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IR Magnet Analysis

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DISCLAIMER

IR Magnet Analysis

Jie Wei, BNL, June 17, 1996

I. Introduction

II. Field Quality Issues

* triplet quadrupole-corrector assembly
* dipole D0
* dipole DX
* other insertion-region magnets
* tune footprints and dynamic apertures

III. Alignment & Assembly Issues

* multi-layer corrector
* corrector-quadrupole assembly
* ring installation
* dynamic apertures

IV. Summary

I. Introduction

- Due to intra-beam scattering growth at storage, beam size at low-β^* ($\beta^* = 1$ m) IR is much larger than the size anywhere at injection.
- With $\beta^* = 1$ m, the storage performance is totally determined by the field and alignment quality of the IR magnets (triplet and D0) at high-β locations.
- Beam-beam effects are insignificant.

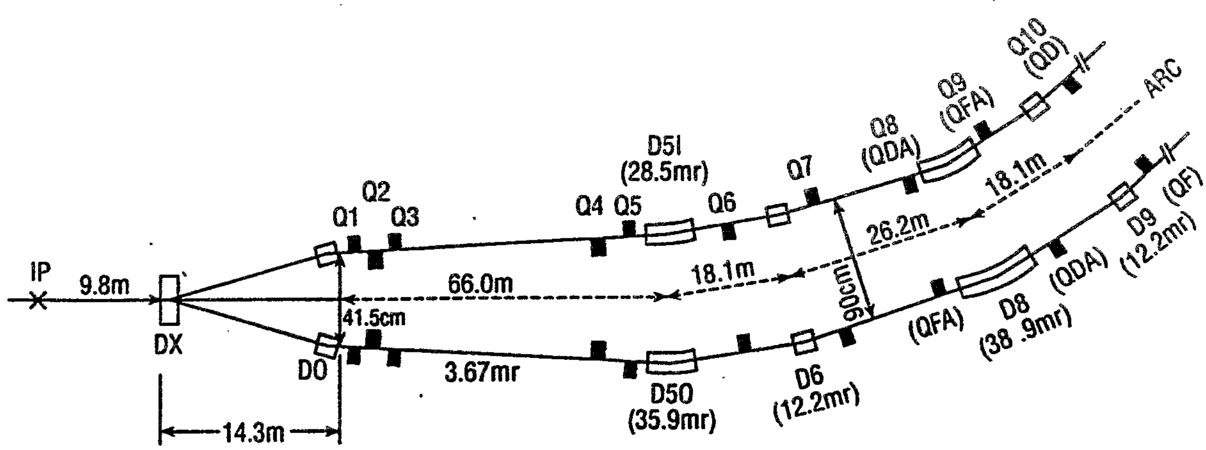
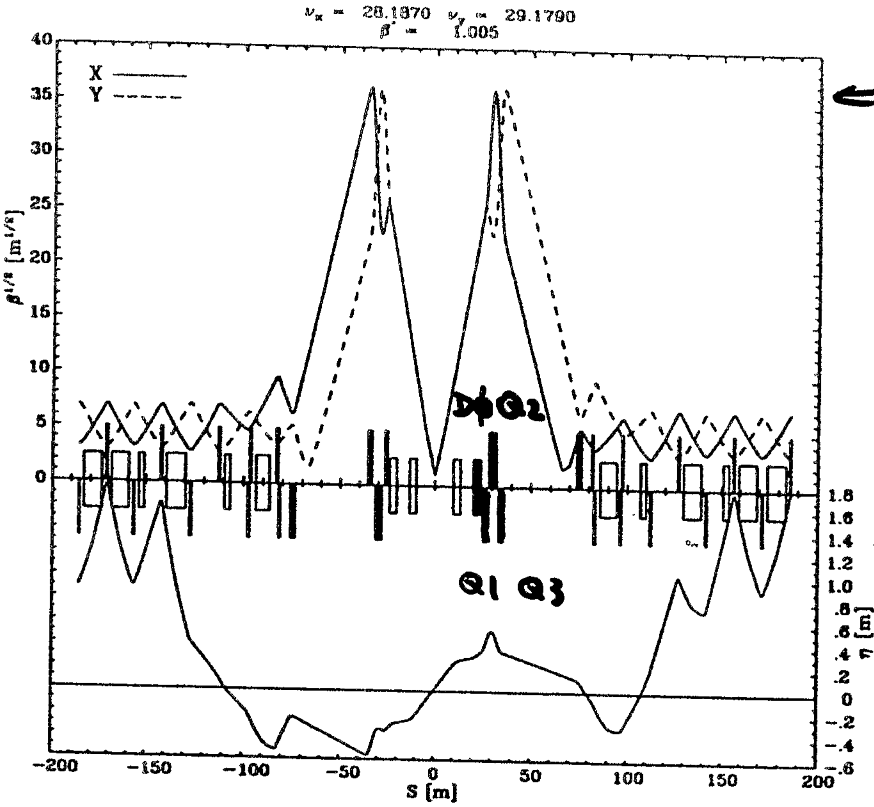


Fig. 11-5. Expanded layout of half-insertion.

