BNL-102183-2014-TECH

RHIC/AP/75;BNL-102183-2013-IR

Magnetic Error Compensation and Computer Modeling in RHIC

J. Wei

October 1995

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

Talk at LHC 95 Workshop, Montreux, 1995

RHIC/AP/75

Magnetic Error Compensation and Computer Modeling in RHIC

I. Introduction

II. Triplet (IR) region error compensation

field quality issues

misalignment issues

III. Arc region error compensation

field quality issues

misalignment issues

IV. Computer modeling

TEAPOT filters

tune diagram comparison, tracking

V. Conclusion

Jie Wei
BNL
Oct. 1995

I. Introduction

* Large beam size at storage ——

triplet dominates, multipole dominates

Au^{79+}, IBS growth strong ;

beam - beam $\Delta\nu \lesssim 0.005$, 0 cross angle mostly

* Two- ring, separated mostly, small crosstalk

exception: triplet in common cryostat

* high injection field, small persistant b_2

B(5 kA) / B(0.6 kA) ~ 8.5

small filament, small random

* multi-layer correctors, common cryostat

need good alignment

C-Q-S, Triplet

Injection (1 minute) (Au^{79+}, $\gamma = 12.6$)

arc dominates (+ space charge, $\Delta\nu \approx 0.02$)

arc dipole, b_2, b_4, and a_1
arc quadrupole, b_3, b_5

Storage (10 hours) (Au^{79+}, $\gamma = 107.$)

triplet dominates (+ beam-beam, $\Delta\nu$: 0.015 → 0.004)

Q1, Q2, Q3, b_3, b_5, a_5, b_2 (random)

	injection	storage ($\beta^* = 1$m)
ε_N (95%)	10 π mm mr	40 π mm mr
$\sigma_{\Delta p/p}$	0.43×10^{-3}	0.89×10^{-3}
β_{arc}	50 m	50 m
$\beta_{triplet}$	145 m	1400 m
$\sigma_{x\ arc}$	2.5 mm	1.8 mm
$\sigma_{x\ triplet}$	4.5 mm	9.3 mm

coil ID: arc 80 mm, triplet 130 mm
reference radius (5/8): 25 mm. 40 mm

II. Triplet region error compensation

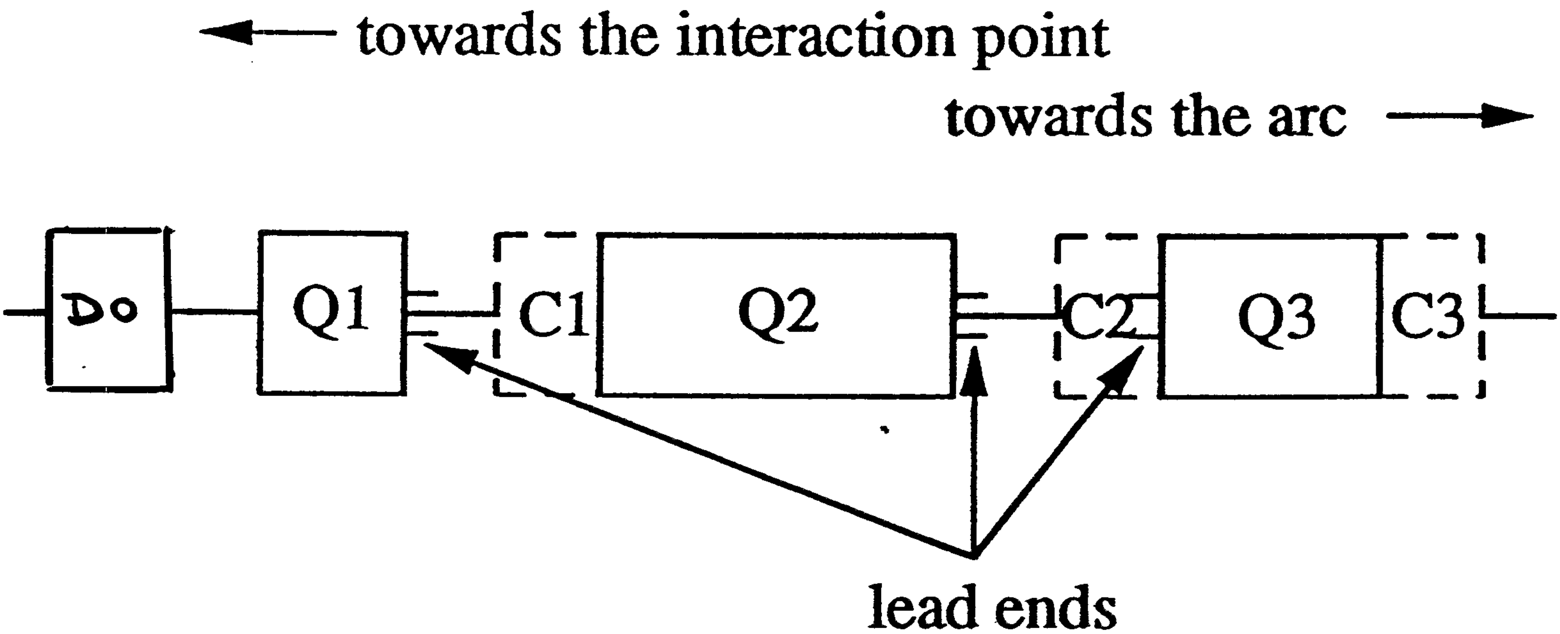


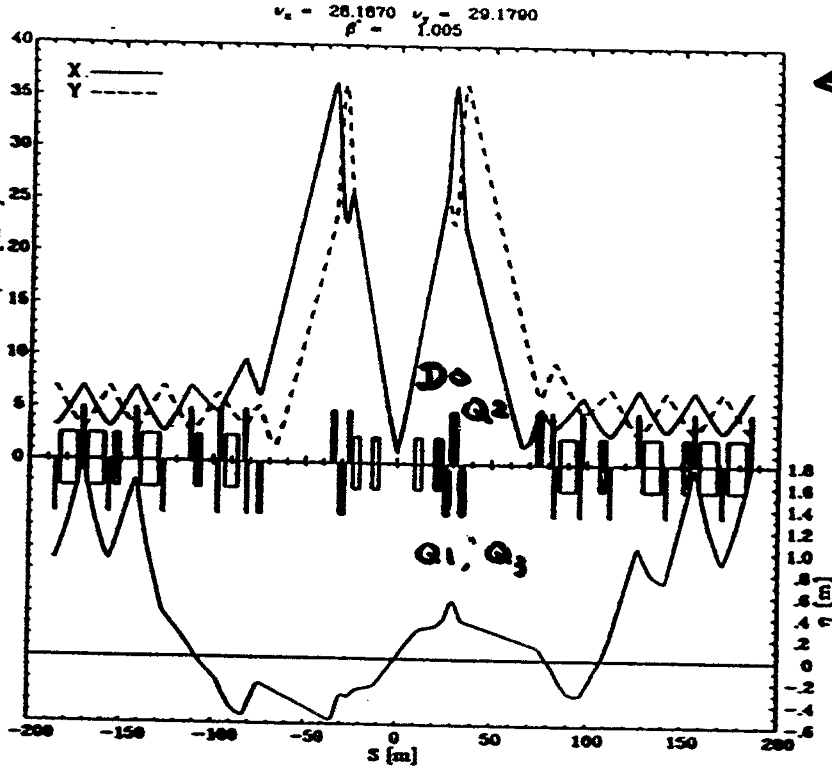
Figure 1 Schematic layout of the RHIC triplet, showing the quadrupoles, the orientation of the quadrupole lead ends, and the local correctors C1, C2, and C3 .

6. Interaction points

2 IP: $\beta^* = 1m$

← $\beta \sim 1400m$

anti-symmetr



4 IP : $\beta^* = 10m$

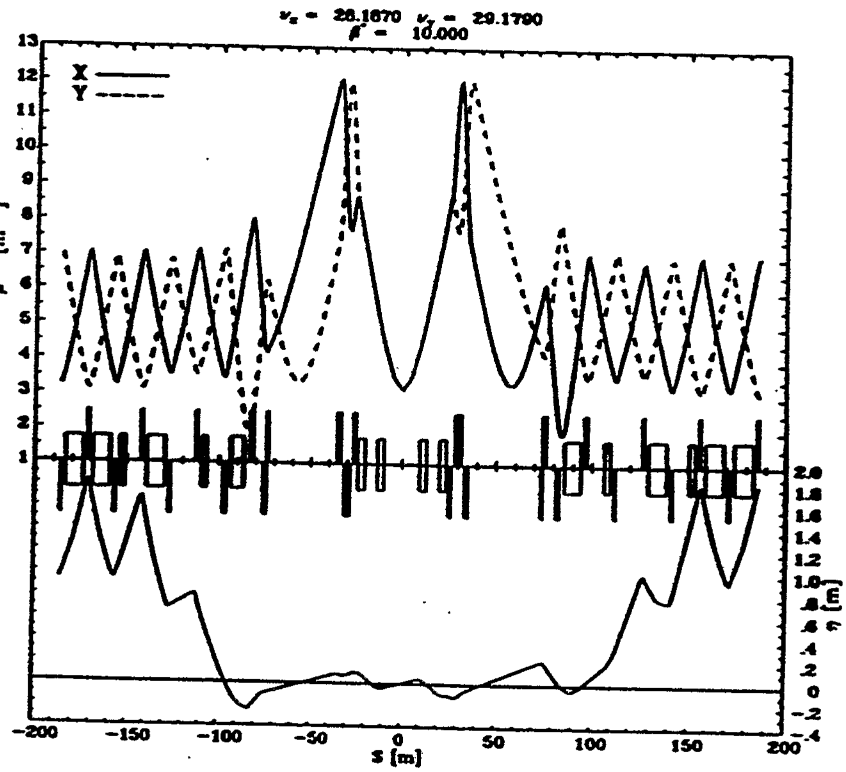


Fig. 11-6. Betatron and dispersion functions in the insertion region.

Field quality issues

error source

* Q1, Q2, Q3 quadrupoles

  lead end : b_5, a_5

  body : b_3, b_5 (systematic)

  (b_3 ↑ asym. in H, V plane; b_5 ↖ allowed)

  b_2 (random)

* D0 dipole

  ends & body : b_2, b_4, a_1

  (b_2, b_4 ↑ ↗ allowed; a_1 ↑ asym. in V placement)

  cross talk : b_1, b_3, ...

Triplet quadrupole expected harmonics

Sep 8, 1994 EXPECTED_QRK.TABLE2k_E

QRK (Q3) Table 2k(e)

Expected values of body harmonics in 130 mm Insertion Quadrupoles
QRK (Q2) at 5000 A : storage, after shimming

[<bn> = mean, d(bn) = uncertainty in mean, sig(bn) = sigma for bn]

n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)
1	0	10.	10	0	0	10
2	0.	0.5	2.4	0.0	0.1	1.2
3	0	1.0	.6	0.0	0.3	.7
4	0.	0.3	.6	0.0	0.1	.5
5	-1.2	0.5	.5	0.0	0.4	.6
6	0.0	0.12	.11	0.0	0.09	.12
7	-0.2	.05	.05	0.0	0.03	.12
8	0.0	0.04	.05	0.0	0.05	.09
9	0.0	0.2	.03	0.0	0.03	.03

body compensation

Expected body harmonics at 660 A
(same as above except for b5 and b9)

5	-4.7	0.5	.5
9	-0.2	0.2	.03

Expected body harmonics at 1450 A
(same as above except for b5 and b9)

5	-2.2	0.5	.5
9	-0.1	0.2	.03

Expected values of harmonics in LEAD END at "ALL" currents (Unit-m)

n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	0	0	0	0	0	0
2	0.0	0.1	0.7	0.0	1.	2.
3	0.0	0.3	.3	0.0	0.4	.8
4	0.0	0.1	.3	0.0	0.3	.4
5	4.6	.5	.3	-1.5	0.5	.2
6	.0	0.01	.04	0.0	0.06	.06
7	0.0	0.04	.05	0.0	0.02	.01
8	0.0	0.04	.05	0.0	0.02	.02
9	-0.5	.05	.02	0.2	.05	.03

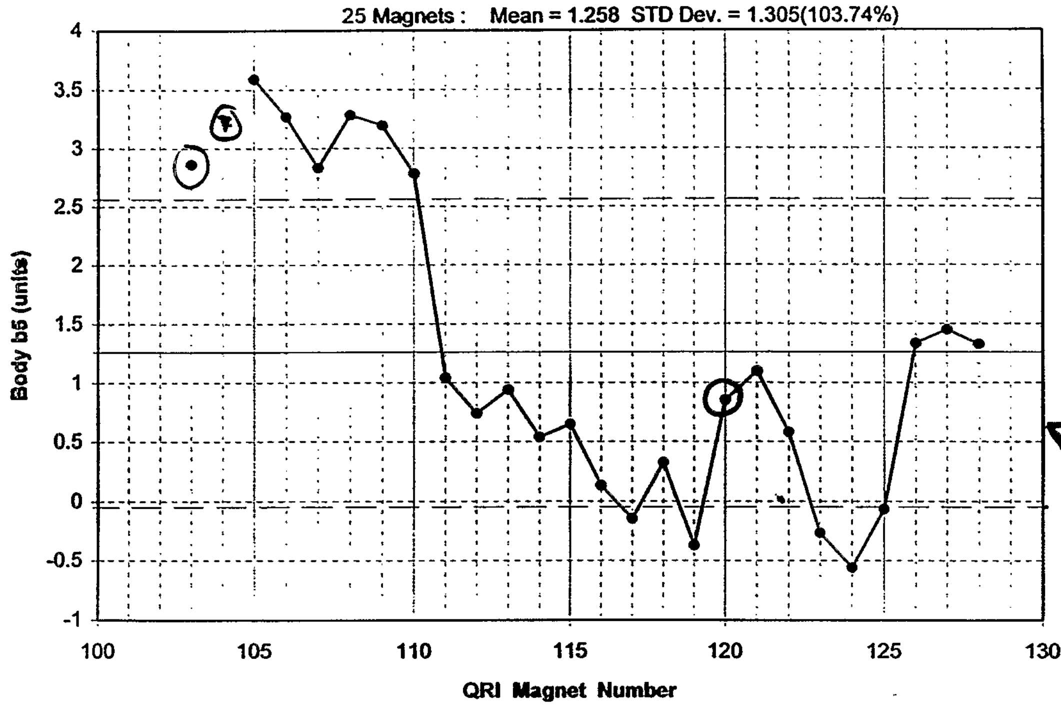
strong Lead end b_5, a_5

Expected values of harmonics in RETURN END at "ALL" currents (Unit-m)

n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	0	0	0	0	0	0
2	0.0	0.3	1.8	0.0	0.7	1.
3	0.0	0.1	.2	0.0	0.1	.3
4	0.0	0	.25	0.0	0.2	.2
5	1.	0	.6	0.0	0.1	.1
6	0.0	0.06	.03	0.0	0.06	.02

Q1 warm measurement

QRI (Q1) Storage Units -- Body b5 (Warm)



Desired value = 1

With tuning shim at 5ka

$b_5 = -1.2$

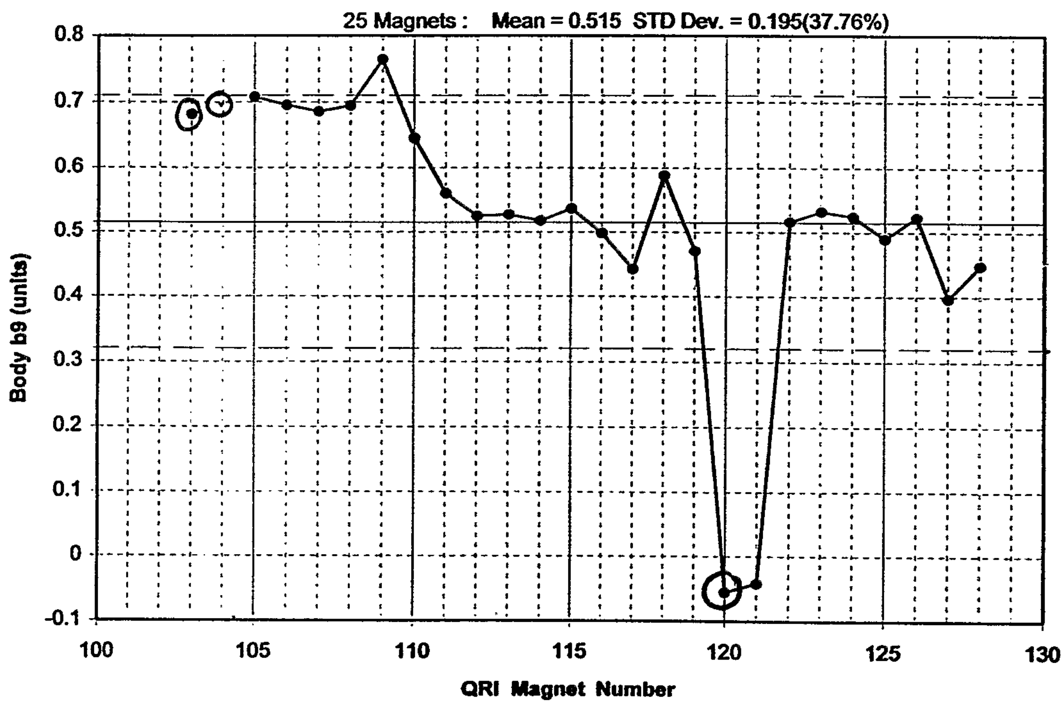
← need $b_5 = 0.8$ before tuning shim insertion

Tuning shim can fix most of b_5 but a large change in T.F.

Q1TREND.XLS 7/27/95

⊙ = Completed Unit

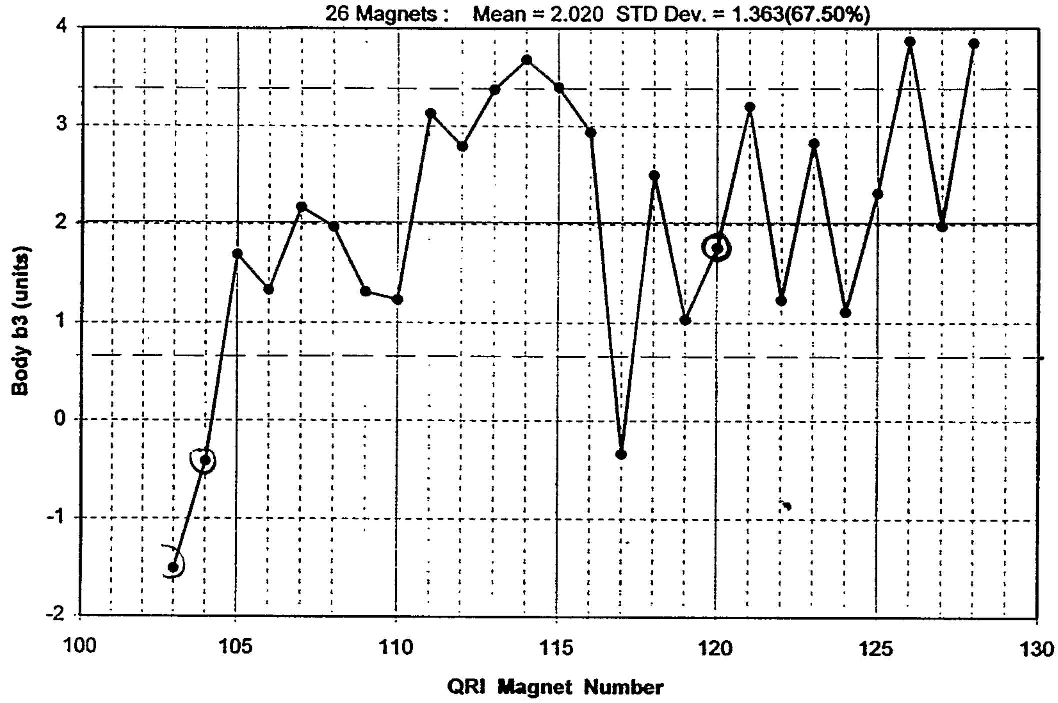
QRI (Q1) Storage Units -- Body b9 (Warm)



← used cross-section for Q2, Q

Q1TREND.XLS 7/27/95

QRI (Q1) Storage Units -- Body b3 (Warm)



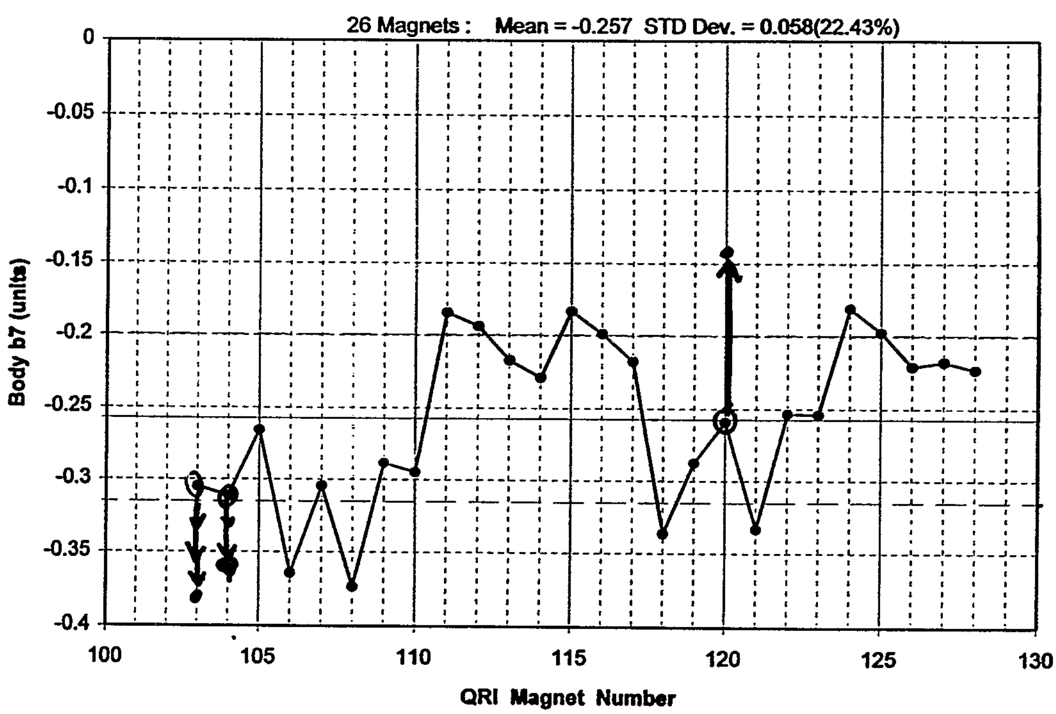
Tuning shim can make all this zero

Q1TREND.XLS

⊙ Completed Unit

7/27/95

QRI (Q1) Storage Units -- Body b7 (Warm)



