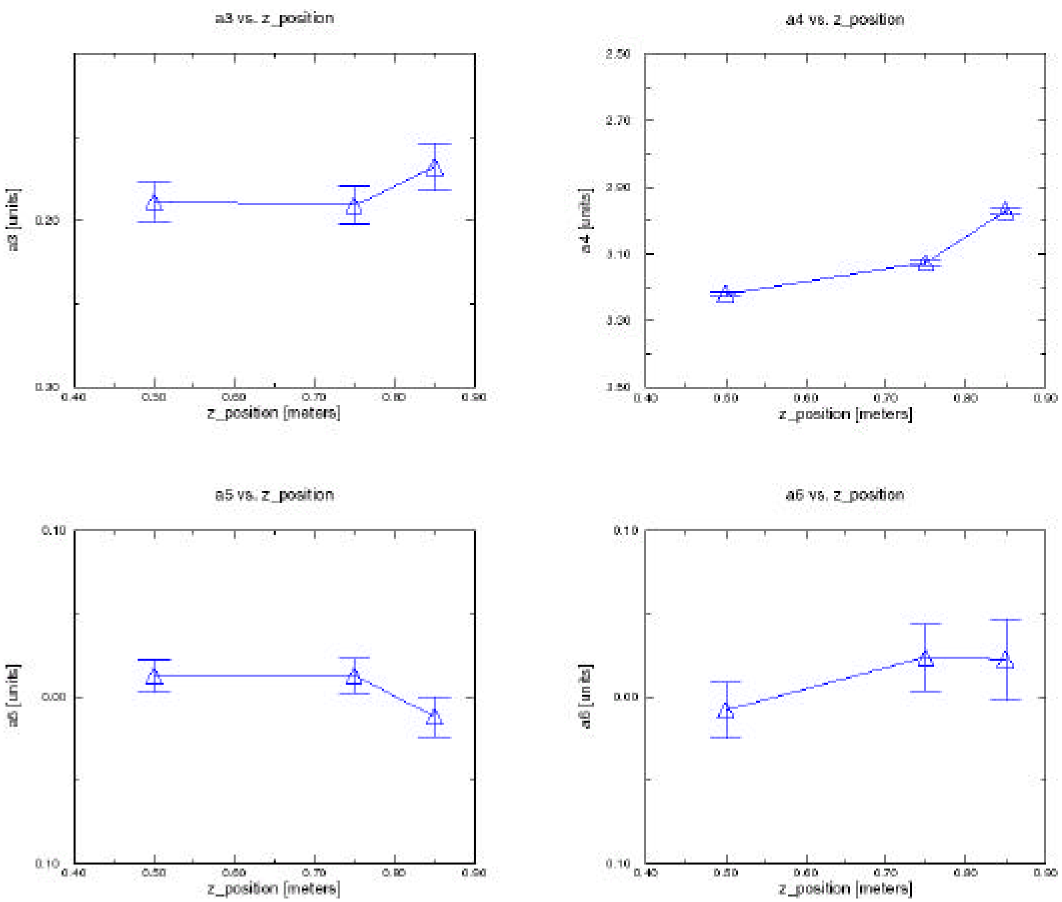


Tuning Shims: measured, predicted field changes

- after completion of cold testing, HGQ03 was used to test our ability to tune the field
- a shim pattern was selected which would tune skew octupole (a_4) leaving other harmonics unchanged
- required shims of 4.1, 15.9 mm nominal thickness
- expected changes:
  - a_4 -2.9 units
  - other harmonics "unchanged"
- measured changes:
  - a_4 -3.1 units
  - small changes in sextupole

n	normal	skew
3	0.34±0.01	-0.19±0.01
4	0.05±0.01	-3.13±0.01
5	0.01±0.01	0.01±0.01
6	0.04±0.02	0.02±0.02

Tuning Shims: axial variation



- skew octupole varies by 0.25±0.01 units from one end of the magnet to the other
- measured variation in other harmonics consistent with no variation at the 1-2 σ level

Change in Field with Shim Thickness

- two sets of shims allow us to calculate Δb_n (Δa_n)/ Δf
  - f is the thickness of the magnetic part of the shim

	calculated		measured	
n	**Db_n/Df**	**Da_n/Df**	**Db_n/Df**	**Da_n/Df**
3	**0.51**	**0.00**	**0.48**	**0.00**
4	**0.14**	**-0.08**	**0.10**	**-0.07**
5	**0.01**	**-0.03**	**0.01**	**-0.02**

Summary of Studies of Tuning Shims

- We have targeted a tuned field and achieved it with 0.2-0.3 units accuracy based on calculations of the field change as a function of shim thickness
  - In practice, better accuracy would be achieved as we would use the measured field change as a function of shim thickness and use these functions to choose shim sizes
  - Accuracy set by the accuracy of magnetic measurements which in turn is a function of how much current we can safely put through the magnet
- The variation in the tuned field along the length of the magnet is consistent with zero except for the skew octupole which varies by 0.25 units
- No variation in the field due to variations in shim manufacturing is measured
- We have what we need (including the measured change in field as a function of shim thickness) to use tuning shims except for the correlation between field of collared coil measured warm and field of cold cryostated magnet

Summary of Field Harmonics of the 4 Models

- Field quality in HGQ05 adequate for a production magnet
- Model magnet ensemble field quality adequate, after correcting for production defects which we can control (and have in HGQ05)

* MQX field quality adequate without resorting to tuning shims

- End field quality will improve with new end design of HGQ06