6 IP total

2 @ $\beta^* = 1$ m

4 @ $\beta^* = 10$ m



← $\beta_{max} = 1400$ m

Table 1: Storage and injection beam parameter comparison.

Quantity	Injection	Storage ($\beta^* = 1$ m)
ϵ_N (95%)	10 πmm·mr	40 πmm·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

II. Field Quality Issues

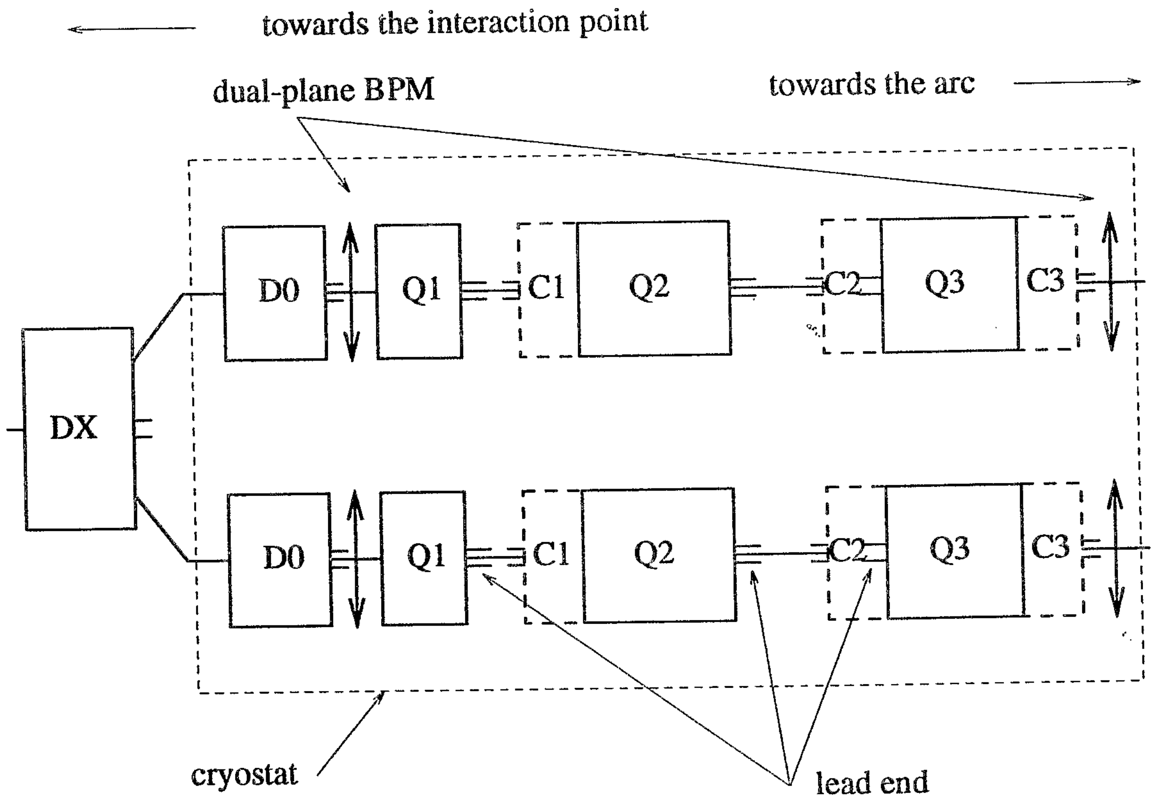


Figure 1: Schematic layout of the RHIC triplet region, showing the dipoles (D0), quadrupoles (Q1, Q2, Q3), local corrector packages (C1, C2, C3), and BPMs of both rings, and the common dipole (DX).

	triplet cQ	DΦ	DX	arc
Coil ID (mm)	130	100	180	80
Ref. R_o (mm)	40	31	57	25

* Triplet quadrupole-corrector assembly

Planned compensation methods:

Figure of merit:

to minimize

$$\frac{(2J)^{\frac{n-1}{2}}}{\rho} \boxed{\int b_n \, \beta^{\frac{n+1}{2}} \, dl} \sim \frac{\Delta J}{J} \quad \text{(action kick)}$$

- Choose lead-end orientation to minimize the effects of the stronger end.