After (QRI 110-120) asymmtric tuning shim

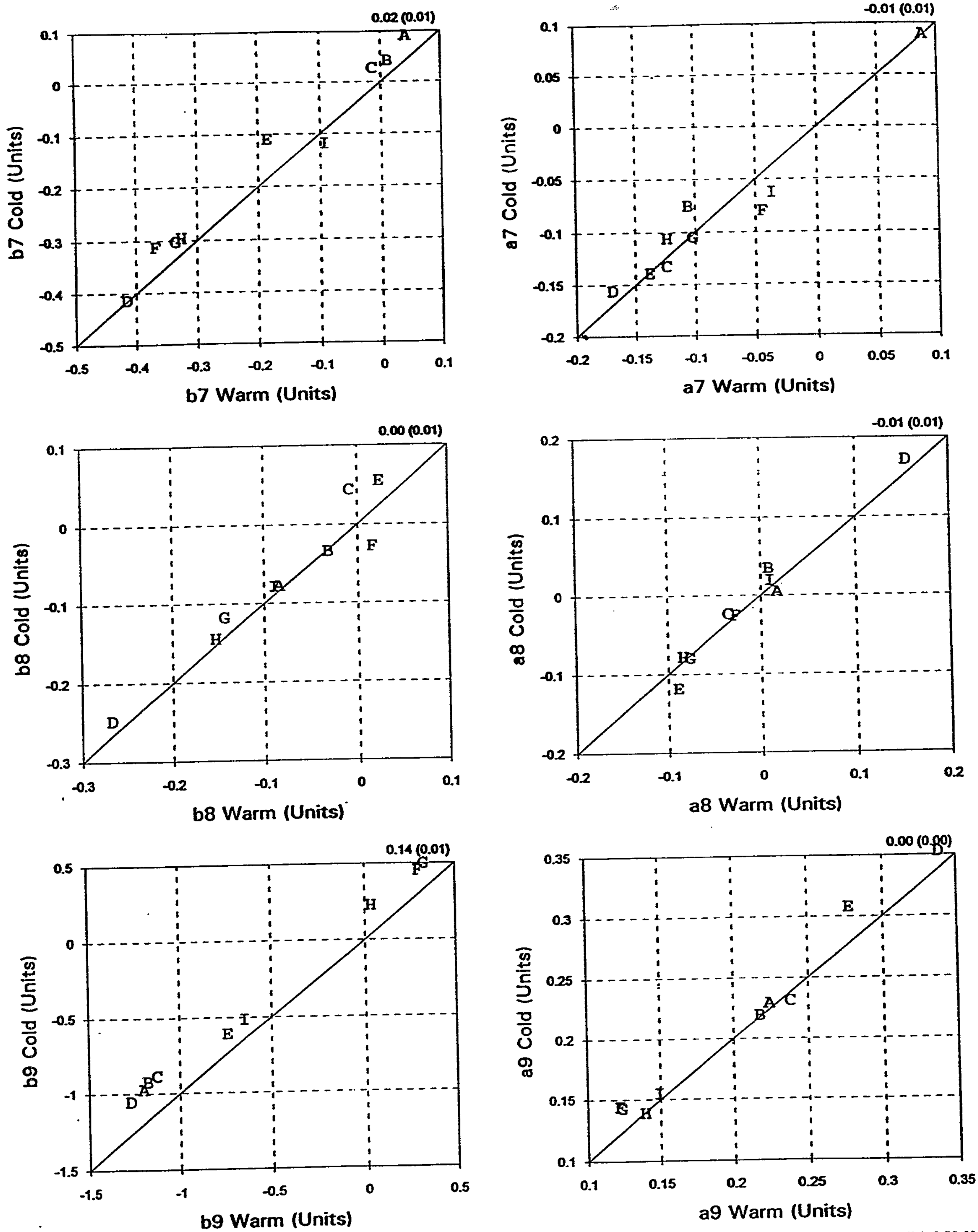
Q1TREND.XLS

7/27/95

G QRI104 29 34 36   H QRI104 71 77 78 (with Shims)   I QRI120 44 67 68 (with Shims)

Warm-Cold Correlations for 13cm Insertion Quadrupoles (QRI)

Warm = 10A in Dewar; Cold = 5000A, Avg. of Up and Dn Ramps

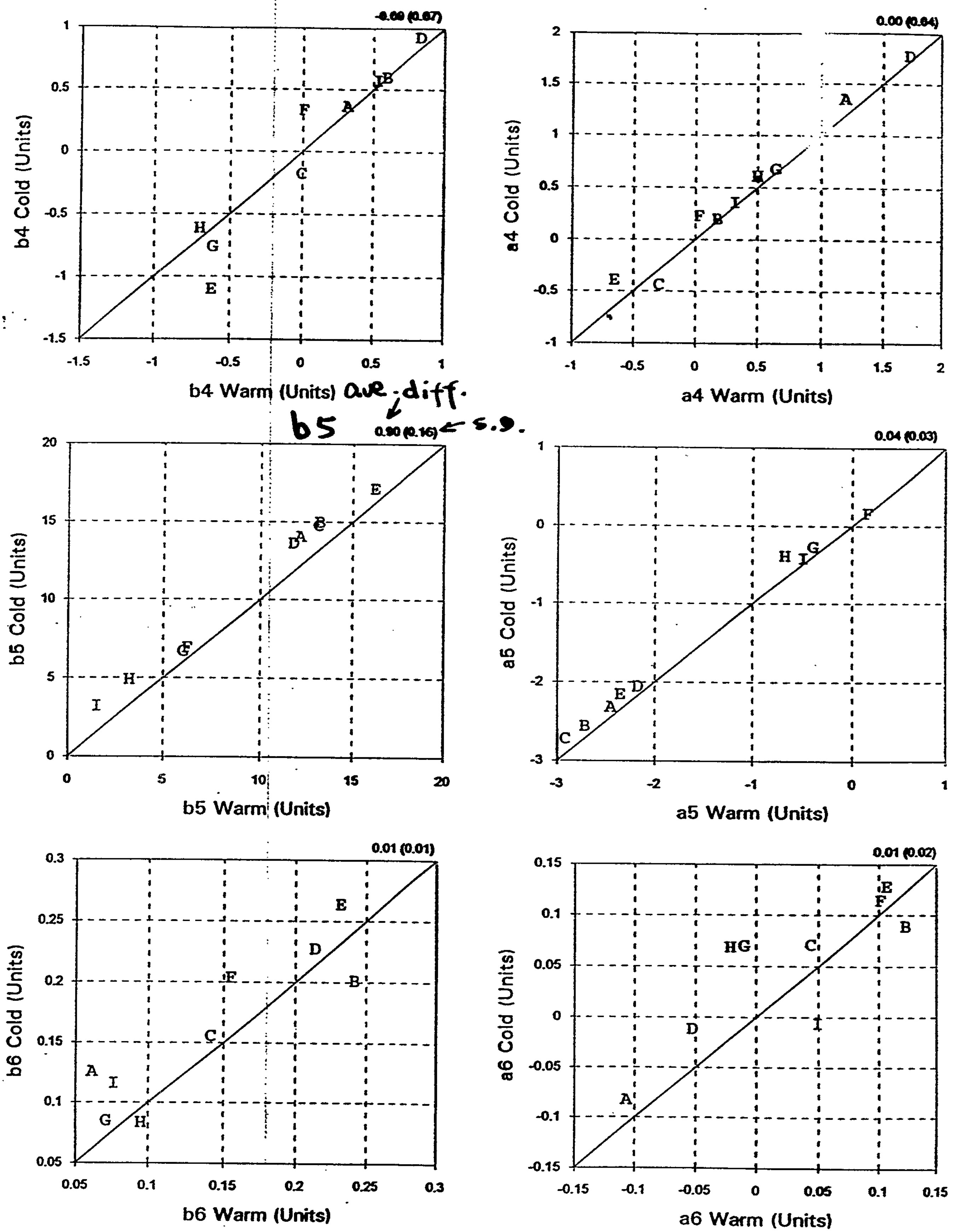


6/8/94 8:50 AM

A QRI001 02 23 30 B QRI002 05 18 19 C QRI002 H8 D6 D7 D QRI002 I1 L8 L9 E QRI002 Q1 T3 T4 F QRI103 04 22 23
G QRI104 29 34 36 H QRI104 71 77 78 (with Shims) I QRI120 44 67 68 (with Shims)

Warm-Cold Correlations for 13cm Insertion Quadrupoles (QRI)

Warm = 10A in Dewar; Cold = 5000A, Avg. of Up and Dn Ramps



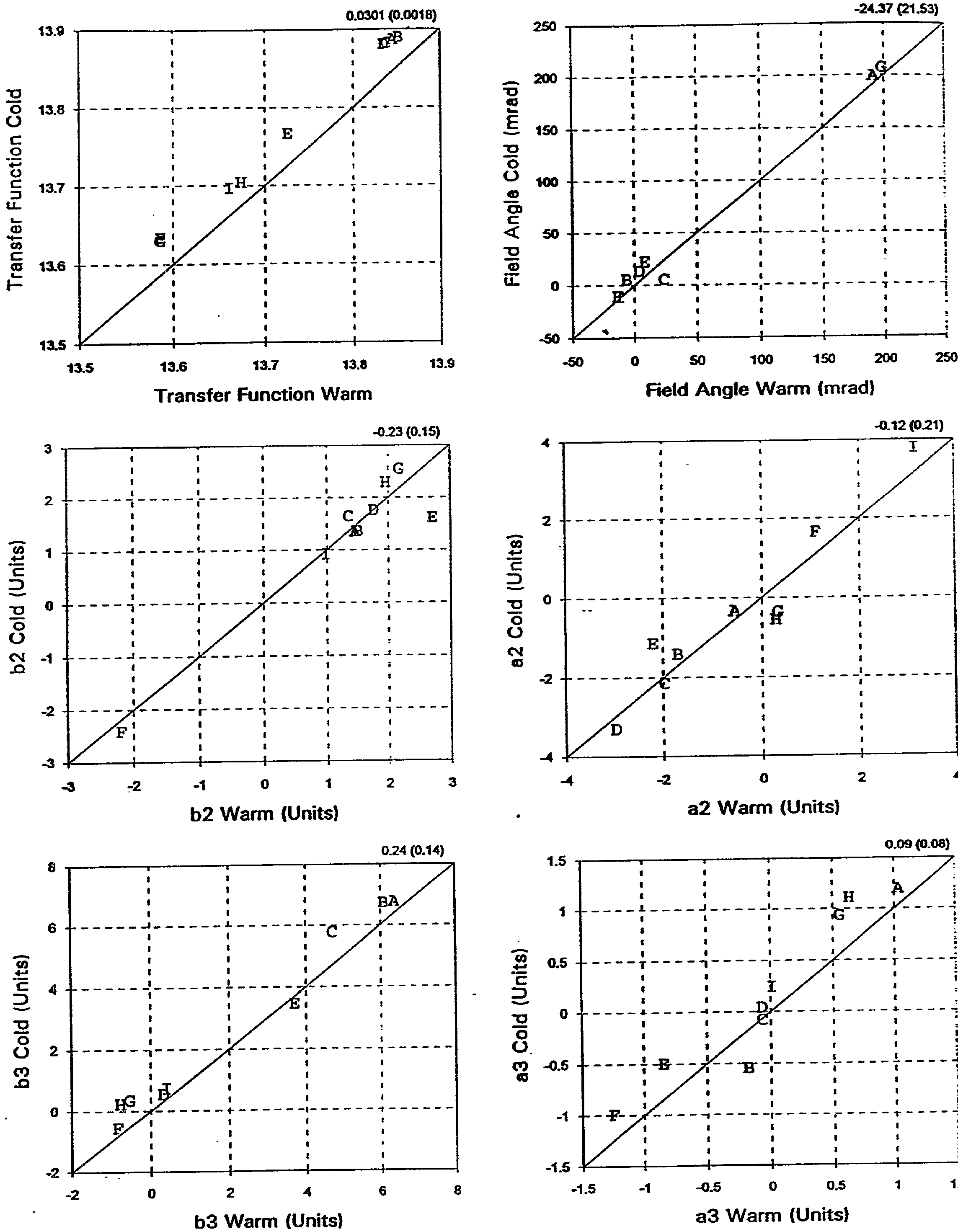
6/8/94 8:50 AM

G QRI104 29 34 36   H QRI104 71 77 78   I QRI120 44 67 68

(with shims)   (with shims)

Warm-Cold Correlations for 13cm Insertion Quadrupoles (QRI)

Warm = 10A in Dewar; Cold = 5000A, Avg. of Up and Dn Ramps



6/8/94 8:49 AM

Expected harmonics in D0 dipole (5 kA)

Oct 18, 1993 EXPECTED_D10.TABLE4_D

Table 4(d)

Expected values of body harmonics in 100 mm Insertion Arc dipoles D0 at 5000 A : @ 31 mm radius

[<bn> = mean, d(bn) = uncertainty in mean, sig(bn) = sigma for bn]

n	<bn>	d(bn)	sig(bn)	<an>	d(an)	sig(an)
1	0.4	0	0.8	~~-2.5~~ 0	1.	1.3
2	0	2	2.3	-0.4	0	.5
3	0.2	0	.3	0	.3	1.0
4	0	.5	.6	0	.06	.2
5	0	.03	.1	-0.1	0	.26
6	0.0	.1	.1	0	.03	.1
7	0	.03	.1	0	.03	.1
8	0.0	.1	.1	0	.03	.1
9	0.0	.03	.1	0	.03	.1

optimized at 5 kA.

b_2, b_4, b_6 are stronger at lower currents

Cross talk between D0 dipoles

10 cm coil ID (instead of 10 cm), minimized

$b_1 < 0.5$

$b_3, b_5, \cdots < 0.3$

Figure of merit" in IR error compensation

minimize "action kick"

$$\frac{\Delta J}{J} \sim \frac{1}{\rho} \sum b_n \cdot L \cdot \beta^{\frac{n+1}{2}} \cdot (2J)^{\frac{n-1}{2}} \cdot \quad (2 \sin\chi \cdot \cos^n \chi$$

$\uparrow b_{n+1}$

$\uparrow$ no phase ~~adva~~ advance

$$J = \frac{1}{2\beta} \left(x^2 + (\alpha x + \beta x')^2\right)$$

this has the same scaling as tune shift

e.g. $\boxed{\frac{1}{\rho} \cdot \sum b_n \cdot L \cdot \beta^{\frac{n+1}{2}} \cdot (2J)^{\frac{n-1}{2}}} < 10^{-3}$?

for each triplet

using separated lead end, return end, and body harmonics

Compensation method

only correct at top field. (5 kA)

* coil, cross section iteration ($\lesssim$ 0.1 mm level)

  body - ends compensation on allowed harmoni

  use body & ends harmonics — allowed

  weighted by β-function variation — systematic + semi.

  b_5, b_3

* iron modification, tuning shims (~ 1 mm level

  minimize body a_2, a_3, a_4, a_5, b_2, b_3, b_4

  after warm measurement, actual (systematic + random

* choose lead-end orientation & corrector locations

  low β for lead ends, c_3, & c_2, c_3 cancellatio

  orthogonal locations (H, V) for correctors

* use local correctors, a_2/b_2, a_3/b_3, b_4, a_5/b_5

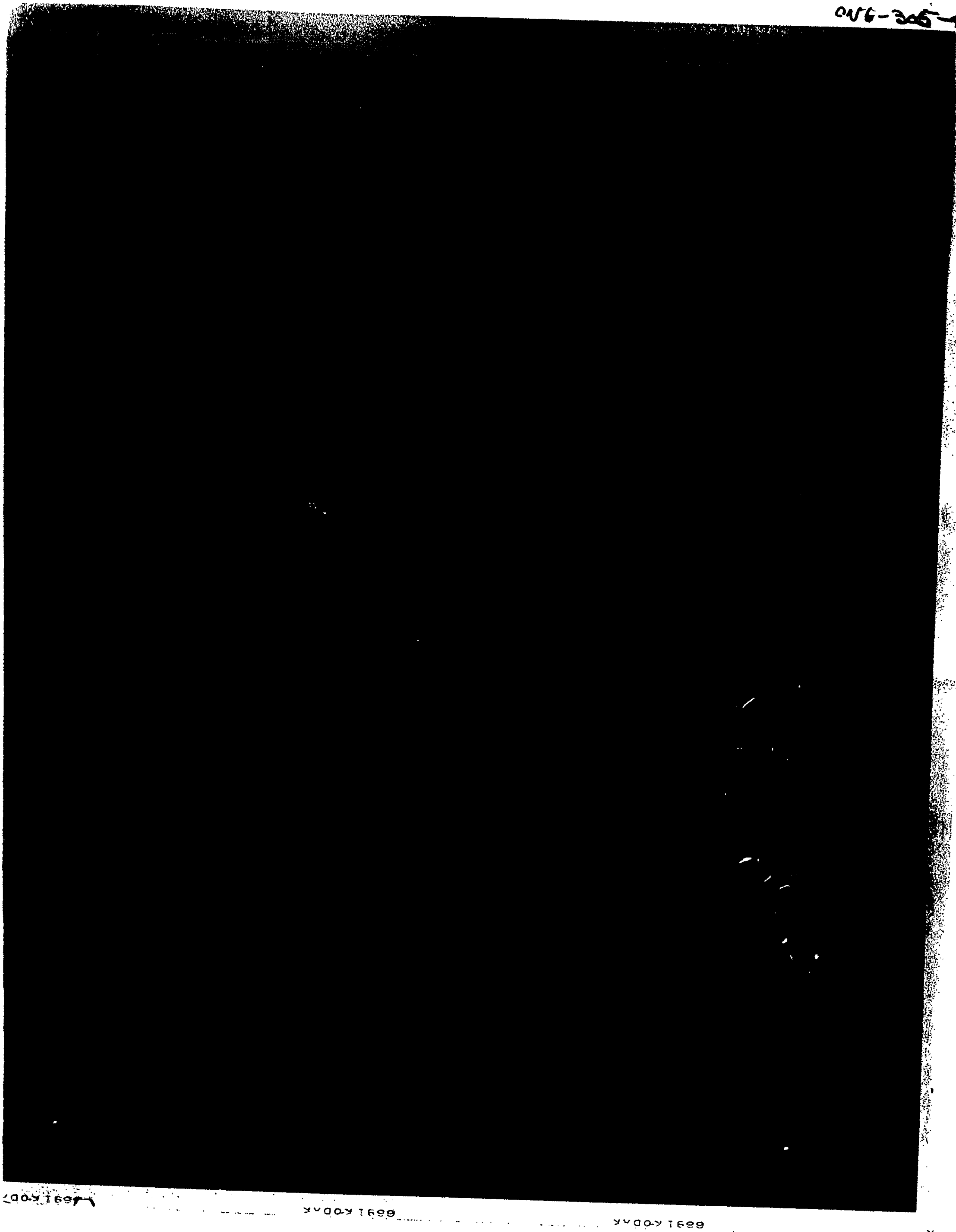
  correction based on magnetic measurements

  weighted by β-function variation "active" knob

* sort "golden" magnets for $\beta^* = 1$ m IP.

  split tune, 90° phase advance between IP

ONG-305-93



* body - end b_5 compensation

based on the minimization of "action kicks" over each triplet pair

$$\frac{\Delta J_x}{J_x} \sim b_n L \cdot \beta_x^{\frac{n+1}{2}} \cdot (2J_x)^{\frac{n-1}{2}} \cdot (2 \sin\chi_x \cdot \cos^n\chi_x)$$

$$\Rightarrow \int_{FDF} G \beta_x^3 b_5 \, ds + \int_{DFD} G \beta_x^3 b_5 \, ds = 0$$

$$\int_{FDF} G \beta_y^3 b_5 \, ds + \int_{DFD} G \beta_y^3 b_5 \, ds = 0$$

optimized lead end location ↙

$$\boxed{b_5 \text{ (body)} = -0.17 \; B_{5\,Lead} - 0.35 \; B_{5\,return}}$$

-1.2 unit ↑ $[m^{-1}]$ ↑ 4.6 (unit·m) ↑ $[m^{-1}]$ ↑ 1.0 (unit·m)

* works for any β^*
* compensated within each triplet, using Q2, Q3 cancellation to minimize b_5(body)
* same b_5 body for all three quads of diff. length

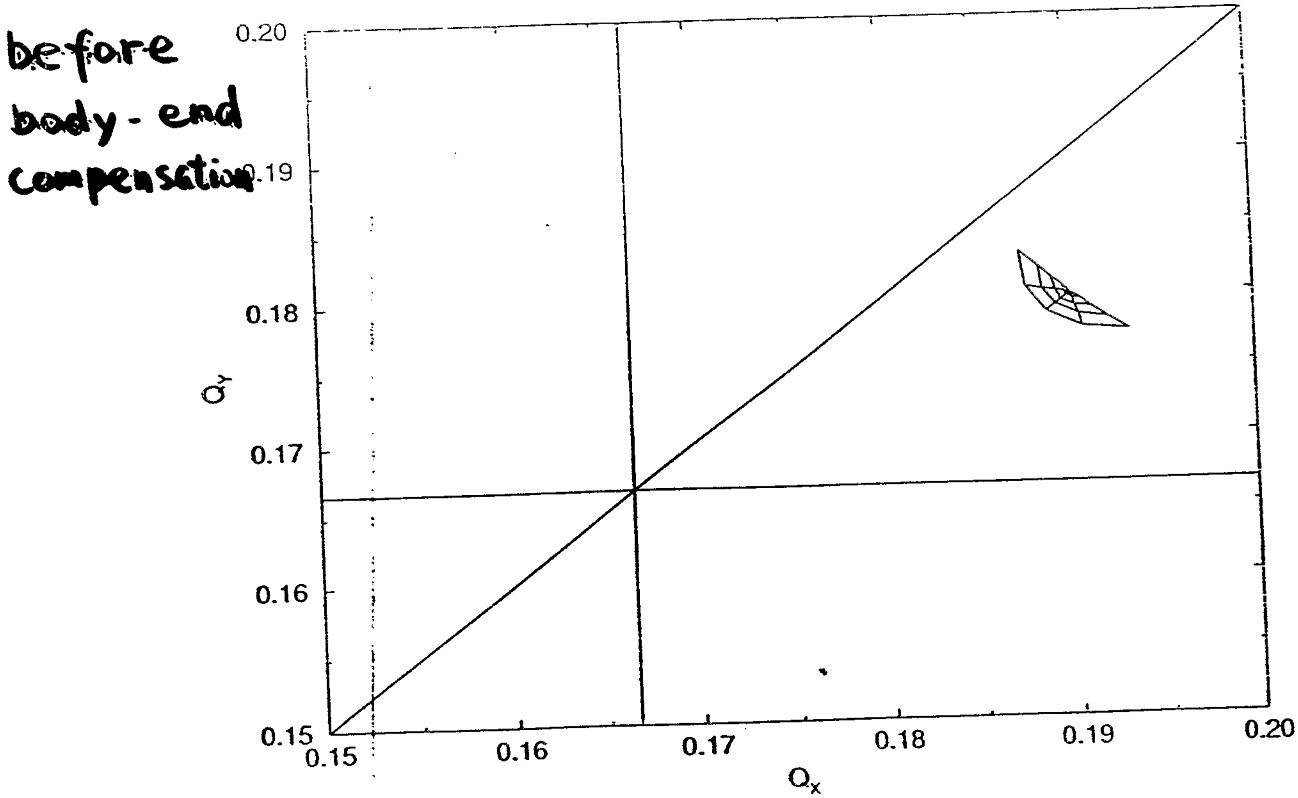


Figure 2: Tune shift of on-momentum particles with betatron amplitude from 0 to 5 σ with the 1 meter β^* storage lattice produced by one pair of triplet with lead end error $B_5 = 4.6$ unit·m and return end error $B_5 = 1.0$ unit·m. The horizontal and vertical integer tunes are 28 and 29, respectively.

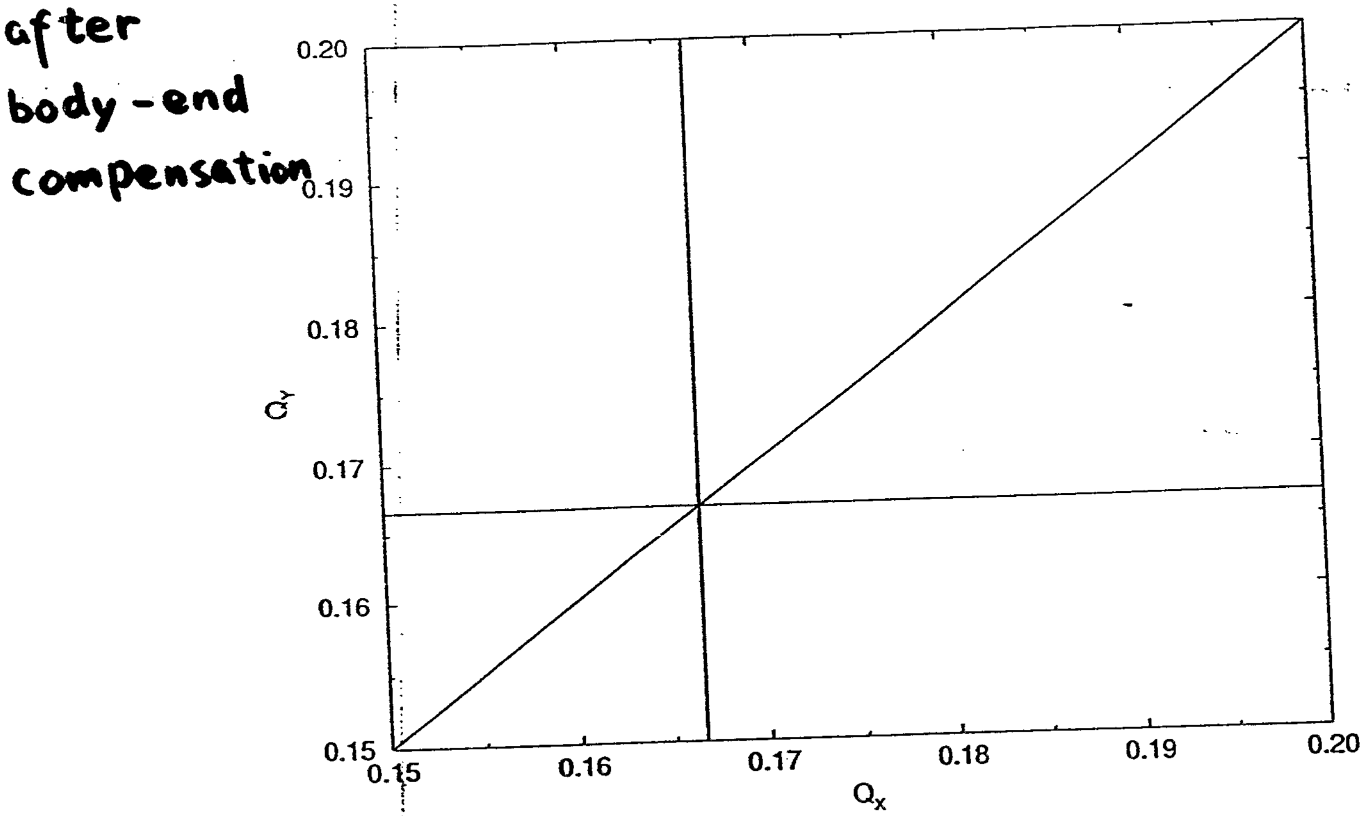


Figure 3: Similar to Figure 2, with $b_5 = -1.2$ unit in the body for compensation.

* tuning shims

* 8 shims in quadrupole symmetry, can correct 8 multipoles

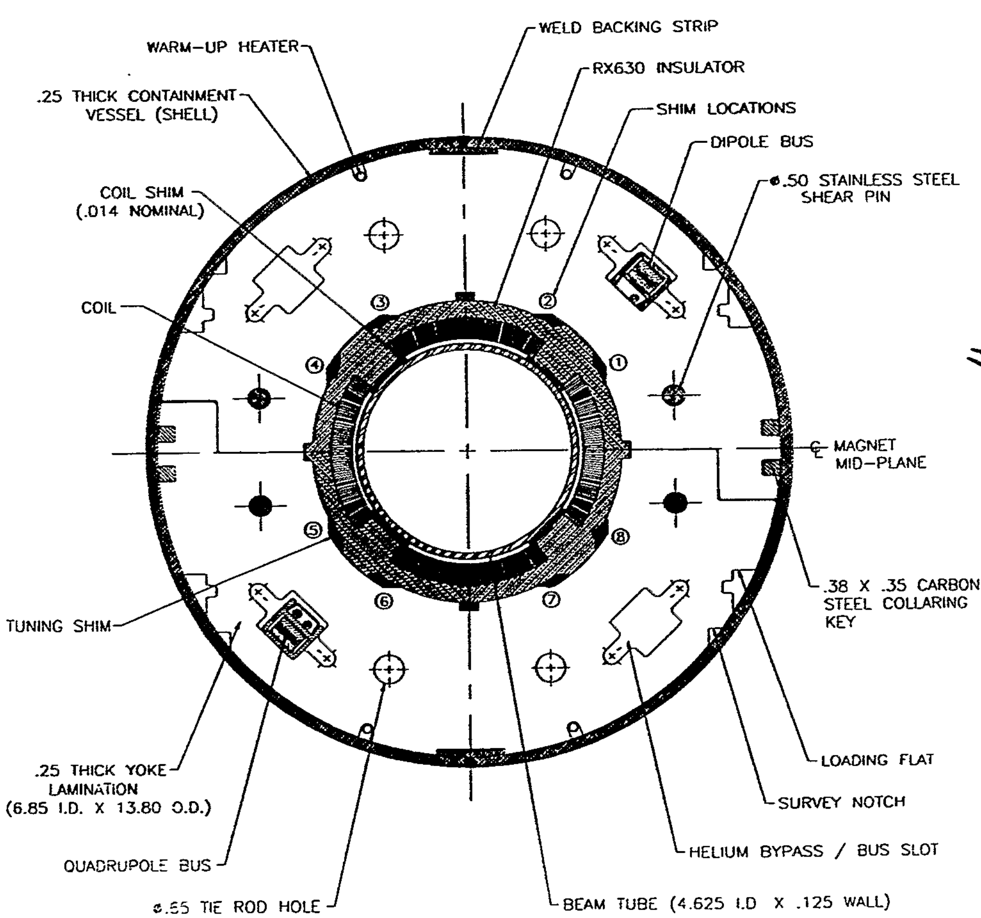
  a_2 a_3 a_4 a_5 , b_2, b_3, b_4, (b_5)
  random

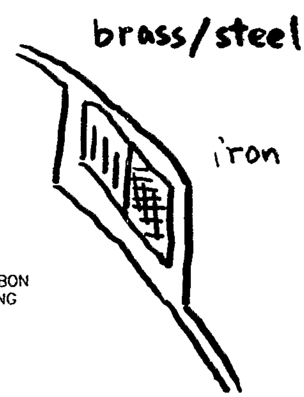
* limited by shim thickness (3.1 mm) and feed-ups

* shim size determined by warm measurement $\Rightarrow \int b_n\, ds =$ (a_i)

  (in simulation, assume 10% r.m.s. measurement error

RHIC 13cm INSERTION QUADRUPOLE





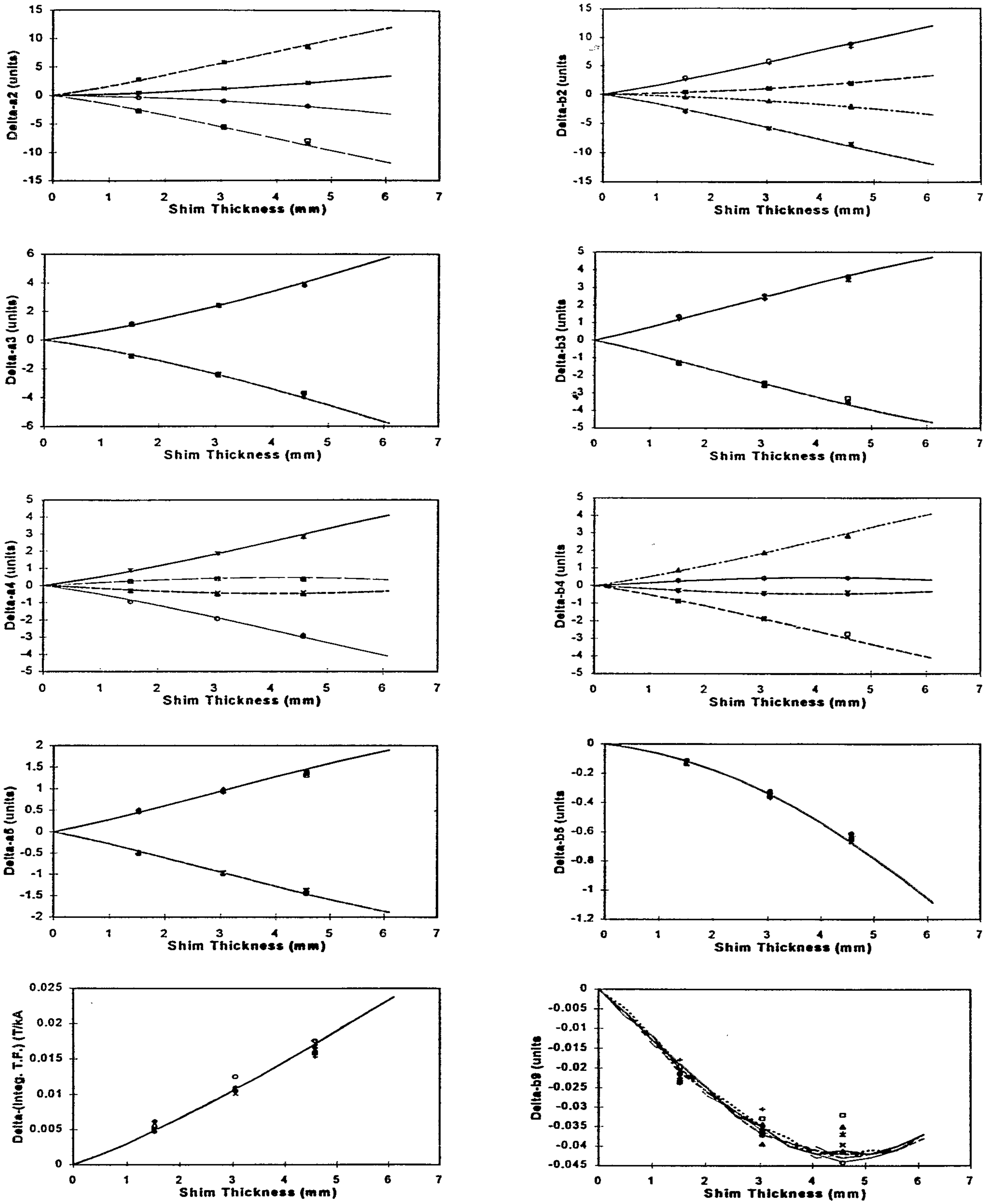


Fig. 3. A comparison between calculations and warm measurements for the field harmonics created by tuning shims. These are the changes in harmonics relative to the "no shim" or "zero iron thickness" case for each shim. The eight symbols represent the measurements for the eight tuning shim locations and eight lines are the calculations for these locations.

From : Ramesh Gupta
To : A. Jain, S. Kahn, G. Morgan, P. Thompson, P. Wanderer, E. Willen
Subj : Shim Experiment at 5 kA

There is a good agreement between the predicted (computed) and measured harmonics due to shims at 5 kA (the current for which the shims are designed). In magnet QRI104 eight shims of nominal thickness were inserted. The harmonics were measured with and without shims. Since the eight shims have the same thickness, then in a pure quadrupole field, the change would be expected only in the transfer function and b5, b9, ... harmonics.

Enclosed are the tables prepared by Animesh Jain where he has listed the harmonics due to shims in QRI104 at 5 kA. He has obtained this from the two sets of measurements (a) harmonics without shims and (b) harmonics with shims. (b)-(a) gives harmonics due to shims. Animesh has divided the measurements in integral, body and ends parts.

Here is the comparison between the computed and measured change

	T.F. (T/kA)	d(b5) (unit)	d(b9) (unit)	d(b13) (unit)
Measured (5 kA)	.075	-1.75	-0.29	+0.02
Computed (5 kA)	.065	-1.76	-0.23	+0.02
Measured (Warm)		-2.7	-0.3	0.03
Computed (Warm)		-2.4	-0.23	0.02

Since the overall transfer function is about 13.6 T/kA, the error is 0.7 part in 1,000 (I guess within the measurement accuracy).

It may be mentioned that the calculated harmonics are for the case when there is a perfect contact between the shim and the yoke. A good agreement between the measurements and calculations can also be seen that the shims were pulled towards the iron when the magnet was energized. I have also included the results of computations.

Non-zero harmonics in the lead end might be due to the interaction of shims with the leads. This simple explanation needs to be verified with calculations.

It may be pointed out that these shims were, though very close to the actual shims, were not exactly the same. The next step will be to do a detailed experiment with the actual shims where the harmonics due to the individual shims are obtained. That will give the coefficients to be used in fixing the harmonics in the future magnets.

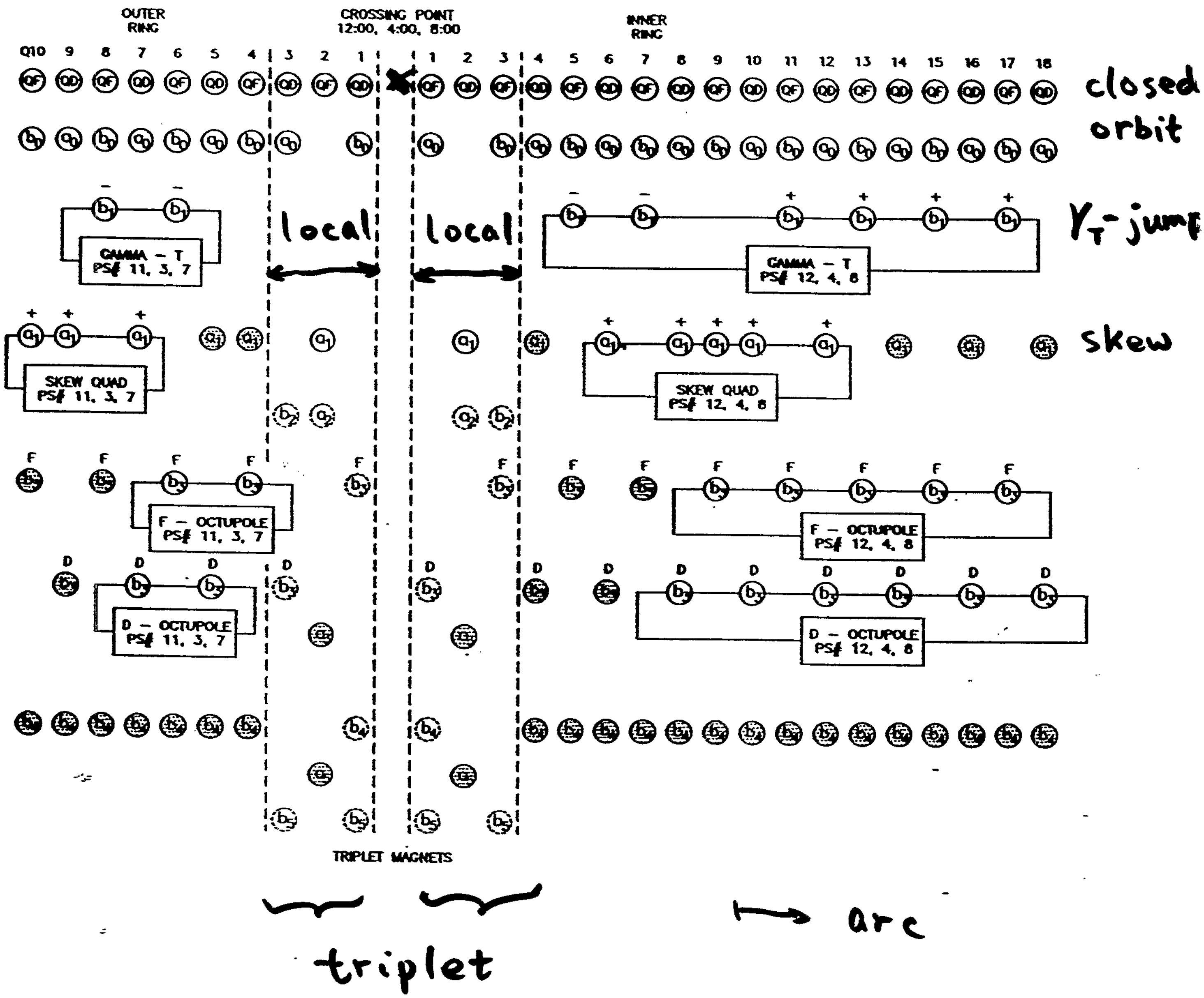
* Local b_2, b_3, b_4, b_5, a_1, a_2 correctors

b_3, & b_5 correctors, 2 per triplet
↑ most effective

* correct both errors from DΦ, and residual errors from triplet quadrupoles
* based on the minimization of action kicks over each triplet
* strength determined by cold measurement (assume 10% r.m.s. error in simulation) and design β function

a_1 correctors, 1 per triplet

* correct both magnetic error (triplet & DΦ) and misalignment effect
* minimize $\int \sqrt{\beta_x \beta_y}\, a_1\, ds$
* use the minimization of verticle dispersion
  S. Tepikian & S. Peggs
  or by observing BPM turn-by-turn data "eigenmodes" F. Pilat et. al.



shaded: not power supplies connected.

Fig. 2-13. Corrector power supplies at 12, 4 and 8 o'clock.

ORDER, n	NORMAL, b_n	SKEW, a_n
0	C1 or C3	C3 or C1
1	-	C2
2	S, (C3)	S (C2)
3	B. S, C1, C3	S, (C2)
4	S, C1	S
5	B. S, C1, C3	S, (C2)
6+	-	-

ble 4 The triplet quadrupole correction strategy.