- Use magnet body to compensate the ends on systematic b_5 and a_5, taking into account the expected beam size variation in the magnet.

- Iterate quad cross-section, and shim individually using 8 tuning shims after warm/cold measurements.

- Sort golden quads and correctors for two low-β^* IRs.

- Use IR correctors for orbit smoothing, decoupling, and higher order compensation.

Current activities and results:

- Measurement data confirms that the choice of lead end orientation is very helpful.

  a factor of 2 reduction in eff. strength

- Measurement data confirms that body-ends compensation is successful.

- Cold measurements of pre- and post-shimming quad harmonics indicate that tuning shims are highly effective in reducing multipole errors.

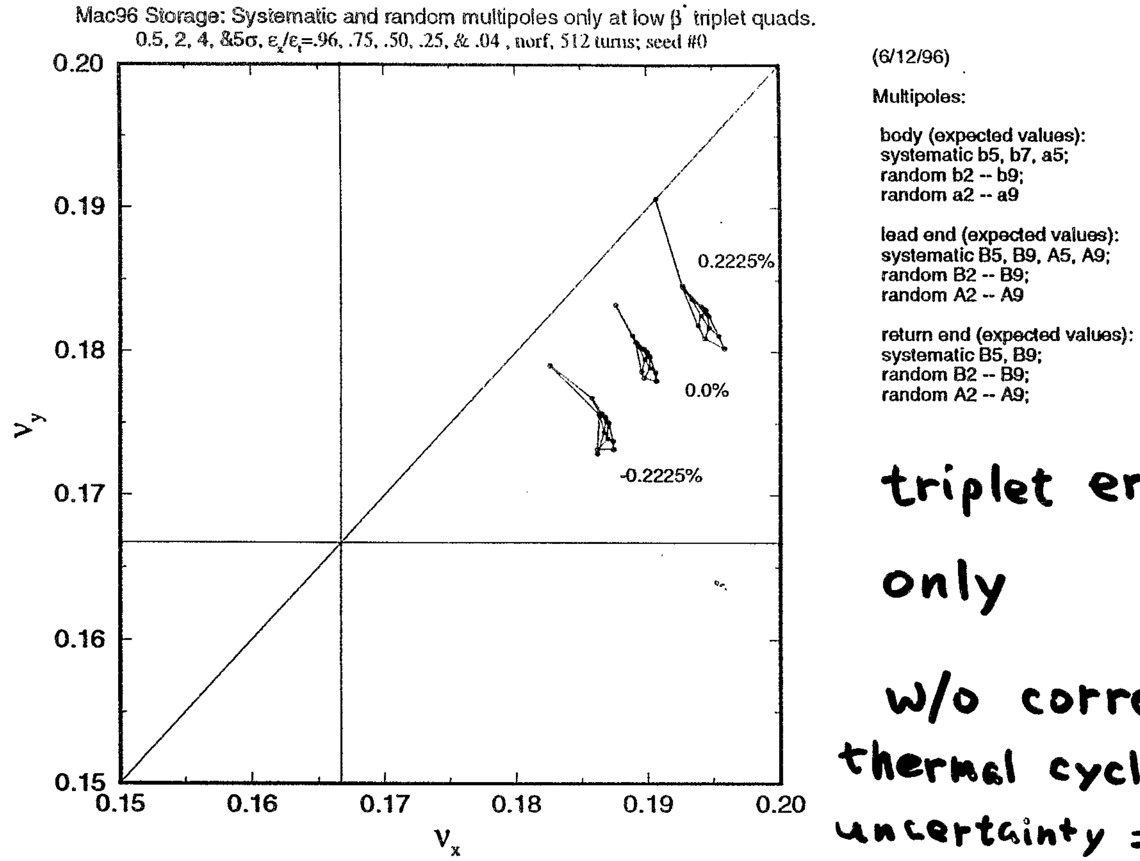
- Multiple measurements indicate dependence of certain multipole values on quench and thermal cycle. investigation under way

  Post-shimming expected harmonics includes the uncertainties in shimming and measurement, and the dependence on quench and thermal cycle.

- Golden quads and correctors selected for low-β^* IRs.

  for sextant test

- Dependence of certain field multipole values on quench and thermal cycle makes higher-order dead-reckoned correction less effective.



triplet error only w/o correcto thermal cycle uncertainty ⇒ 0.5 ~ 1 σ reductio in D.A.

Figure 4: Effects of IR triplet field quality errors (expected value), without activating the triplet correctors.