B : body-ends compensation

S : tuning shims effective

Cn: use Cn corrector

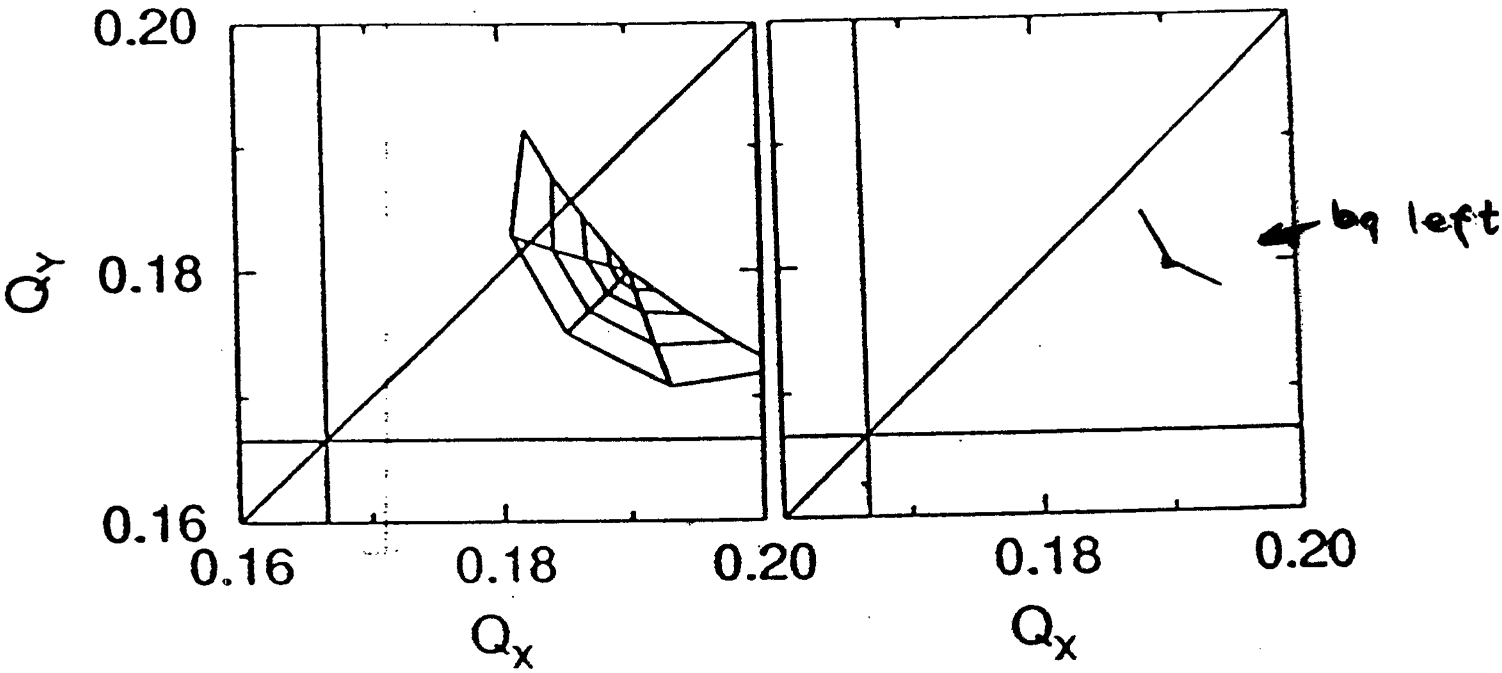
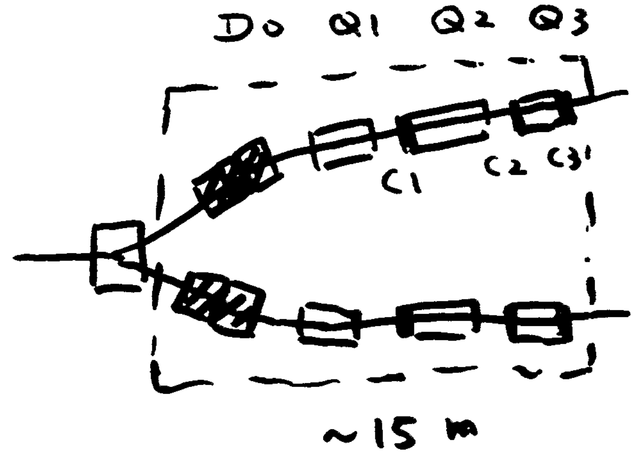


Figure 2 The tune footprint before and after correction, by shimming and excitation of the local correctors. The tune spread after correction is negligible compared to the tune spread due to linear chromaticity. (assume $\xi = -3 \rightarrow +2$)

Misalignment issues



error source

* misalignments between 4 corrector layer

* misalignments between quadrupole and attached correctors

* misalignment between individual magnets

  one cryostat contains 8 elements of 2 rings

* misalignment of the cryostat

* warm - cold play

⇒ center offset, roll, play

high β, large closed orbit error

triplet dipole correctors are crucial.

Table 2: Effects of a transverse offset of the magnet center in the triplet assembly from its design beam trajectory. When not specified, it is assumed that $\beta^* = 1$ m at storage, the quadrupoles Q1, Q2, and Q3 are operating at 5 kA, and the various layers of the correctors C1, C2, and C3 are operating at 50 A.

Magnet	Offset (mm)	Effects for $\beta^* = 1$ m operation (for $\beta^* = 2$ m operation)	Correction needed (if available)
D0	0.5	aperture reduction of 8% rms beam radius (11% rms beam radius at $\beta^* = 2$ m)	local triplet ↓
Q1	0.5	closed orbit offset of 7 mm at arc[a] (5 mm if $\beta^* = 2$ m)	a_0/b_0 corrector at 5 A
Q2	0.5	closed orbit offset of 23 mm at arc[a] (16 mm if $\beta^* = 2$ m)	a_0/b_0 corrector at 13 A
Q3	0.5	closed orbit offset of 14 mm at arc[a] (10 mm if $\beta^* = 2$ m)	a_0/b_0 corrector at 8 A
C2 (a_1)	1	equivalent to 4×10^{-3} I_{max} in a_0/b_0 [b] layer	
C2, C3 (a_2/b_2)	1	equivalent to 20×10^{-3} I_{max} in a_1/b_1 [b] layer	
C1, C2, C3 (a_3/b_3)	1	equivalent to 30×10^{-3} I_{max} in a_2/b_2 [b] layer	
C1 (b_4)	1	equivalent to 60×10^{-3} I_{max} in a_3/b_3 [b] layer	
C1, C3 (a_5/b_5)	1	equivalent to 100×10^{-3} I_{max} in a_4/b_4 [b] layer	

a) At arc section with $\beta = 50$ m.

b) The amount of feed-down produced is expressed relative to the maximum current I_{max} (Table 1) of the specified 13 cm corrector layer.

Table 3: Effects of a roll of the magnet along the beam trajectory in the triplet assembly. It is assumed that D0, Q1, Q2, and Q3 are operating at 5 kA, and the various layers of C1, C2, and C3 are operating at 50 A.

Magnet	Roll (mrad)	Effects for $\beta^* = 1$ m operation (for $\beta^* = 2$ m operation)	Correction needed (if available)
D0	0.5	closed orbit offset of 1.3 mm at arc (0.9 mm at $\beta^* = 2$ m)	a_0/b_0 corrector at 1 A
Q1	0.5	equivalent to $\Delta Q_{min} = 0.006$ [a] ($\Delta Q_{min} = 0.003$ at $\beta^* = 2$ m)	a_1 corrector at 3 A
Q2	0.5	equivalent to $\Delta Q_{min} = 0.026$ [a] ($\Delta Q_{min} = 0.013$ at $\beta^* = 2$ m)	a_1 corrector at 7 A
Q3	0.5	equivalent to $\Delta Q_{min} = 0.016$ [a] ($\Delta Q_{min} = 0.008$ at $\beta^* = 2$ m)	a_1 corrector at 5 A
C1, C3 (a_0/b_0)	5	equivalent to 5×10^{-3} I_{max} in b_0/a_0 [b] layer	
C2 (a_1)	5	equivalent to 10×10^{-3} I_{max} in b_1/a_1 [b] layer	
C2, C3 (a_2/b_2)	5	equivalent to 15×10^{-3} I_{max} in b_2/a_2 [b] layer	
C1, C2, C3 (a_3/b_3)	5	equivalent to 20×10^{-3} I_{max} in b_3/a_3 [b] layer	
C1 (b_4)	5	equivalent to 25×10^{-3} I_{max} in a_4 [b] layer	
C1, C3 (a_5/b_5)	5	equivalent to 30×10^{-3} I_{max} in b_5/a_5 [b] layer	

a) Minimum tune split due to linear coupling.

b) Relative to the maximum-current strength of the specified 13 cm corrector layer.

III. Arc region error compensation

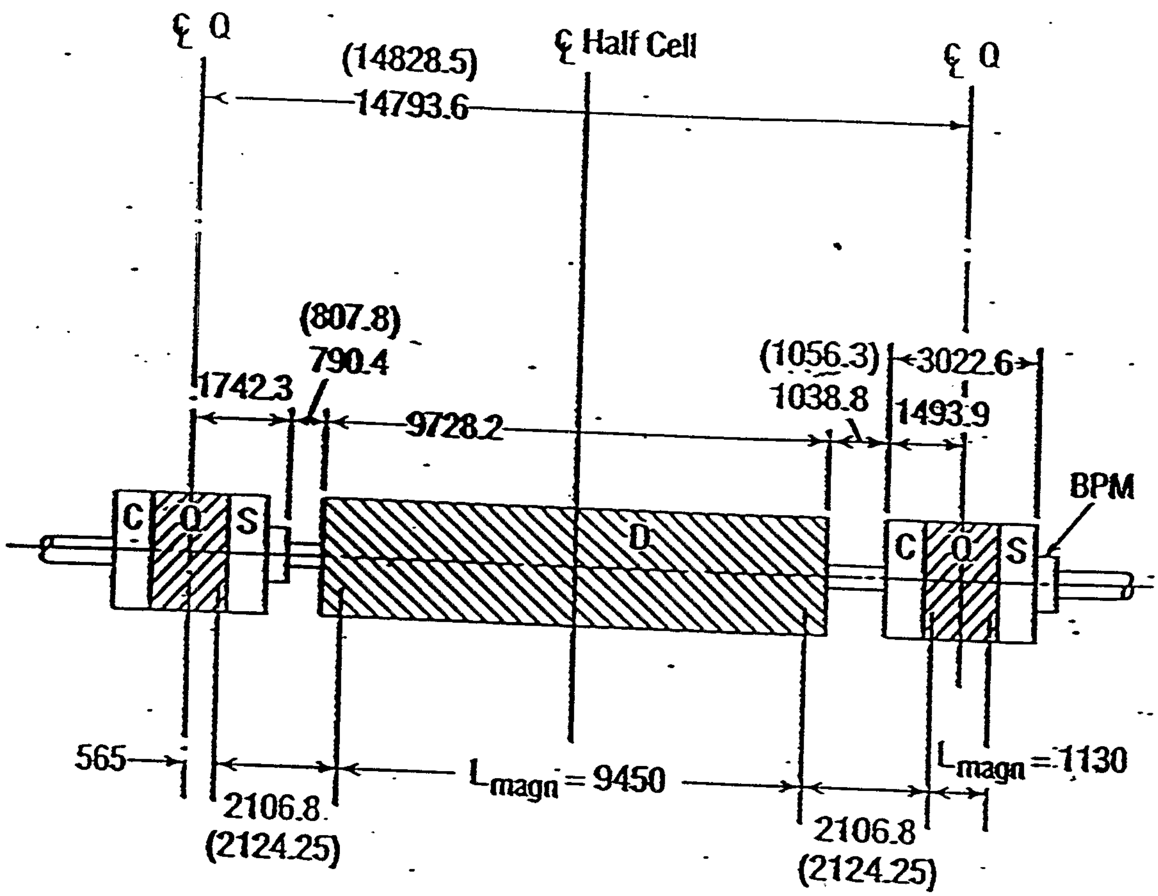


Fig. 11-2. Layout of inner(outer) arc half cell.

Field quality issues

error source

* arc dipole

integral transfer function variation ~ 3×10^{-4} s

integral field angle ~ 1 mr s.d.

b2, b4, a1

↖ allowed ↗ ↖ coldmass asym. in V

body field angle twist pol. proton

* arc quadrupole

ITF ~ 5×10^{-4} s.d.

IFA ~ −1.8 mr. systematic from ends

b5, a5, b3

↖ allowed ↗ ↑ asym. in H, V. plane

Table II

Some integral multipole harmonics of the RHIC dipoles measured at various test currents (mean±standard deviation in prime units[6] at the reference radius of 2.5 cm).

	a_1	b_2	a_2	b_4
30 A (warm)	0.1±1.5	4.8±1.4	-1.0±0.2	0.0±0.4
660 A (cold)	0.7±1.3	1.0±1.4	-1.0±0.2	-0.6±0.5
1450 A (cold)	0.6±1.2	2.9±1.4	-1.0±0.2	-0.4±0.5
5000 A (cold)	-1.3±1.4	1.4±1.5	-1.1±0.2	-0.1±0.5

Table IV

Some integral multipole harmonics of the RHIC quadrupole magnets measured at various test currents (mean±standard deviation in prime units[6] at the reference radius of 2.5 cm).

	b_3	b_5	a_5
10 A (warm)	-1.4±1.2	1.4±0.5	-3.7±0.3
660 A (cold)	-0.7±1.7	-1.9±0.6	-3.7±0.4
1450 A (cold)	-0.7±1.7	0.5±0.6	-3.7±0.3
5000 A (cold)	-0.7±1.7	5.6±0.6	-3.8±0.3

Table III

Warm measured means and standard deviations (SD) of the integral and body transfer function, integral field angle, body field angle standard deviation, and center offsets of the RHIC arc magnets.

	DRG	QRG	SRE
Integ. trans. func. (relative SD)	3.0×10^{-4}	4.8×10^{-4}	1.8×10^{-3}
Body trans. func. (relative SD)	3.1×10^{-4}	—	—
Integ. field angle (Mean±SD) (mr)	-0.5±0.8	-1.8±0.4	0.0±0.3
Body field angle SD (Mean) (mr)	0.8	—	—
Center offset X_0 (Mean±SD) (mm)	—	0.03±0.06	0.02±0.09
Center offset Y_0 (Mean±SD) (mm)	—	0.13±0.06	0.03±0.03

early stage of arc dipoles; improved later

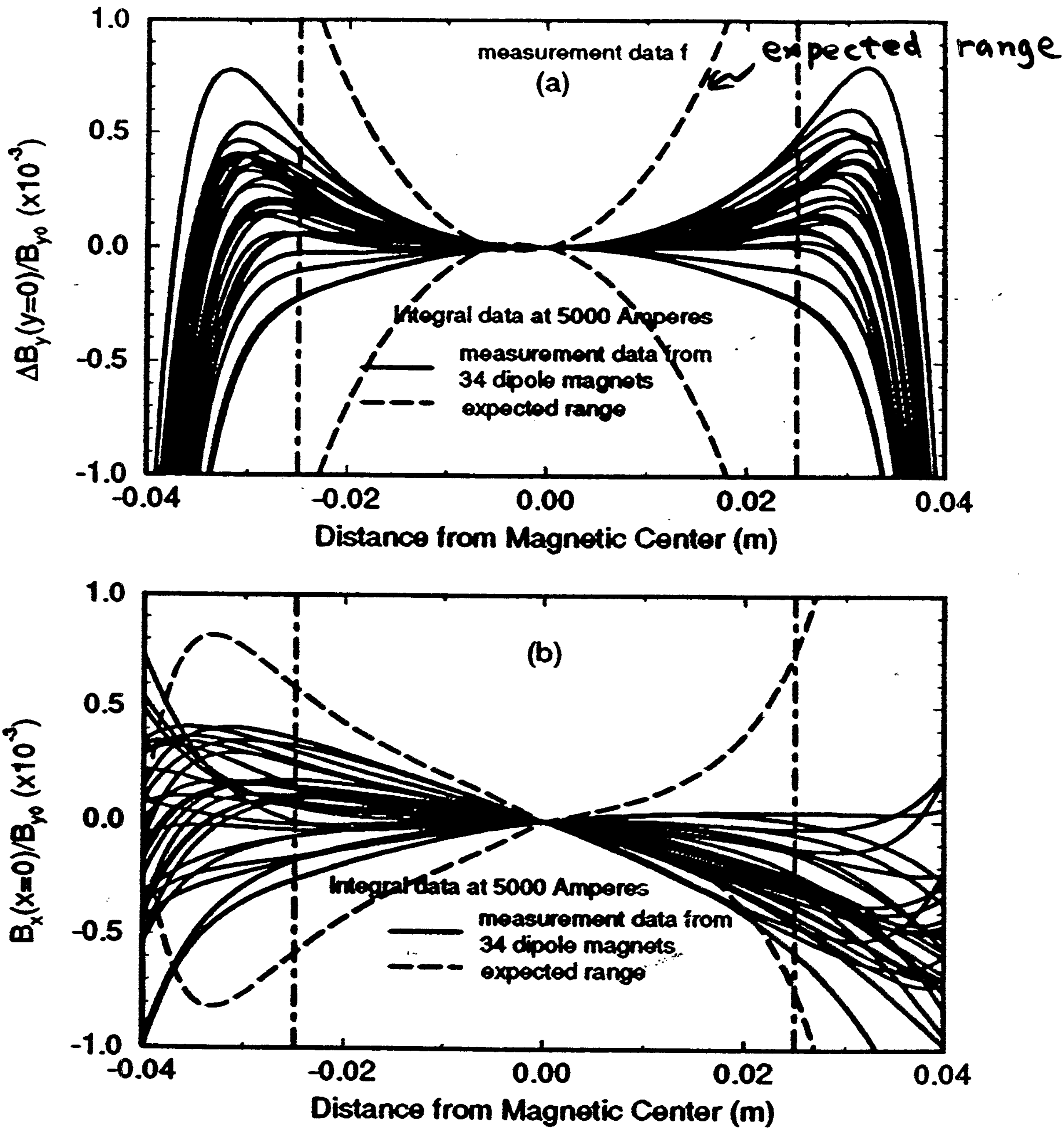


Figure. 2. RHIC dipole magnet a) vertical field profile at horizontal midplane and b) horizontal field profile at vertical midplane.

Compensation method

* cross section iteration at design & early production stage no b_3, b_4 corr. needed

  minimize systematics at injection & storage

* quick feed-back from BNL to builder

  when ITF drops 10^{-3}, fixed in 2 weeks

  ~20 magnets

* sort dipoles on ITF, minimize corrector strength

* spare "silver" magnets

* use correctors

  a_0/b_0, a_1, (b_3, b_4)

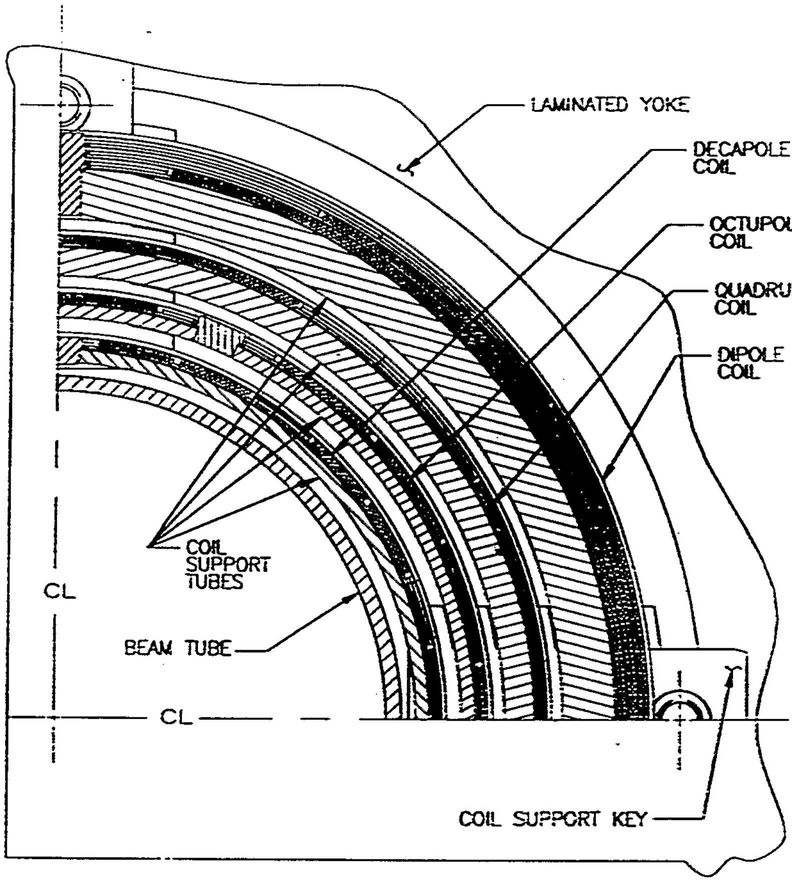


Fig. 1-11. Arc corrector coil cross-section.

Table 1-19. Operating Parameters of Arc Correctors

Multipole	Inductance (mH)	I_{op} (A)	Field @ 2.5 cm (T)	L_{eff} (m)	I_Q (A)	b_n'
Decapole	4.3	59.0	0.0154	0.575	202	44.6
Octupole	6.9	50.6	0.0164	0.571	198	47.5
Quadrupole	25.0	49.8	0.0675	0.555	190	195.7
Dipole	687	52.2	0.5903	0.508	160	

Misalignment issues

error source

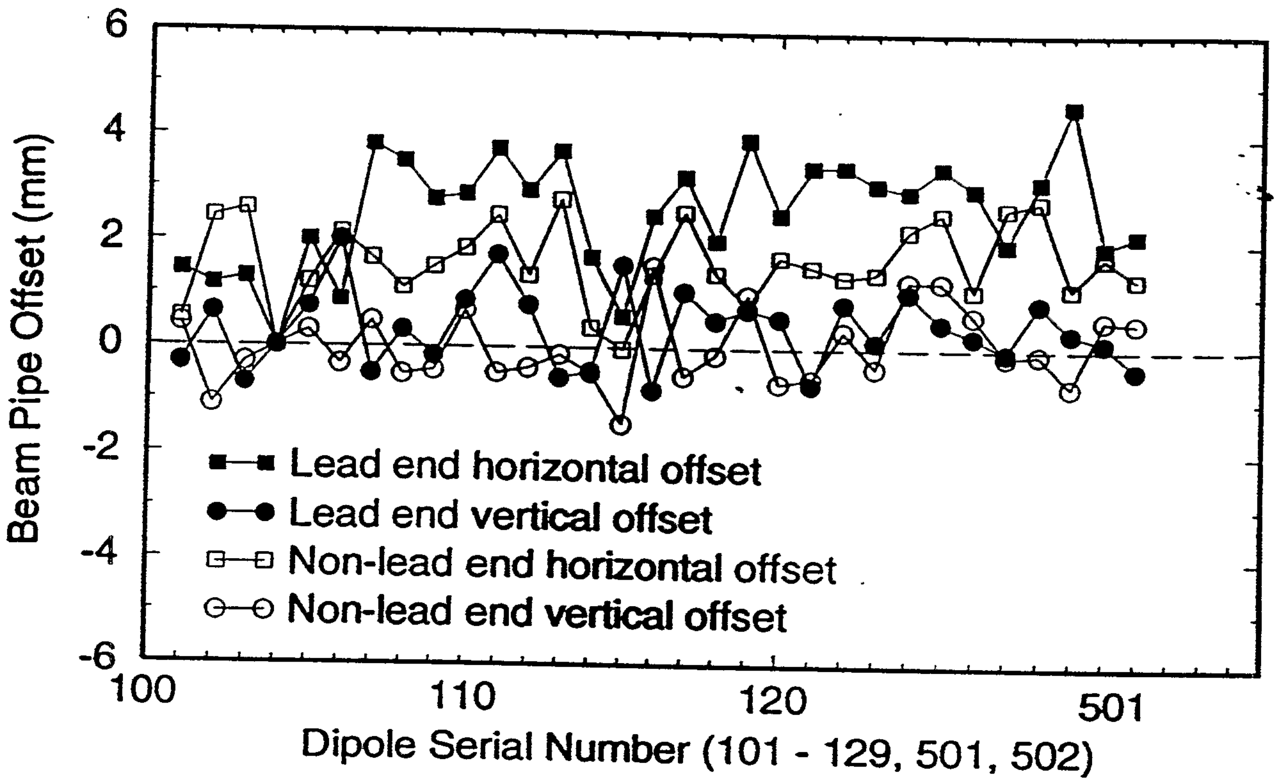
* dipole : displacement of iron center line w.r.t. beam trajectory (sagitta complicatio[n]) pipe mismatch,
* relative alignment error between sextupole, quadrupole, corrector.

  each cryostat contains C, Q, S, (BPM)

* transverse & longitudinal plays in cryostat

  "springs" inserted

⇒ center offset, roll, play



igure 3: Beam-pipe position measurement data from the survey of 31 dipole (DRG) ıagnets performed before July 1995.

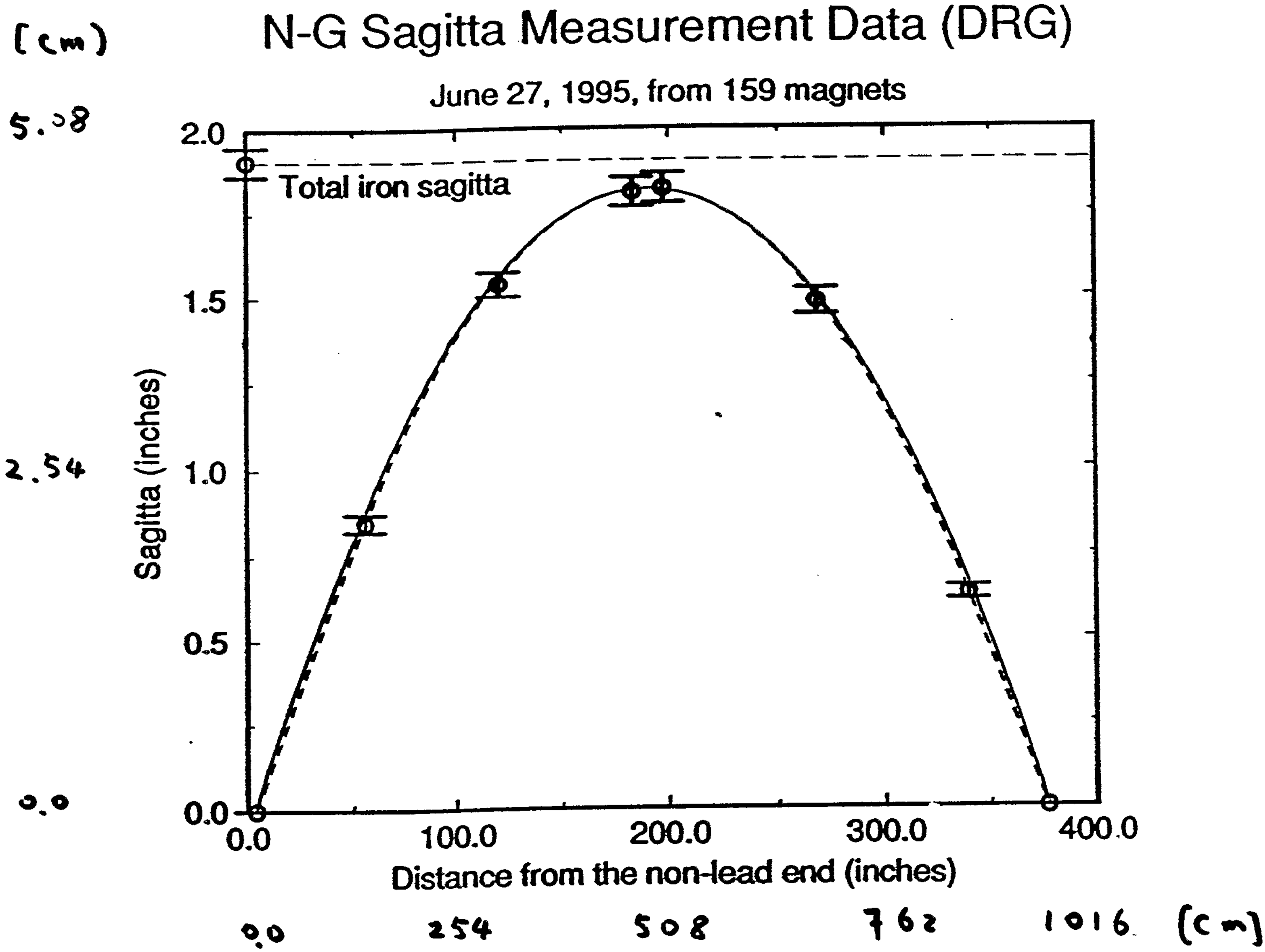


Figure 1: Single arc (solid line) and arc plus straight ends (dashed line) fits to measurements of the iron profile.

mechanically measured at 8 locations

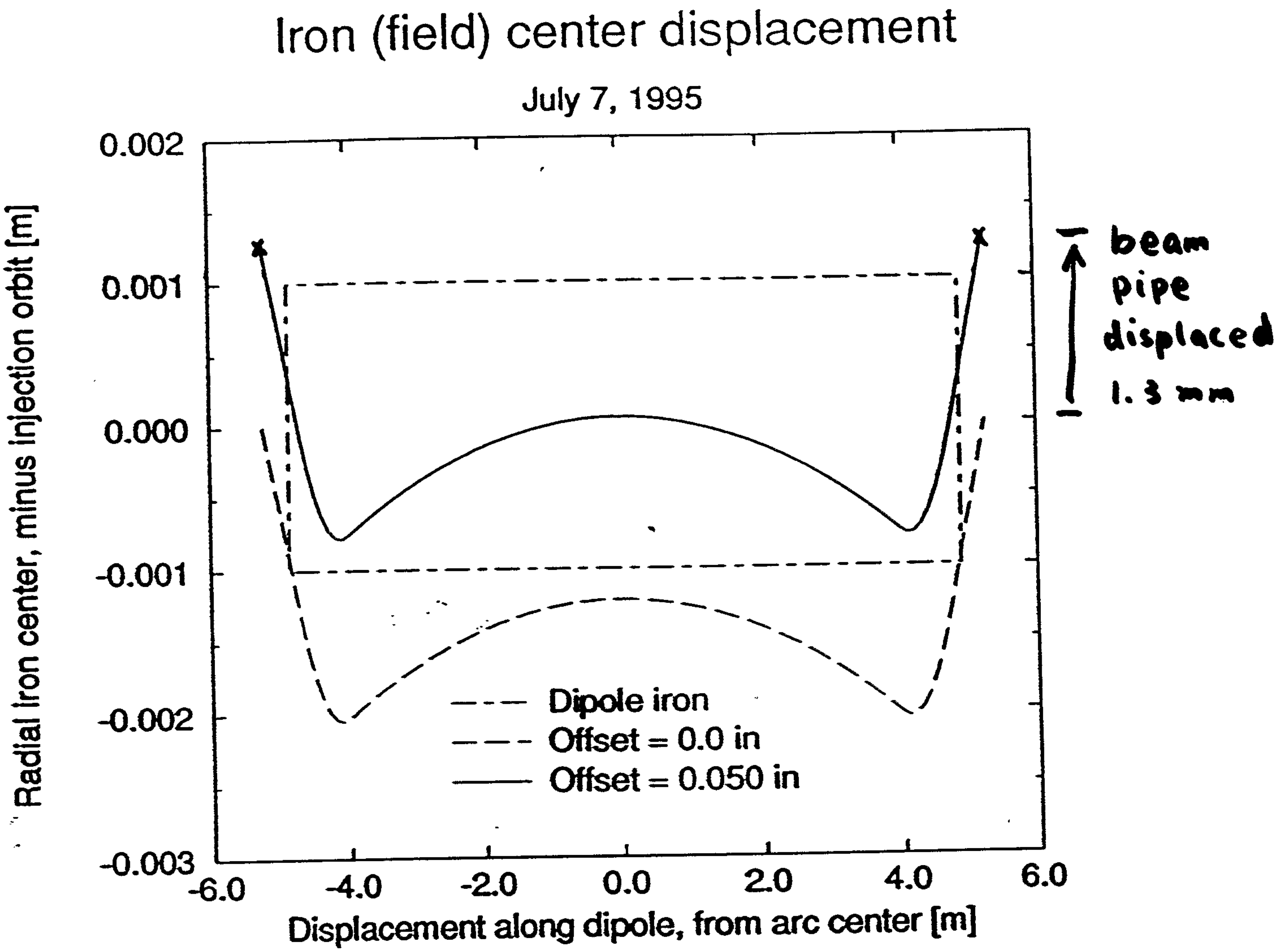


Figure 2: The radial displacement of the iron center line, relative to the injection trajectory, for dipole placement with the recommended radial offset of 50 mils (solid line), and no offset (dashed line). A positive radial displacement means that the magnet is moved away from the ring center. The end points of the curves are the "beam tubes" referred to in Tables 1 and 2.

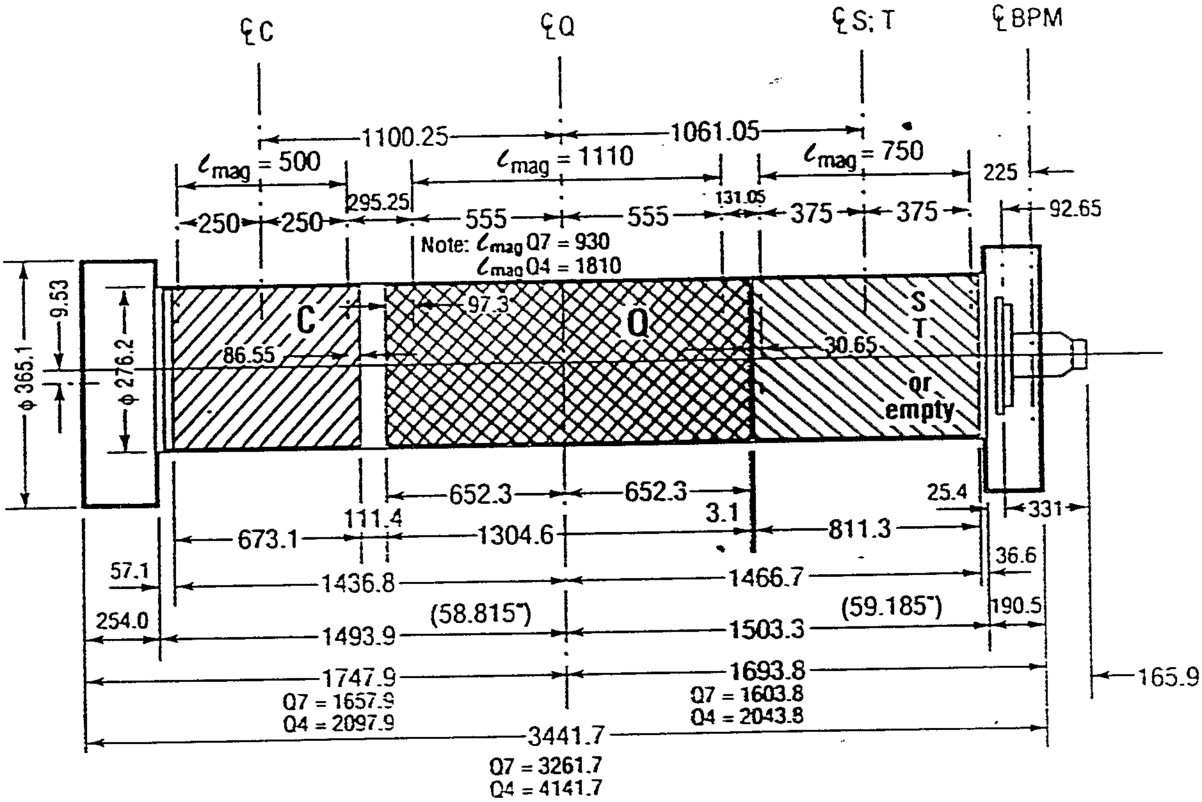
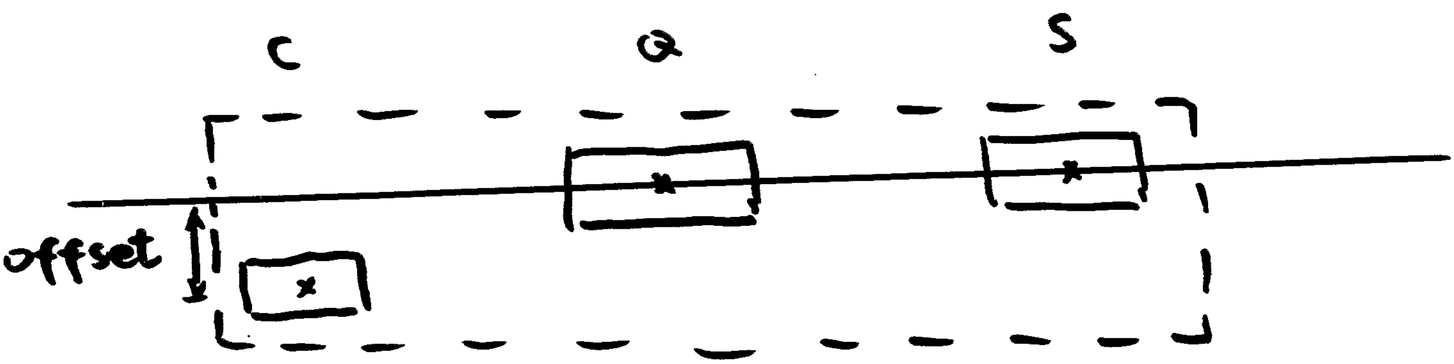
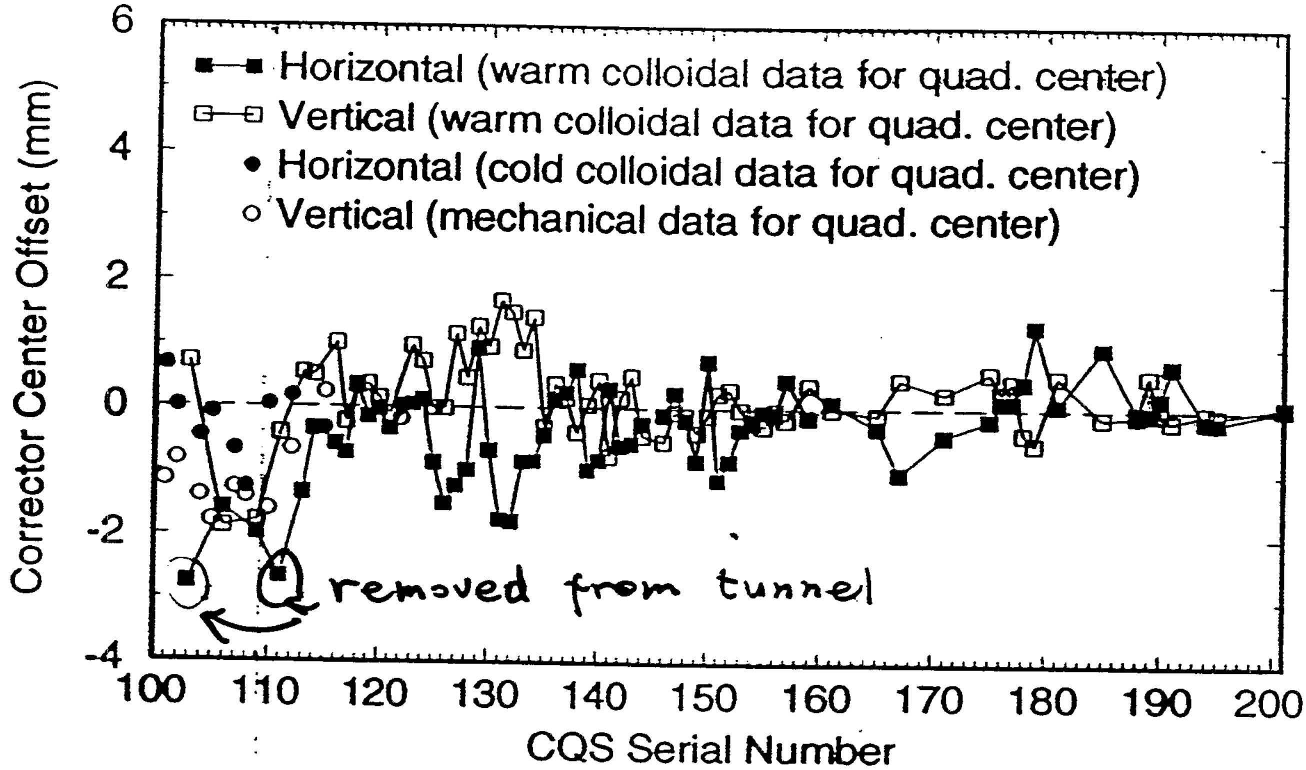


Fig. 1-5. Corrector, quadrupole, sextupole (CQS) assembly. Lamination length is shown.



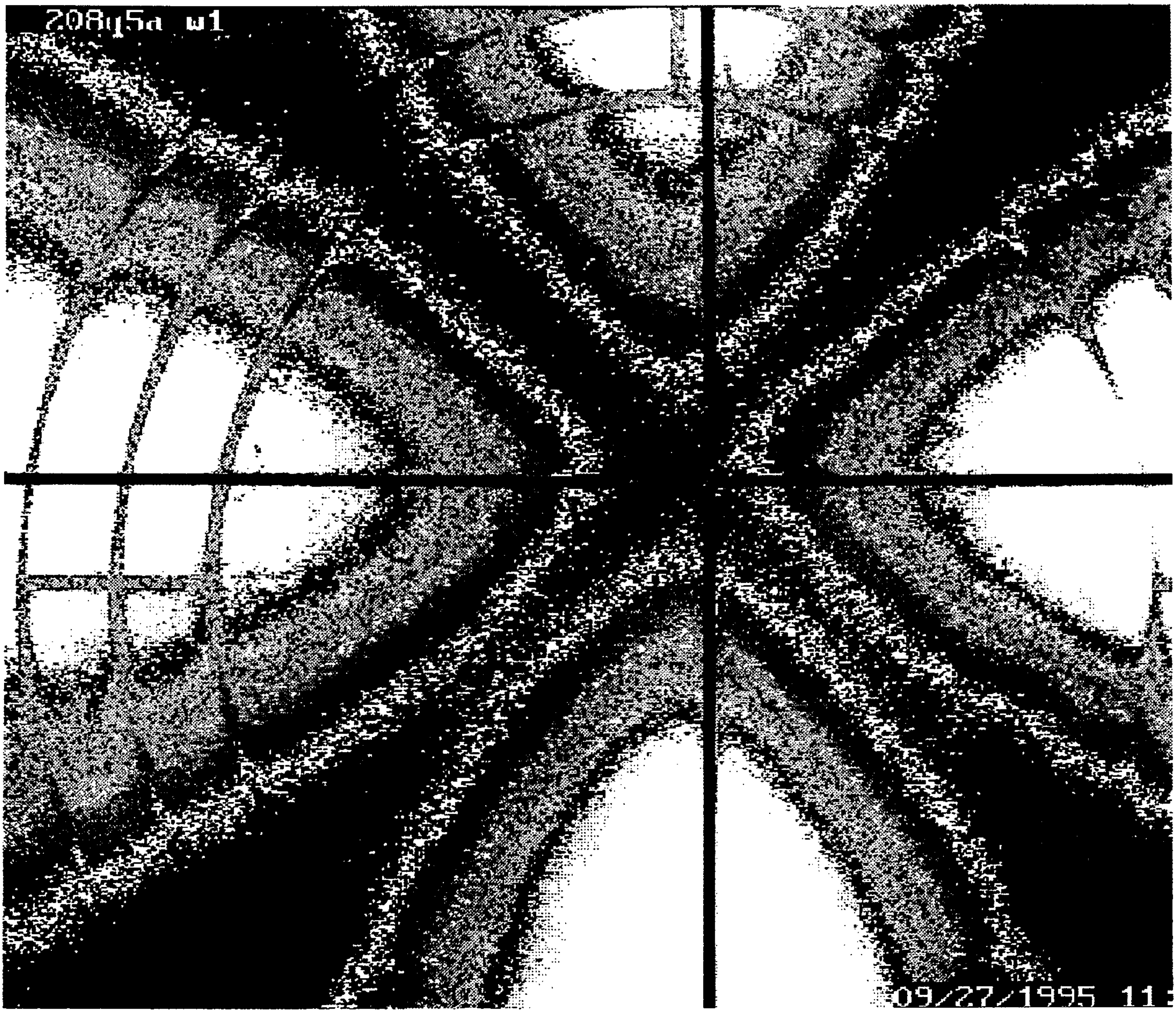


'igure 2: Corrector center offset from the ideal beam orbit determined by averaging th
'arm-measured positions of the four corrector mechanical fiducials.

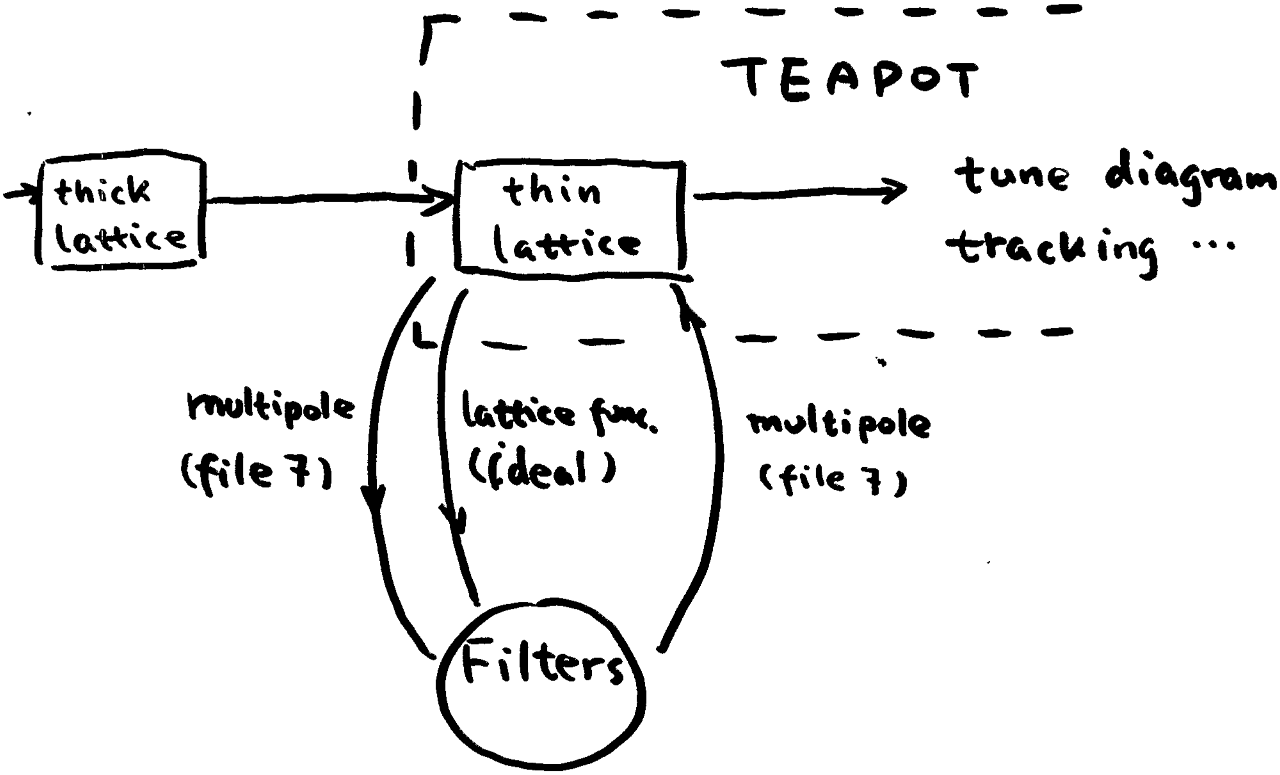
Compensation method

* accurately determine magnetic center
  use colloidal cell measurement
* correct dipole and quadrupole roll
  individually during installation
* align CQS by centering Q and S.
* align C using welding "choreograph"
* quick feed-back from AP group to
  magnet division

  See corrector offset trend


208y5a w1
09/27/1995 11

IV. Computer Modeling



TEAPOT filters:

IR correction

split thick dipole, add feeddown

⋮

Comparison between analytical formula & TEAPOT (storage)

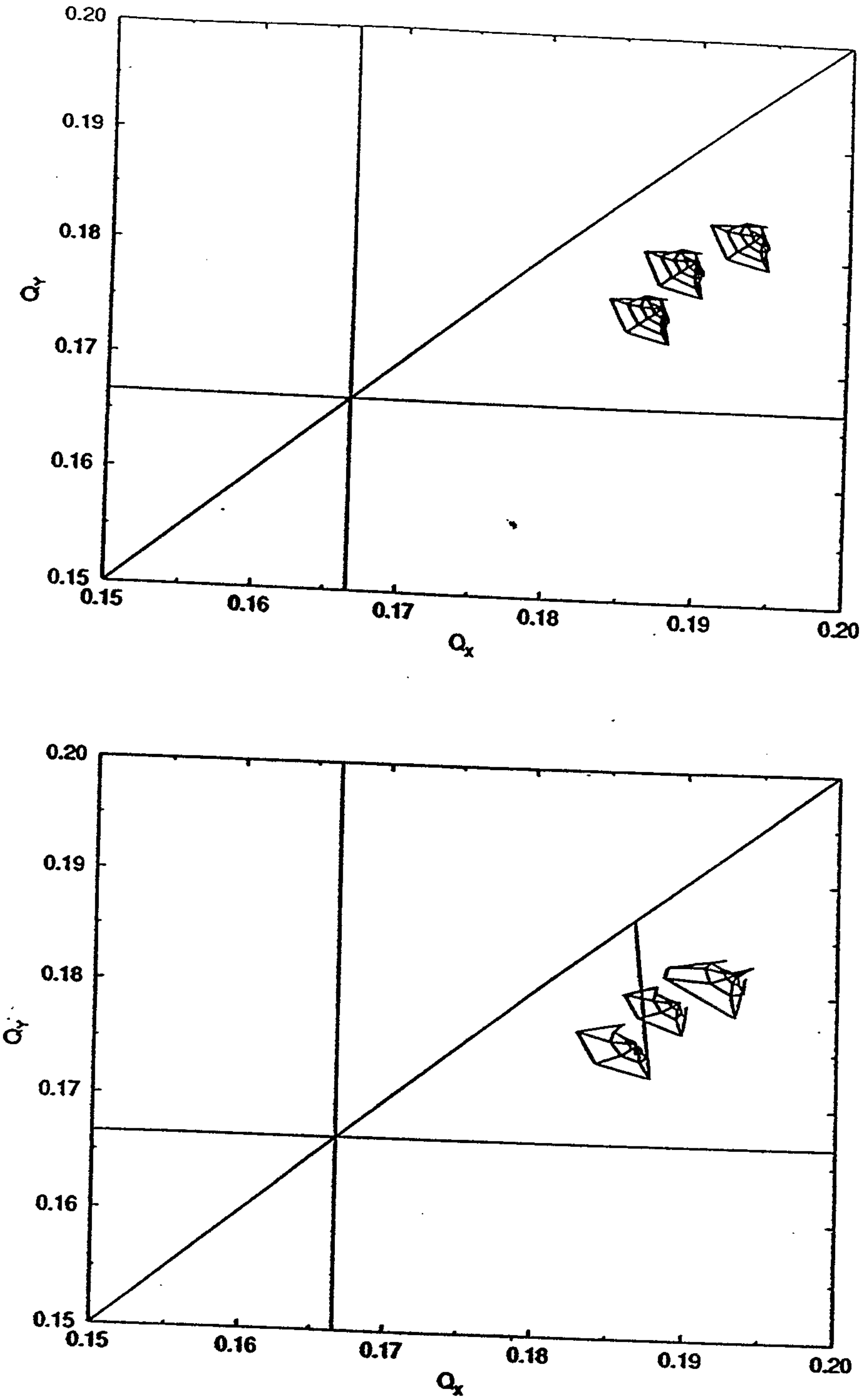
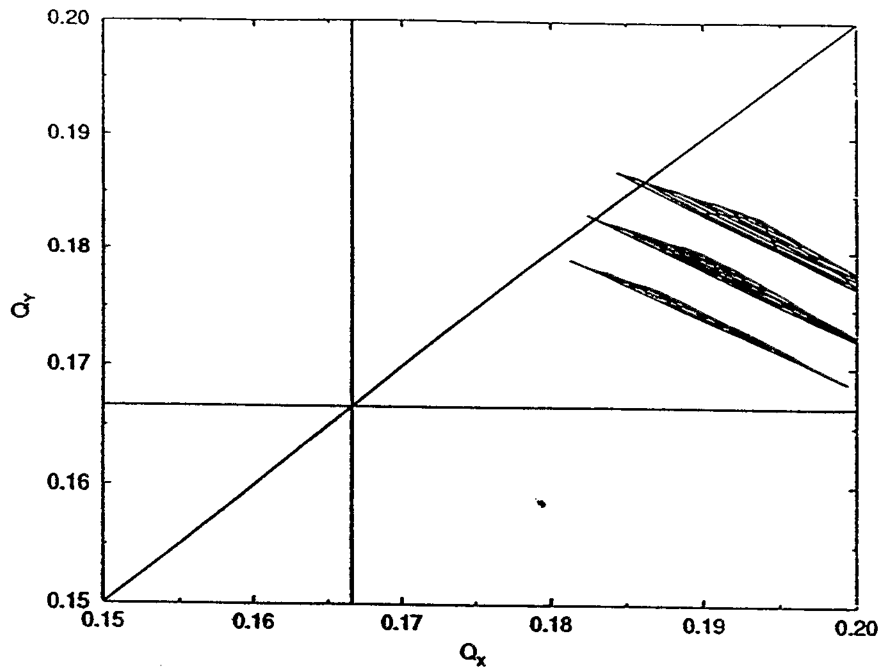


Figure 2: Tune shift of particles of momentum deviation $\Delta p/p = 0, \pm 2.5\ \sigma_p$ and betatron amplitude from 0 to 5 σ with the storage lattice and the multipole error in Table 1 when the tuning shims are inserted, calculated a) by using the perturbation methods with HARMON output; b) from the TEAPOT tracking data.

(1993 data)

Comparison between analytical formula & TEAPOT (injection)



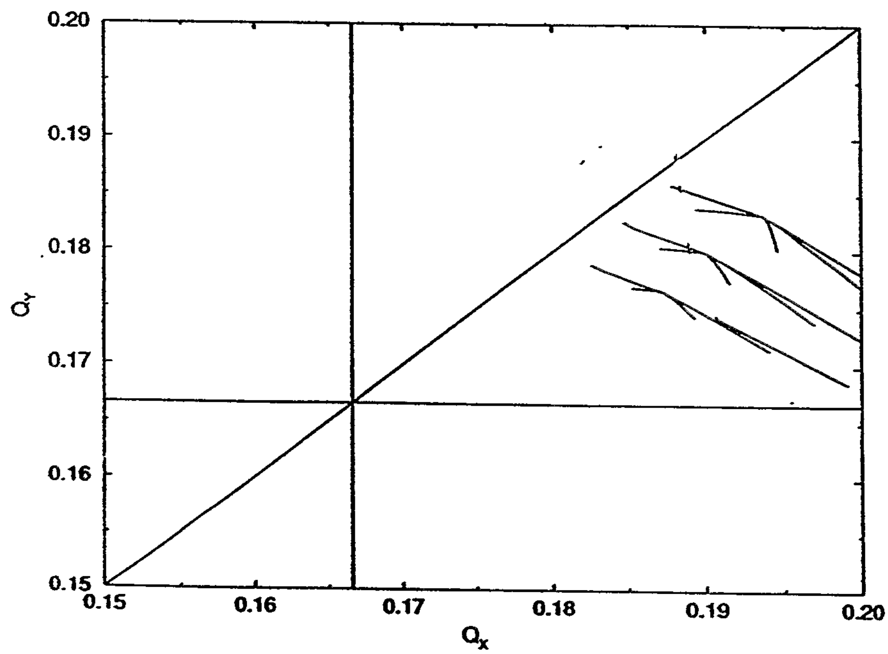


Figure 4: Tune shift of particles of momentum deviation $\Delta p/p = 0, \pm 2.5\sigma_p$ and betatron amplitude from 0 to 7 σ with the injection lattice and the multipole error for MAC93 tracking run seed #0, calculated a) by using the perturbation methods with HARMON output; b) from the TEAPOT tracking data. Tuning shims are inserted, but octupole and decapole corrections are not.

(1993 data)

Au^{79+} Storage in RHIC

↗ systematic ⟨a_n/b_n⟩ only

	Baseline[a]	Baseline & random[b]	Baseline $\pm\|db_3\|$ (max) (triplet)[c]	Baseline $\pm\|db_9\|$ (max) (triplet)[d]	Baseline & random[b] & db_n [e]
$\Delta\beta_{x,\text{trip}}/\beta_{x,\text{trip}}$	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.02	0.09 ± 0.02
$\Delta\beta_{y,\text{trip}}/\beta_{y,\text{trip}}$	0.20 ± 0.15	0.21 ± 0.15	0.20 ± 0.15	0.20 ± 0.15	0.20 ± 0.15
$\Delta\beta^*_x/\beta^*_x$	-0.03 ± 0.01	-0.03 ± 0.01	-0.03 ± 0.01	-0.03 ± 0.01	-0.03 ± 0.01
$\Delta\beta^*_y/\beta^*_y$	0.10 ± 0.09	0.10 ± 0.08	0.10 ± 0.09	0.10 ± 0.09	0.10 ± 0.09
$\Delta D_{x,max}$ (m)	0.07 ± 0.05	0.08 ± 0.08	0.07 ± 0.05	0.07 ± 0.05	0.07 ± 0.05
$\Delta D_{y,max}$ (m)	0.9 ± 0.5	1.0 ± 0.5	0.9 ± 0.5	0.9 ± 0.5	1.0 ± 0.5
|Shim size| (mm) (maximum)[f]	1.35 ± 0.03	2.69 ± 0.09	1.55 ± 0.03	1.35 ± 0.03	2.56 ± 0.06
Corrector strength:[g]					
$\|a_{1,max}\|$ (Amp.)	18 ± 3	19 ± 4	18 ± 3	18 ± 3	19 ± 4
$\|b_{3,max}\|$ (Amp.)	0.8 ± 0.1	0.9 ± 0.5	0.8 ± 0.1	0.8 ± 0.1	0.8 ± 0.1
$\|b_{4,max}\|$ (Amp.)	0.1 ± 0.0	3 ± 1	0.1 ± 0.0	0.1 ± 0.0	0.5 ± 0.2
$\|b_{5,max}\|$ (Amp.)	10 ± 2	15 ± 2	10 ± 2	10 ± 2	15 ± 2
Tune shift:					
$\Delta Q_{max}(5\sigma)$ ($\times 10^{-3}$) (before corrections)[h]	3.0 ± 0.1	5.7 ± 1.6	6.5 ± 0.3	5.4 ± 0.3	7.5 ± 1.2
$\Delta Q_{max}(5\sigma)$ ($\times 10^{-3}$) (after corrections)[h]	3.1 ± 0.4	4.0 ± 1.5	3.9 ± 1.0	5.5 ± 0.8	5.5 ± 0.8
0 corr. D. Aperture ($\sigma_{x,y}$) ($\Delta p/p = 0$)[i]	5.8 ± 0.4	5.1 ± 0.2	5.5 ± 0.3	5.1 ± 0.2	5.6 ± 0.4
2σ → D. Aperture ($\sigma_{x,y}$) ($\Delta p/p = 2.5\sigma_p$)[i]	5.1 ± 0.2	4.9 ± 0.2	5.0 ± 0.2	4.6 ± 0.2	5.3 ± 0.4

Table 1: The study is based on Au^{79+} ions stored at 100 GeV/u with 95% normalized transverse emittance $\epsilon_N = 40\pi$ mm·mr, r.m.s. momentum spread $\sigma_p = 0.00089$, and $\beta^* = 1$ m. The value listed corresponds to "mean ± r.m.s." calculated from the four cases of random number seeds #0, 1, 2, and 3.

30 k turns, 100 sync. osc. period
(1993 data)

V. Conclusion

Triplet :

* An effective triplet compensation requires the knowledge of fringe fields + warm-cold correlation
* Magnetic field quality can be optimized individually after measurement of coldmass
* Triplet correctors are crucial for misalignment correction

Arc :

* Field quality can be improved and maintained at design and production.
  "cost negative" : no need for decapole correction
* Accurate survey techniques like the colloidal cell measurement is essential for good alignment

Acknowledgements

The authors would like to thank G. Ganetis for many helpful discussions.
S. Peggs, R. Gupta, M. Harrison, A. Jain, P. Wanderer, S. Tepikian, D. Trbojevic, et.al.

References

[1] J. Wei and M. Harrison, *Tune Shift Due to Magnetic Multipoles in RHIC*, XV Intern. Conf. High Energy Accel. (Hamburg), p.1031 (1992).

[2] J. Wei, R. Gupta, and S. Peggs, *Magnetic Correction of RHIC Triplets*, Proc. 1993 Particle Accelerator Conferences, Washington, D.C., p. 258 (1993).

[3] J. Wei and S. Peggs, *Requested Systematic Body b_5 Multipoles in RHIC Triplet Quadrupoles*, Note RHIC/AP/18 (1993).

[4] J. Wei, S. Peggs, S. Tepikian, P.A. Thompson, and D. Trbojevic, *Effects of CQS and Dipole Misalignments in RHIC*, Note RHIC/AP/71 (1995).

[5] F. Pilat, private communications (1995).

6. S. Peggs, S. Tepikian, D. Trbojevic, J. Wei, The warm Iron Geometry of Average RHIC Dipole, RHIC/AP/62 (1995)

7. J. Wei, M. Harrison, S. Peggs, P. Thompson, D. Trbojevic An estimate on the effect of RHIC Triplet Misalignment, RHIC/AP/72 (1995)

8. J. Wei, F. Dell, S. Peggs, T. Satogata, S. Tepikian Comparison of Pertubation Method and TEAPOT Tracking on Tune Shift Calculation, RHIC/AP/5 (1993)

Tue Sep 19 16:50:45 1995
Survey information for 'CQS' magnet CQS179; (Model) 8; (BPM type) Horizontal

---

BNL optical measurement of the fiducials [Inches]:
(x - radially inward;
y - longitudinal;
z - vertical upward)

(** means more than either 2SD from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
M1(x) :	46.567	40.084	-0.012	-1.2
M4(x) :	47.364	40.773	-0.011	-1.2
M5(x) :	36.966	40.078	-9.621	-1.2
M8(x) :	37.772	40.763	-9.609	-1.2
M1(y) :	47.348	40.753	-0.002	-1.2
M4(y) :	155.296	40.742	107.954	-1.2
M5(y) :	47.411	40.809	0.002	-1.2
M8(y) :	155.367	40.808	107.963	-1.2
M1(z) :	-6.702	5.765	-0.004	1.2
M4(z) :	-6.700	5.769	-0.003	1.2
M5(z) :	-6.713	5.774	-0.019	1.2
M8(z) :	-6.703	5.781	-0.017	1.2

BNL magdiv mechanical measurement of the fiducials [Inches]:

(** means more than either 2SD or 20 mil from mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
M1(x) :	-0.005	0.007	-0.006	-0.2
M4(x) :	-0.002	0.007	-0.005	-0.3
M5(x) :	-9.605	0.011	-9.611	-0.6
M8(x) :	-9.593	0.019	-9.602	-0.5
M1(y) :	0.000	0.000	0.000	NaN
M4(y) :	108.000	0.000	108.000	NaN
M5(y) :	0.002	0.001	0.002	-0.2
M8(y) :	108.002	0.001	108.002	-0.2
M1(z) :	-0.003	0.005	-0.004	-0.3
M4(z) :	-0.000	0.008	-0.001	-0.1
M5(z) :	-0.005	0.009	-0.017	-1.3
M8(z) :	0.005	0.025	-0.017**	-0.9

magdiv mechanical measurement of the flats [Inches]:
(** means more than either 2SD or 20 mil from mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
MP1(x):	0.000	0.000	0.000	NaN
MP2(x):	-0.001	0.002	-0.001	0.1
MP3(x):	0.005	0.004	0.011	1.3
MP4(x):	0.000	0.000	0.000	NaN
MP5(x):	-9.602	0.003	-9.600	0.7
MP6(x):	-9.603	0.004	-9.599	0.9
MP7(x):	-9.595	0.004	-9.593	0.5
MP8(x):	-9.601	0.002	-9.599	1.4
ML1(x):	0.002	0.002	0.005	1.9
ML2(x):	-0.001	0.006	0.005	0.9
ML3(x):	-0.007	0.006	-0.001	1.2
ML4(x):	0.001	0.004	0.006	1.4
ML5(x):	-9.600	0.003	-9.596	1.1
ML6(x):	-9.602	0.006	-9.598	0.7
ML7(x):	-9.607	0.006	-9.597	1.6
ML8(x):	-9.602	0.005	-9.594	1.6
MP1(y):	0.000	0.000	0.000	NaN
MP2(y):	36.000	0.000	36.000	NaN
MP3(y):	71.000	0.000	71.000	NaN
MP4(y):	108.000	0.000	108.000	NaN
MP5(y):	0.002	0.001	0.002	-0.2
MP6(y):	36.002	0.001	36.002	-0.2
MP7(y):	71.002	0.001	71.002	-0.2
MP8(y):	108.002	0.001	108.002	-0.2
ML1(y):	0.000	0.000	-0.001	-1.5
ML2(y):	36.000	0.000	35.999	-1.5
ML3(y):	71.000	0.000	70.999	-1.5
ML4(y):	108.000	0.000	107.999	-1.5
ML5(y):	0.002	0.001	0.001	-1.0
ML6(y):	36.002	0.001	36.001	-1.0
ML7(y):	71.002	0.001	71.001	-1.0
ML8(y):	108.002	0.001	108.001	-1.0
MP1(z):	0.000	0.000	0.000	NaN
MP2(z):	-0.002	0.006	-0.006	-0.7
MP3(z):	-0.009	0.007	-0.015	-0.9
MP4(z):	0.000	0.000	0.000	NaN
MP5(z):	0.000	0.000	0.000	NaN
MP6(z):	-0.004	0.006	-0.009	-0.8
MP7(z):	0.005	0.005	-0.002	-1.5
MP8(z):	-0.000	0.004	-0.007	-1.6
ML1(z):	-9.602	0.002	-9.602	0.0
ML2(z):	-9.601	0.007	-9.604	-0.5
ML3(z):	-9.606	0.008	-9.612	-0.8
ML4(z):	-9.599	0.002	-9.599	-0.3
ML5(z):	-9.602	0.002	-9.603	-0.4
ML6(z):	-9.602	0.007	-9.607	-0.8
ML7(z):	-9.591	0.007	-9.598	-1.0
ML8(z):	-9.599	0.006	-9.606	-1.2

Transformation between magdiv mechanical and survey optical data:

(** means more than either 2SD or 20 mil from mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
T_theta :			0.000	
T_psi :			0.000	
T_phi :			-0.000	
T_x[In] :			0.008	
T_y[In] :			0.022	
T_z[In] :			0.000	
T_rms[In]:			0.002	

Transformation between magdiv mechanical and local beam system:

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
Theta :			1.928	
Psi :			-0.726	
Phi :			1.571	
X :			-0.000	
Y :			-0.000	
Z :			-0.000	
rms :			0.000	

Raw warm colloidal data [Inches]:
(5 points for each CQS element)

(** means more than either 2SD or 20 mil from mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
Count :	5.000	0.000	5.000	NaN
Mean(x):	-0.026	0.018	-0.041	-0.8
S.D.(x):	0.003	0.003	0.010**	2.6
Mean(y):	73.054	0.000	73.054	0.0
S.D.(y):	12.847	0.000	12.847	NaN
Mean(z):	0.012	0.007	0.022	1.5
S.D.(z):	0.002	0.001	0.003	0.2

Centers of the individual components:
(magdiv coordinate system: x - radially inward;
y - longitudinal;
z - vertical upward)
(Except for colloidal measurement, the y data is from the design value)

Quadrupole center from warm colloidal data [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
(x) :	-122.096	0.252	-122.499	-1.6
(y) :	1376.299	0.000	1376.299	0.0
(z) :	-121.964	0.201	-121.717	1.2

Quadrupole center from mechanical data [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
(x) :	-121.955	0.098	-121.835	1.2
(y) :	1376.299	0.000	1376.299	0.0
(z) :	-121.946	0.137	-122.087	-1.0

Sextupole center from mechanical data [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
(x) :	-121.918	0.043	-121.858	1.4
(y) :	315.250	0.000	315.250	0.0
(z) :	-121.950	0.022	-121.956	-0.2

Corrector center from mechanical data [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
(x) :	-121.933	0.058	-121.836	1.7
(y) :	2476.551	0.000	2476.551	0.0
(z) :	-121.907	0.061	-122.000	-1.5

Beam position monitor center from mechanical data [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
(x) :	-121.763	0.357	-121.739	0.1
(y) :	-286.851	0.471	-287.773	-2.0
(z) :	-122.428	0.300	-122.638	-0.7

Individual warm colloidal data [mm]:
(relative to local beam coordinate system)
(** means more than either 2 SD or 1 mm from the mean)

	Mean	Standard deviation	Measured	Dev. from mean (sigma)
COLW1 x:	-122.085	0.309	-122.603	-1.7
COLW2 x:	-122.112	0.270	-122.567	-1.7
COLW3 x:	-122.106	0.280	-122.684**	-2.1
COLW4 x:	-122.092	0.217	-122.394	-1.4
COLW5 x:	-122.086	0.223	-122.256	-0.8
COLW1 y:	958.977	0.417	958.323	-1.6
COLW2 y:	1165.361	0.422	1164.698	-1.6
COLW3 y:	1371.746	0.427	1371.073	-1.6
COLW4 y:	1578.130	0.432	1577.448	-1.6
COLW5 y:	1784.514	0.437	1783.823	-1.6
COLW1 z:	-122.006	0.224	-121.624	1.7
COLW2 z:	-121.992	0.209	-121.700	1.4
COLW3 z:	-121.959	0.215	-121.726	1.1
COLW4 z:	-121.938	0.206	-121.726	1.0
COLW5 z:	-121.927	0.192	-121.802	0.7

reviewed f
Acceptanc

BNL magdiv magnetic measurement of the field angles [m rad]:

(** means more than either 2SD or 2 mrad (Q, S) or 10 mrad (C) from zero)

	Mean	Standard deviation	Measured	Dev. from zero (sigma)
Quad :	-1.971	0.531	-1.940	0.1
Sext :	-0.846	0.335	-1.070	-0.7
Corr1 :	-6.290	3.435	-10.010**	-1.1
Corr2 :	-5.940	4.934	-11.410**	-1.1
Corr4 :	-4.165	4.043	-6.040	-0.5
Corr5 :	-5.109	2.349	-4.650	0.2

Difference and offset information:
(magdiv coordinate system: H - radially inward;
V - vertical upward;

Quadrupole center (colloidal - mechanical) [mm]:
(relative to magdiv coordinate system)
(** means more than either 2 SD or 0.25 mm from 0)

	Mean	Standard deviation	Measured	Dev. from zero (sigma)
(H) :	-0.141	0.252	-0.664**	-2.1
(V) :	-0.018	0.176	0.371**	2.2
TOTAL :	0.260	0.204	0.761**	2.4

Corrector (mechanical) offset from beam system origin [mm]:
(relative to local beam coordinate system)
(** means more than either 2 SD or 1 mm from 0)

	Mean	Standard deviation	Measured	Dev. from zero (sigma)
(H) :	0.347	0.525	1.327**	1.9
(V) :	0.071	0.392	-0.531	-1.5
TOTAL :	0.626	0.366	1.430**	2.2

Beam position monitor (electrical) offset from beam system origin [mm]:
(relative to local beam coordinate system)
(** means more than either 2 SD or 1 mm from 0)

	Mean	Standard deviation	Measured	Dev. from zero (sigma)
(H) :	0.054	0.308	-0.244	-1.0
(V) :	-0.486	0.291	-0.547	-0.2
TOTAL :	0.592	0.236	0.599	0.0

Statistical report on alignment (CQS)

jwei@bnl.gov

Tue Sep 19 16:34:35 1995

Survey statistics for 'CQS' magnets:

Data from MAGBASE and SURVBASE
The following magnets from SURVBASE are represented:

CQS150 CQS165 CQS175 CQS176 CQS178 CQS179 CQS181 CQS185 CQS189 CQS190

(total 10 elements)

Survey information for 'CQS' magnet

BNL optical survey measurement of the fiducials [Inches]:

	Mean	Standard deviation	Magnet counted
M1(x) :	46.567	40.084	10
M4(x) :	47.364	40.773	10
M5(x) :	36.966	40.078	10
M8(x) :	37.772	40.763	10
M1(y) :	47.348	40.753	10
M4(y) :	155.296	40.742	10
M5(y) :	47.411	40.809	10
M8(y) :	155.367	40.808	10
M1(z) :	-6.702	5.765	10
M4(z) :	-6.700	5.769	10
M5(z) :	-6.713	5.774	10
M8(z) :	-6.703	5.781	10

BNL magdiv mechanical measurement of the fiducials [Inches]:
(magdiv coordinate system: x - radially inward;
y - longitudinal;
z - vertical upward)
(Except for colloidal measurement, the y data is from the design value)

	Mean	Standard deviation	Magnet counted
M1(x) :	-0.005	0.007	10
M4(x) :	-0.002	0.007	10
M5(x) :	-9.605	0.011	10
M8(x) :	-9.593	0.019	10
M1(y) :	0.000	0.000	10
M4(y) :	108.000	0.000	10
M5(y) :	0.002	0.001	10
M8(y) :	108.002	0.001	10
M1(z) :	-0.003	0.005	10
M4(z) :	-0.000	0.008	10
M5(z) :	-0.005	0.009	10
M8(z) :	0.005	0.025	10

magdiv mechanical measurement of the flats [Inches]:

	Mean	Standard deviation	Magnet counted
MP1(x):	0.000	0.000	10
MP2(x):	-0.001	0.002	10
MP3(x):	0.005	0.004	10
MP4(x):	0.000	0.000	10
MP5(x):	-9.602	0.003	10
MP6(x):	-9.603	0.004	10
MP7(x):	-9.595	0.004	10
MP8(x):	-9.601	0.002	10
ML1(x):	0.002	0.002	10
ML2(x):	-0.001	0.006	10
ML3(x):	-0.007	0.006	10
ML4(x):	0.001	0.004	10
ML5(x):	-9.600	0.003	10
ML6(x):	-9.602	0.006	10
ML7(x):	-9.607	0.006	10
ML8(x):	-9.602	0.005	10
MP1(y):	0.000	0.000	10
MP2(y):	36.000	0.000	10
MP3(y):	71.000	0.000	10
MP4(y):	108.000	0.000	10
MP5(y):	0.002	0.001	10
MP6(y):	36.002	0.001	10
MP7(y):	71.002	0.001	10
MP8(y):	108.002	0.001	10
ML1(y):	0.000	0.000	10
ML2(y):	36.000	0.000	10
ML3(y):	71.000	0.000	10
ML4(y):	108.000	0.000	10
ML5(y):	0.002	0.001	10
ML6(y):	36.002	0.001	10
ML7(y):	71.002	0.001	10
ML8(y):	108.002	0.001	10
MP1(z):	0.000	0.000	10
MP2(z):	-0.002	0.006	10
MP3(z):	-0.009	0.007	10
MP4(z):	0.000	0.000	10
MP5(z):	0.000	0.000	10
MP6(z):	-0.004	0.006	10
MP7(z):	0.005	0.005	10
MP8(z):	-0.000	0.004	10
ML1(z):	-9.602	0.002	10
ML2(z):	-9.601	0.007	10
ML3(z):	-9.606	0.008	10
ML4(z):	-9.599	0.002	10
ML5(z):	-9.602	0.002	10
ML6(z):	-9.602	0.007	10
ML7(z):	-9.591	0.007	10
ML8(z):	-9.599	0.006	10

Transformation between magdiv mechanical and survey optical data:

	Mean	Standard deviation	Magnet counted
T_rms[In]:	0.002	0.001	10

Raw warm colloidal data [Inches]:
(5 points for each CQS element)

	Mean	Standard deviation	Magnet counted
Count :	5.000	0.000	10
Mean(x):	-0.026	0.018	10
S.D.(x):	0.003	0.003	10
Mean(y):	73.054	0.000	10
S.D.(y):	12.847	0.000	10
Mean(z):	0.012	0.007	10
S.D.(z):	0.002	0.001	10

Centers of the individual components:
(magdiv coordinate system: H - radially inward;

```
##############################################
Distribution statistics for 'DRG' magnets        Tue Oct 10 13:22:04 1995
##############################################

Harmonic data were read from file
'/home/owl/public/magdiv_data/sds/sel5.sds'

The following magnets are fully or partially represented:
DRG101 DRG102 DRG103 DRG104 DRG105 DRG106 DRG107 DRG108 DRG109 DRG110 DRG111
DRG112 DRG113 DRG114 DRG115 DRG116 DRG117 DRG118 DRG119 DRG120 DRG121 DRG122
DRG123 DRG124 DRG125 DRG126 DRG127 DRG128 DRG129 DRG130 DRG131 DRG132 DRG133
DRG134 DRG135 DRG136 DRG137 DRG138 DRG139 DRG140 DRG141 DRG142 DRG143 DRG144
DRG145 DRG146 DRG147 DRG148 DRG149 DRG150 DRG151 DRG152 DRG153 DRG154 DRG155
DRG156 DRG157 DRG158 DRG159 DRG160 DRG161 DRG162 DRG163 DRG164 DRG165 DRG166
DRG167 DRG168 DRG169 DRG170 DRG171 DRG172 DRG173 DRG174 DRG175 DRG176 DRG177
DRG178 DRG179 DRG180 DRG181 DRG182 DRG183 DRG184 DRG185 DRG186 DRG187 DRG188
DRG190 DRG191 DRG192 DRG193 DRG194 DRG195 DRG196 DRG197 DRG198 DRG199 DRG200
DRG201 DRG202 DRG203 DRG204 DRG205 DRG206 DRG207 DRG208 DRG209 DRG210 DRG211
DRG212 DRG213 DRG214 DRG215 DRG216 DRG217 DRG218 DRG219 DRG220 DRG221 DRG222
DRG223 DRG224 DRG501 DRG502 DRG503 DRG504 DRG505 DRG506 DRG507 DRG508 DRG509
DRG510 DRG511 DRG512 DRG513 DRG514 DRG515 DRG516 DRG517 DRG518 DRG519 DRG520
DRG521 DRG522 DRG523 DRG524 DRG525 DRG526 DRG527 DRG528 DRG529 DRG530 DRG531
DRG532 DRG533 DRG534 DRG535 DRG536 DRG537 DRG538 DRG539 DRG540 DRG541 DRG542
DRG543 DRG544 DRG545 DRG546 DRG547 DRG548 DRG549 DRG550 DRG551 DRG552 DRG553
DRG554 DRG555 DRG556 DRG557 DRG558 DRG559 DRG560 DRG561 DRG562 DRG563 DRG564
DRG565 DRG566 DRG567 DRG568 DRG569 DRG570 DRG571 DRG572 DRG573 DRG574 DRG575
DRG576 DRG577 DRG578 DRG579 DRG580 DRG581 DRG582 DRG583 DRG584 DRG585 DRG586
DRG587 DRG588 DRG589 DRG590 DRG591 DRG592 DRG593 DRG594 DRG595 DRG596 DRG597
DRG598 DRG599 DRG600 DRG601 DRG602 DRG603 DRG604 DRG605 DRG606 DRG607 DRG608
DRG609 DRG610 DRG611 DRG612 DRG613 DRG614 DRG615 DRG616 DRG617 DRG618 DRG619
DRG620
```

Test current (Amps)	Up, Down, Warm	average	standard deviation	no. of elements evaluated	
Effective Magnetic Length [m]					
30.0	W	9.4485	0.0022		
570.0	U	9.4218	0.0041		
660.0	U	9.4235	0.0031		
1405.0	U	9.4154	0.0000		
1450.0	U	9.4308	0.0034		
2400.0	U	9.4291	0.0049		
5000.0	U	9.4414	0.0036		
6800.0	U	9.4386	0.0000		
Mechanical Length (N-G) [m]					
		9.7170	0.0017	241	
Integrated Transfer Function [Tm/kA] (>< means from intfield table)					
30.0	W	6.65348	0.00273	243	
30.0	U	6.65479	0.00215	240	><
570.0	U	6.66657	0.00373	11	
660.0	U	6.67015	0.00264	51	><
660.0	D	6.69135	0.00263	50	><
1405.0	U	6.66506	0.00000	1	
1450.0	U	6.67716	0.00214	51	><
1450.0	D	6.68624	0.00211	50	><
2400.0	U	6.67397	0.00200	51	><
2400.0	D	6.67984	0.00197	50	><
5000.0	U	6.41767	0.00242	51	><
5000.0	D	6.42042	0.00221	50	><
6800.0	U	6.06393	0.00000	1	
Body Transfer Function [T/kA]					
30.0	W	0.70418	0.00022	243	
570.0	U	0.70757	0.00036	11	
660.0	U	0.70785	0.00033	55	
1405.0	U	0.70789	0.00000	1	
1450.0	U	0.70800	0.00030	52	
2400.0	U	0.70780	0.00015	8	
5000.0	U	0.67971	0.00032	54	
6800.0	U	0.64246	0.00000	1	
Integrated Field Angle [mrad]					
30.0	W	-0.7208	0.7348	243	
570.0	U	-0.6400	0.7145	11	
660.0	U	-1.0010	1.0413	50	
1405.0	U	0.7900	0.0000	1	
1450.0	U	-1.0448	1.0188	50	
2400.0	U	-1.3025	0.9140	8	
5000.0	U	-1.0818	1.0439	51	
6800.0	U	-0.8400	0.0000	1	
Body Field Angle Average [mrad]					
30.0	W	-0.5840	0.7624	243	
570.0	U	-0.4464	0.8322	11	
660.0	U	-0.9145	1.0836	55	
1405.0	U	1.1400	0.0000	1	
1450.0	U	-0.9842	1.0544	52	
2400.0	U	-1.1887	0.8800	8	
5000.0	U	-0.9441	1.0793	54	
6800.0	U	-0.7100	0.0000	1	
Body Field Angle Maximum Absolute Deviation [mrad]					
30.0	W	1.1111	0.5563	243	
570.0	U	1.2409	0.6234	11	
660.0	U	1.1515	0.6304	55	
1405.0	U	0.4300	0.0000	1	
1450.0	U	1.1692	0.6332	52	
2400.0	U	0.7113	0.2459	8	
5000.0	U	1.1580	0.6373	54	
6800.0	U	0.5100	0.0000	1	
Body Field Angle Standard Deviation [mrad]					
30.0	W	0.6820	0.3405	243	
570.0	U	0.7645	0.4075	11	
660.0	U	0.6940	0.3825	55	
1405.0	U	0.2300	0.0000	1	
1450.0	U	0.7085	0.3839	52	
2400.0	U	0.4587	0.2009	8	
5000.0	U	0.7013	0.3838	54	
6800.0	U	0.3300	0.0000	1	
Center Offset X_0 [mm]					
Center Offset Y_0 [mm]					

N-G Mechanical Data:

Field Angle Average [mrad]			
	-0.0547	0.0753	241
Field Angle Standard Deviation [mrad]			
	0.9645	0.5363	241
Field Angle Twist (Max. - Min.) [mrad]			
	2.3679	1.2733	241

V - vertical upward;
L - longitudinal)
(Except for colloidal measurement, the L data is from the design value)

		Mean	Standard deviation	Magnet counted

Quadrupole center from warm colloidal data [mm]:
(relative to magdiv coordinate system)

H	:	-122.096	0.252	10
V	:	-121.964	0.201	10
L	:	1376.299	0.000	10

Quadrupole center from mechanical data [mm]:
(relative to magdiv coordinate system)

H	:	-121.955	0.098	10
V	:	-121.946	0.137	10
L	:	1376.299	0.000	10

Sextupole center from mechanical data [mm]:
(relative to magdiv coordinate system)

H	:	-121.933	0.058	10
V	:	-121.907	0.061	10
L	:	2476.551	0.000	10

corrector center from mechanical data [mm]:
(relative to magdiv coordinate system)

H	:	-121.933	0.058	10
V	:	-121.907	0.061	10
L	:	2476.551	0.000	10

Beam Position Monitor center from mechanical data [mm]:
(relative to magdiv coordinate system)

H	:	-121.763	0.357	10
V	:	-122.428	0.300	10
L	:	-286.851	0.471	10

Individual colloidal data [mm]:
(relative to magdiv coordinate system)

COLW1 x:	-122.085	0.309	10
COLW2 x:	-122.112	0.270	10
COLW3 x:	-122.106	0.280	10
COLW4 x:	-122.092	0.217	10
COLW5 x:	-122.086	0.223	10
COLW1 y:	958.977	0.417	10
COLW2 y:	1165.361	0.422	10
COLW3 y:	1371.746	0.427	10
COLW4 y:	1578.130	0.432	10
COLW5 y:	1784.514	0.437	10
COLW1 z:	-122.006	0.224	10
COLW2 z:	-121.992	0.209	10
COLW3 z:	-121.959	0.215	10
COLW4 z:	-121.938	0.206	10
COLW5 z:	-121.927	0.192	10

BNL magdiv magnetic measurement of the field angles [m rad]:
(relative to base plate fiducials):

		Mean	Standard deviation	Magnet counted
Quad	:	-1.971	0.531	10
Sext	:	-0.846	0.335	10
Corr1	:	-6.290	3.435	10
Corr2	:	-5.940	4.934	8
Corr4	:	-4.165	4.043	8
Corr5	:	-5.109	2.349	8

Difference and offset information:
(magdiv coordinate system: H - radially inward;
V - vertical upward;
L - longitudinal)
(Except for colloidal measurement, the L data is from the design value.
The beam system is defined by quad center measured by warm colloid
and sextupole center measured mechanically)

		Mean	Standard deviation	Magnet counted

Quadrupole center (colloidal - mechanical) [mm]:
(relative to magdiv coordinate system)

H	:	-0.141	0.252	10
V	:	-0.018	0.176	10
L	:	0.000	0.000	10
TOTAL	:	0.260	0.204	10

Corrector (mechanical) offset from beam system origin [mm]:
(relative to local beam coordinate system)

H	:	0.347	0.525	10
V	:	0.071	0.392	10
L	:	0.000	0.000	10
TOTAL	:	0.626	0.366	10

Beam position monitor (electrical) offset from beam system origin [mm]:
(relative to local beam coordinate system)

H	:	0.054	0.308	10
V	:	-0.486	0.291	10
L	:	-0.000	0.000	10
TOTAL	:	0.592	0.236	10

```
Mean Cold Mass Sagitta (N-G) (m)
                         0.0485          0.0011         240

Fiducial Deviation (Ref: 4.8 Inches) (Inches):
(LE:  Lead end;      H: Horizontal; I: Inner)
(NLE: Non-lead end; V: Vertical;    O: Outer)
LEIH                 -0.001          0.009          212
LEIV                 -0.002          0.009          216
LEOH                 -0.004          0.011          222
LEOV                  0.000          0.012          218
NLEIH                -0.003          0.010          216
NLEIV                -0.001          0.010          220
NLEOH                -0.002          0.008          221
NLEOV                -0.002          0.008          215

Sagitta (Inches):
SAGITTA1               0.000           0.000            0 (at          4.000 inches f
+ rom LE)
SAGITTA2               0.636           0.019          240 (at         56.000 inches f
+ rom LE)
SAGITTA3               1.487           0.037          240 (at        120.000 inches f
+ rom LE)
SAGITTA4               1.825           0.043          240 (at        183.200 inches f
+ rom LE)
SAGITTA5               1.814           0.042          240 (at        197.600 inches f
+ rom LE)
SAGITTA6               1.540           0.035          240 (at        268.200 inches f
+ rom LE)
SAGITTA7               0.848           0.023          240 (at        339.200 inches f
+ rom LE)
SAGITTA8               0.000           0.000            0 (at        376.800 inches f
+ rom LE)

Upper Yoke Weight (lb) (starting Seq. No.63)
                 3038.7914         2.2990          179

Lower Yoke Weight (lb) (starting Seq. No.63)
                 3045.7724         2.1793          179

Total Yoke Weight (lb) (starting Seq. No.63)
                 6084.5638         2.3736          179

-------------------------------------------


~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
Harmonics reported below are sometimes followed by '! ', '* ' or '**'
This means either that
 1) <b>    is outside its expected <b> +/- D<b> range by 'error', or
 2) sig(b) is larger than its expected sig(b) by 'error', where
   '! '    means 'error' > 0.1,
   '* '    means 'error' > 0.5, and
   '**'    means 'error' > 2.0
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
INTEGRAL harmonics in Units
--------------------------------------------------------------------------
```

	Normal harmonics					Skew harmonics				
	Expected			Measured		Expected			Measured	
n	<b>	D<b>	sig(b)	<b>	sig(b)	<a>	D<a>	sig(a)	<a>	sig(a)
30.0 Amps W (from 243 elements)										
0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.2	0.4	0.0	1.0	1.3	-0.1	1.6!
2	4.0	4.0	2.3	3.8	1.7	-1.1	0.1	0.5	-1.1	0.2
3	0.0	0.2	0.3	-0.0	0.1	0.0	0.3	1.0	0.0	0.5
4	0.5	1.0	0.6	0.2	0.5	0.2	0.1	0.2	0.2	0.1
5	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	-0.0	0.2
6	0.3	0.2	0.1	0.1	0.1	-0.1	0.0	0.1	-0.1	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	0.0	0.0
8	0.3	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0
9	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.5	0.0	0.0	0.0	0.1	-0.0	0.0
570.0 Amps U (from 11 elements)										
0				10000.0	0.0				0.0	0.0
1				0.2	0.3				-0.5	1.3
2				-1.9	1.3				-0.9	0.2
3				0.0	0.1				0.2	0.4
4				0.0	0.5				0.2	0.1
5				0.0	0.0				0.1	0.2
6				-0.1	0.1				-0.1	0.0
7				-0.0	0.0				0.0	0.1
8				0.0	0.1				0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0
660.0 Amps U (from 50 elements)										
0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.1	0.2	0.0	1.0	1.3	0.4	1.4!
2	0.0	4.0	2.3	0.3	2.0	-1.1	0.1	0.5	-1.0	0.2
3	0.0	0.2	0.3	0.0	0.1	0.0	0.3	1.0	0.0	0.4
4	0.0	1.0	0.6	-0.4	0.6	0.2	0.1	0.2	0.2	0.1
5	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.2
6	0.0	0.2	0.2	-0.1	0.1	-0.1	0.0	0.1	-0.1	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	-0.0	0.0
8	0.3	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.6	0.0	0.0	0.0	0.1	-0.0	0.0
1405.0 Amps U (from 1 elements)										
0				10000.0	0.0				0.0	0.0
1				0.2	0.0				-2.1	0.0
2				1.6	0.0				-0.8	0.0
3				-0.0	0.0				0.2	0.0
4				0.5	0.0				0.2	0.0
5				0.0	0.0				0.2	0.0
6				-0.0	0.0				-0.1	0.0
7				0.0	0.0				0.0	0.0
8				-0.0	0.0				0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0
1450.0 Amps U (from 50 elements)										
0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.0	0.2	0.0	1.0	1.3	0.4	1.4
2	1.7	4.0	2.3	2.5	1.6	-1.1	0.1	0.5	-1.0	0.2
3	0.0	0.2	0.3	-0.0	0.1	0.0	0.3	1.0	0.0	0.4
4	0.2	1.0	0.6	-0.2	0.6	0.2	0.1	0.2	0.2	0.1
5	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.1
6	0.1	0.2	0.2	-0.0	0.1	-0.1	0.0	0.1	-0.1	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	-0.0	0.0
8	0.3	0.1	0.1	0.2	0.1	0.0	0.0	0.1	0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.6	0.0	0.0	0.0	0.1	-0.0	0.0
2400.0 Amps U (from 8 elements)										
0				10000.0	0.0				0.0	0.0
1				-0.0	0.2				1.5	1.3
2				4.1	1.0				-1.1	0.2
3				0.0	0.1				-0.1	0.4
4				-0.8	0.3				0.2	0.0
5				0.0	0.0				-0.1	0.1

6				-0.1	0.1				-0.1	0.0
7				-0.0	0.0				-0.0	0.0
8				0.2	0.1				0.0	0.0
9				0.0	0.0				0.0	0.0
10				-0.6	0.0				-0.0	0.0

5000.0 Amps U (from 51 elements)

0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.1	0.2	-2.0	0.5	1.3	-1.4!	1.4!
2	0.0	4.0	2.3	1.2	1.6	-1.1	0.1	0.5	-1.1	0.2
3	0.0	0.2	0.3	0.0	0.1	0.0	0.3	1.0	-0.3	0.4
4	0.4	1.0	0.6	0.1	0.6	0.2	0.1	0.2	0.2	0.1
5	0.0	0.0	0.1	-0.0	0.0	0.0	0.1	0.3	-0.0	0.2
6	1.3	0.1	0.2	1.2	0.1	-0.1	0.0	0.1	-0.1	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	-0.0	0.0
8	0.3	0.1	0.1	0.1	0.1	0.0	0.0	0.1	0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.6	0.0	0.0	0.0	0.1	-0.0	0.0

6800.0 Amps U (from 1 elements)

0				10000.0	0.0				0.0	0.0
1				0.4	0.0				-1.1	0.0
2				-4.1	0.0				-0.6	0.0
3				0.1	0.0				-0.6	0.0
4				0.4	0.0				0.4	0.0
5				0.0	0.0				-0.0	0.0
6				1.0	0.0				-0.1	0.0
7				-0.0	0.0				0.0	0.0
8				-0.0	0.0				0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0

+++

BODY harmonics in Units

	Normal harmonics					Skew harmonics				
	Expected			Measured		Expected			Measured	
n	<b>	D<b>	sig(b)	<b>	sig(b)	<a>	D<a>	sig(a)	<a>	sig(a)

30.0 Amps W (from 243 elements)

0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.2	0.4	0.0	1.0	1.3	0.2	1.6!
2	1.4	4.0	2.3	1.4	1.7	0.0	0.4	0.5	-0.0	0.2
3	0.0	0.2	0.3	-0.0	0.1	0.0	0.3	1.0	0.0	0.5
4	0.5	1.0	0.6	0.2	0.5	0.0	0.1	0.2	-0.1	0.1
5	0.0	0.0	0.1	-0.0	0.0	0.0	0.1	0.3	0.0	0.2
6	0.2	0.2	0.1	0.0	0.1	0.0	0.0	0.1	-0.0	0.0
7	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.1
8	0.3	0.1	0.1	0.1	0.1	0.0	0.0	0.1	-0.0	0.0
9	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.5	0.0	0.0	0.0	0.1	0.0	0.0

570.0 Amps U (from 11 elements)

0				10000.0	0.0				0.0	0.0
1				0.2	0.2				-0.1	1.3
2				-4.3	1.3				0.1	0.2
3				-0.0	0.1				0.2	0.4
4				0.1	0.6				-0.0	0.1
5				0.0	0.0				0.2	0.2
6				-0.3	0.1				-0.0	0.0
7				0.0	0.0				0.0	0.1
8				0.0	0.1				-0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0

660.0 Amps U (from 55 elements)

0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.1	0.2	0.0	1.0	1.3	0.7	1.5!
2	-2.5	4.0	2.3	-2.2	2.0	0.0	0.4	0.5	0.0	0.2
3	0.0	0.2	0.3	-0.0	0.1	0.0	0.3	1.0	0.0	0.4
4	0.0	1.0	0.6	-0.4	0.6	0.0	0.1	0.2	-0.0	0.1
5	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.2
6	-0.1	0.2	0.2	-0.2	0.1	0.0	0.0	0.1	-0.0	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	-0.0	0.1
8	0.3	0.1	0.1	0.2	0.1	0.0	0.0	0.1	-0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.6	0.0	0.0	0.0	0.1	-0.0	0.0

1405.0 Amps U (from 1 elements)

0				10000.0	0.0				0.0	0.0
1				0.2	0.0				-2.1	0.0
2				-0.8	0.0				0.2	0.0
3				-0.0	0.0				0.2	0.0
4				0.6	0.0				-0.1	0.0
5				0.0	0.0				0.2	0.0
6				-0.1	0.0				-0.0	0.0
7				0.0	0.0				0.0	0.0
8				-0.0	0.0				-0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0

1450.0 Amps U (from 52 elements)

0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.0	0.2	0.0	1.0	1.3	0.6	1.4!
2	-0.8	4.0	2.3	0.1	1.7	0.0	0.4	0.5	0.0	0.2
3	0.0	0.2	0.3	-0.0	0.1	0.0	0.3	1.0	0.0	0.4
4	0.0	1.0	0.6	-0.2	0.6	0.0	0.1	0.2	-0.0	0.1
5	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.3	0.0	0.2
6	0.0	0.2	0.2	-0.1	0.1	0.0	0.0	0.1	-0.0	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	-0.0	0.0
8	0.3	0.1	0.1	0.2	0.1	0.0	0.0	0.1	-0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.5	0.0	0.0	0.0	0.1	-0.0	0.0

2400.0 Amps U (from 8 elements)

0				10000.0	0.0				0.0	0.0
1				0.0	0.2				1.9	1.4
2				2.0	1.1				-0.1	0.2
3				0.0	0.1				-0.1	0.4
4				-0.8	0.3				-0.0	0.0
5				0.0	0.0				-0.1	0.1
6				-0.2	0.1				0.0	0.0
7				-0.0	0.0				-0.0	0.0
8				0.3	0.1				-0.0	0.0
9				0.0	0.0				0.0	0.0
10				-0.5	0.0				-0.0	0.0

5000.0 Amps U (from 54 elements)

0				10000.0	0.0				0.0	0.0
1	0.0	0.4	0.8	0.1	0.2	-2.5	0.5	1.3	-1.3*	1.5!
2	-2.8	4.0	2.3	-1.7	1.6	0.0	0.4	0.5	-0.1	0.2
3	0.0	0.2	0.3	0.0	0.1	0.0	0.3	1.0	-0.4	0.4
4	0.5	1.0	0.6	0.1	0.6	0.0	0.1	0.2	-0.0	0.1
5	0.0	0.0	0.1	-0.0	0.0	0.0	0.1	0.3	-0.0	0.2
6	1.2	0.2	0.2	1.1	0.1	0.0	0.0	0.1	-0.0	0.0
7	0.0	0.0	0.1	-0.0	0.0	0.0	0.0	0.1	0.0	0.1
8	0.3	0.1	0.1	0.2	0.1	0.0	0.0	0.1	-0.0	0.0
9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.0	0.0
10	-0.5	0.0	0.1	-0.6	0.0	0.0	0.0	0.1	-0.0	0.0

6800.0 Amps U (from 1 elements)

0				10000.0	0.0				0.0	0.0
1				0.2	0.0				-0.9	0.0
2				-7.9	0.0				0.5	0.0

3				0.1	0.0				-0.6	0.0
4				0.3	0.0				0.1	0.0
5				0.0	0.0				-0.0	0.0
6				0.9	0.0				0.0	0.0
7				-0.0	0.0				0.0	0.0
8				0.0	0.0				0.0	0.0
9				0.0	0.0				0.1	0.0
10				-0.6	0.0				-0.0	0.0

+++

LEAD END multipoles in Unit meters

	Normal harmonics					Skew harmonics				
	Expected			Measured		Expected			Measured	
n	<b>	D<b>	sig(b)	<b>	sig(b)	<a>	D<a>	sig(a)	<a>	sig(a)
30.0 Amps W (from					243 elements)					
0				0.0	0.0				0.0	0.0
1	-2.0	2.0	1.0	0.7*	0.9	2.0	4.0	1.0	-2.3!	1.8*
2	17.0	2.0	2.0	19.2!	1.0	-10.0	1.0	1.0	-10.1	0.4
3	0.3	0.2	0.2	-0.0!	0.2	0.0	1.0	1.0	-0.1	0.3
4	1.0	0.5	0.2	-0.4*	0.2	2.0	0.5	0.3	2.2	0.1
5	0.0	0.2	0.2	0.1	0.1	0.0	1.0	0.2	-0.1	0.1
6	1.0	0.5	0.1	1.1	0.1	-0.9	0.2	0.2	-0.8	0.1
7	0.0	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	0.0	0.0
8	-0.2	0.2	0.1	-0.1	0.0	0.3	0.1	0.1	0.2	0.0
9	-0.2	0.2	0.2	0.0	0.0	0.0	0.1	0.1	-0.0	0.0
10	0.1	0.1	0.1	-0.1	0.0	-0.1	0.1	0.1	-0.0	0.0
570.0 Amps U (from					11 elements)					
0				0.0	0.0				0.0	0.0
1				-0.2	1.1				-2.8	1.7
2				18.9	0.8				-10.1	0.4
3				0.2	0.2				-0.1	0.2
4				-0.4	0.2				2.3	0.1
5				0.0	0.1				-0.1	0.1
6				1.1	0.0				-0.8	0.0
7				0.0	0.0				-0.0	0.0
8				-0.0	0.0				0.2	0.0
9				-0.0	0.0				-0.0	0.0
10				-0.1	0.0				-0.0	0.0
660.0 Amps U (from					53 elements)					
0				0.0	0.0				0.0	0.0
1	-2.0	2.0	1.0	-0.4	0.9	2.0	4.0	1.0	-2.3!	1.7*
2	17.0	2.0	2.0	18.7	0.9	-10.0	1.0	1.0	-10.0	0.4
3	0.3	0.2	0.2	0.1	0.2	0.0	1.0	1.0	-0.1	0.3
4	1.0	0.5	0.2	-0.2*	0.2	2.0	0.5	0.3	2.2	0.1
5	0.0	0.2	0.2	-0.0	0.1	0.0	1.0	0.2	-0.0	0.1
6	1.0	0.5	0.1	1.1	0.0	-0.9	0.2	0.2	-0.8	0.1
7	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.2	0.1	-0.1	0.0	0.3	0.1	0.1	0.2	0.0
9	-0.2	0.2	0.2	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
10	0.1	0.1	0.1	-0.1	0.0	-0.1	0.1	0.1	-0.0	0.0
1405.0 Amps U (from					1 elements)					
0				0.0	0.0				0.0	0.0
1				-1.3	0.0				-1.7	0.0
2				18.8	0.0				-9.9	0.0
3				0.1	0.0				-0.1	0.0
4				-0.7	0.0				2.2	0.0
5				0.1	0.0				-0.2	0.0
6				1.0	0.0				-0.9	0.0
7				0.0	0.0				-0.1	0.0
8				0.0	0.0				0.2	0.0
9				0.0	0.0				-0.0	0.0
10				-0.1	0.0				-0.0	0.0
1450.0 Amps U (from					51 elements)					
0				0.0	0.0				0.0	0.0
1	-2.0	2.0	1.0	-0.3	0.9	2.0	4.0	1.0	-2.4!	1.7*
2	17.0	2.0	2.0	18.6	0.9	-10.0	1.0	1.0	-9.9	0.4
3	0.3	0.2	0.2	0.1	0.2	0.0	1.0	1.0	-0.1	0.3
4	1.0	0.5	0.2	-0.2*	0.2	2.0	0.5	0.3	2.2	0.1
5	0.0	0.2	0.2	-0.0	0.1	0.0	1.0	0.2	-0.0	0.1
6	1.0	0.5	0.1	1.1	0.0	-0.9	0.2	0.2	-0.8	0.1
7	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.2	0.1	-0.1	0.0	0.3	0.1	0.1	0.2	0.0
9	-0.2	0.2	0.2	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
10	0.1	0.1	0.1	-0.1	0.0	-0.1	0.1	0.1	-0.0	0.0
2400.0 Amps U (from					8 elements)					
0				0.0	0.0				0.0	0.0
1				-0.3	0.7				-2.4	1.4
2				17.6	1.0				-9.7	0.3
3				-0.0	0.2				-0.1	0.2
4				-0.1	0.3				2.1	0.1
5				0.0	0.1				0.0	0.1
6				1.1	0.1				-0.9	0.1
7				-0.0	0.0				-0.0	0.0
8				-0.1	0.0				0.2	0.0
9				-0.0	0.0				-0.0	0.0
10				-0.1	0.0				-0.1	0.0
5000.0 Amps U (from					53 elements)					
0				0.0	0.0				0.0	0.0
1	-2.0	2.0	1.0	-0.5	1.0	2.0	4.0	1.0	-1.4	1.8*
2	21.0	2.0	2.0	22.1	0.9	-10.0	1.0	1.0	-9.9	0.4
3	0.3	0.2	0.2	0.0	0.2	0.0	1.0	1.0	0.1	0.3
4	1.0	0.5	0.2	-0.4*	0.2	2.0	0.5	0.3	2.2	0.1
5	0.0	0.2	0.2	0.0	0.1	0.0	1.0	0.2	0.0	0.1
6	1.0	0.5	0.1	0.9	0.0	-0.9	0.2	0.2	-0.9	0.1
7	0.0	0.1	0.1	0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.2	0.1	-0.0	0.0	0.3	0.1	0.1	0.2	0.0
9	-0.2	0.2	0.2	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
10	0.1	0.1	0.1	-0.1	0.0	-0.1	0.1	0.1	-0.0	0.0
6800.0 Amps U (from					1 elements)					
0				0.0	0.0				0.0	0.0
1				1.2	0.0				-2.5	0.0
2				26.3	0.0				-10.5	0.0
3				0.4	0.0				-0.2	0.0
4				0.4	0.0				2.3	0.0
5				0.2	0.0				-0.1	0.0
6				1.0	0.0				-0.9	0.0
7				0.0	0.0				0.0	0.0
8				0.0	0.0				0.3	0.0
9				-0.0	0.0				-0.0	0.0
10				-0.1	0.0				-0.0	0.0

+++

RETURN END multipoles in Unit meters

	Normal harmonics					Skew harmonics				
	Expected			Measured		Expected			Measured	
n	<b>	D<b>	sig(b)	<b>	sig(b)	<a>	D<a>	sig(a)	<a>	sig(a)
30.0 Amps W (from					243 elements)					
0				0.0	0.0				0.0	0.0
1	1.4	1.0	1.0	0.2!	0.6	3.0	0.5	1.0	-0.0**	1.6*
2	-3.0	1.0	1.0	3.8**	0.9	-0.8	0.5	1.0	0.4*	0.3
3	0.3	0.1	0.1	-0.0!	0.2	0.2	0.3	0.5	-0.0	0.3
4	0.8	0.5	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0.1
5	0.0	0.1	0.1	0.0	0.1	0.2	0.1	0.2	-0.0!	0.1

6	0.0	0.1	0.1	0.1	0.0	0.1	0.1	0.1	-0.0	0.0
7	0.0	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.1	0.1	-0.1	0.0	0.1	0.1	0.1	-0.0	0.0
9	-0.2	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
10	-0.1	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	-0.0	0.0

570.0 Amps U (from 11 elements)

0				0.0	0.0				0.0	0.0
1				0.2	0.7				-0.5	1.3
2				3.4	0.6				0.3	0.4
3				-0.0	0.1				-0.0	0.3
4				0.0	0.2				0.0	0.1
5				-0.0	0.1				-0.1	0.1
6				0.1	0.1				-0.0	0.1
7				-0.0	0.0				-0.0	0.0
8				-0.2	0.0				-0.0	0.0
9				-0.1	0.0				-0.0	0.1
10				-0.1	0.0				0.0	0.0

660.0 Amps U (from 51 elements)

0				0.0	0.0				0.0	0.0
1	1.4	1.0	1.0	0.2!	0.6	3.0	0.5	1.0	-0.4**	1.6*
2	-3.0	1.0	1.0	3.8**	1.0	-0.8	0.5	1.0	0.3*	0.3
3	0.3	0.1	0.1	0.0!	0.2	0.2	0.3	0.5	-0.0	0.3
4	0.8	0.5	0.2	0.2!	0.2	0.2	0.1	0.1	-0.0!	0.1
5	0.0	0.1	0.1	-0.0	0.1	0.2	0.1	0.2	-0.0!	0.1
6	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-0.0	0.0
7	0.0	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.1	0.1	-0.2	0.0	0.1	0.1	0.1	-0.0	0.0
9	-0.2	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	-0.0	0.0
10	-0.1	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	0.0	0.0

1405.0 Amps U (from 1 elements)

0				0.0	0.0				0.0	0.0
1				1.3	0.0				1.8	0.0
2				3.4	0.0				0.9	0.0
3				-0.0	0.0				0.0	0.0
4				-0.2	0.0				-0.1	0.0
5				-0.2	0.0				-0.1	0.0
6				0.0	0.0				-0.1	0.0
7				-0.1	0.0				-0.1	0.0
8				-0.1	0.0				-0.0	0.0
9				-0.1	0.0				-0.1	0.0
10				-0.1	0.0				0.0	0.0

1450.0 Amps U (from 50 elements)

0				0.0	0.0				0.0	0.0
1	1.4	1.0	1.0	0.2!	0.6	3.0	0.5	1.0	-0.5**	1.6*
2	-3.0	1.0	1.0	3.9**	1.0	-0.8	0.5	1.0	0.2*	0.3
3	0.3	0.1	0.1	0.0!	0.2	0.2	0.3	0.5	-0.0	0.3
4	0.8	0.5	0.2	0.2	0.2	0.2	0.1	0.1	0.0	0.1
5	0.0	0.1	0.1	-0.0	0.0	0.2	0.1	0.2	-0.0!	0.1
6	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	-0.0	0.0
7	0.0	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.1	0.1	-0.2	0.0	0.1	0.1	0.1	-0.0	0.0
9	-0.2	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	-0.0	0.0
10	-0.1	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	0.0	0.0

2400.0 Amps U (from 8 elements)

0				0.0	0.0				0.0	0.0
1				0.0	0.5				-1.0	2.1
2				2.7	0.7				0.1	0.2
3				-0.0	0.2				-0.0	0.2
4				0.1	0.3				0.0	0.0
5				-0.0	0.0				-0.0	0.1
6				0.0	0.1				-0.0	0.0
7				-0.0	0.0				-0.0	0.1
8				-0.2	0.0				0.0	0.0
9				-0.0	0.0				-0.0	0.0
10				-0.1	0.0				0.0	0.0

5000.0 Amps U (from 52 elements)

0				0.0	0.0				0.0	0.0
1	1.4	1.0	1.0	0.2!	0.6	3.0	0.5	1.0	0.8*	1.8*
2	-1.0	4.0	1.0	5.9**	1.0	-0.8	0.5	1.0	0.3*	0.3
3	0.3	0.1	0.1	-0.0!	0.2	0.2	0.3	0.5	0.2	0.3
4	0.8	0.5	0.2	0.0!	0.2	0.2	0.1	0.1	0.0	0.1
5	0.0	0.1	0.1	0.0	0.1	0.2	0.1	0.2	-0.0!	0.1
6	0.0	0.1	0.1	-0.0	0.1	0.1	0.1	0.1	-0.0	0.0
7	0.0	0.1	0.1	-0.0	0.0	0.0	0.1	0.1	-0.0	0.0
8	-0.2	0.1	0.1	-0.2	0.0	0.1	0.1	0.1	-0.0	0.0
9	-0.2	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	-0.0	0.0
10	-0.1	0.1	0.1	-0.1	0.0	0.0	0.1	0.1	0.0	0.0

6800.0 Amps U (from 1 elements)

0				0.0	0.0				0.0	0.0
1				0.5	0.0				0.4	0.0
2				10.1	0.0				0.3	0.0
3				0.1	0.0				0.1	0.0
4				0.5	0.0				-0.0	0.0
5				0.0	0.0				-0.2	0.0
6				0.1	0.0				-0.1	0.0
7				-0.0	0.0				-0.0	0.0
8				-0.2	0.0				-0.0	0.0
9				-0.1	0.0				-0.0	0.0
10				-0.1	0.0				0.0	0.0