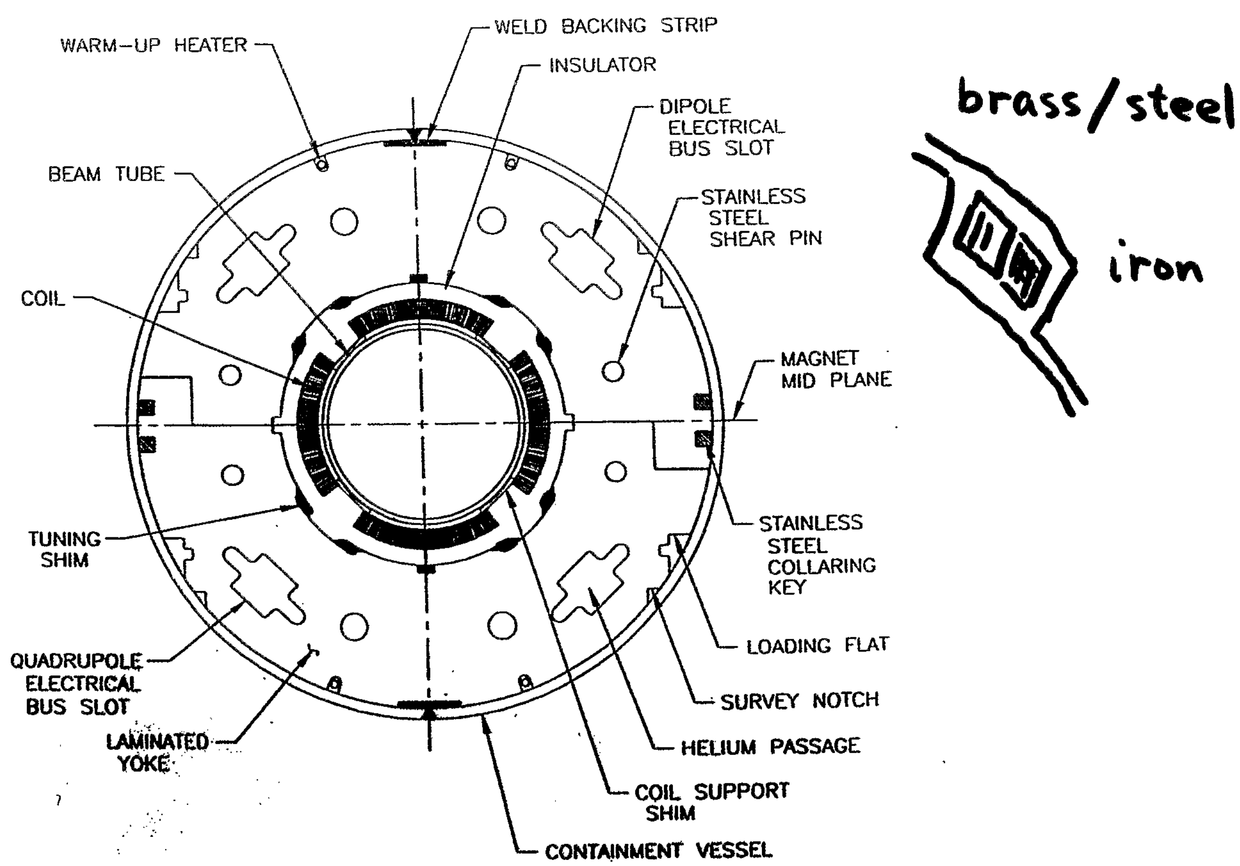


Table 2: Expected post-shimming values of the mean, uncertainty in mean, and standard deviation of the body, lead end, and return end harmonics of the triplet quadrupoles at storage (5 kA).

Order, n		Normal			Skew	
BODY	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
1	0.0	0.0	0.0	0.0	0.0	10.0
2	0.0	0.0	0.5	0.0	0.0	0.5
3	0.0	0.0	0.4	0.0	0.0	0.4
4	0.0	0.0	0.3	0.0	0.0	0.3
5	−1.2	0.0	0.2	−0.5	0.0	0.2
6	0.0	0.1	0.1	0.0	0.1	0.1
7	−0.2	0.05	0.05	0.0	0.03	0.1
9	0.0	0.2	0.03	0.0	0.03	0.03
LEAD END	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	0.0	0.1	0.7	0.0	1.0	2.0
3	0.0	0.3	0.3	0.0	0.4	0.8
5	4.6	0.5	0.3	-1.5	0.5	0.2
9	-0.5	0.1	0.0	0.2	0.1	0.0
RETURN END	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
2	0.0	0.3	1.8	0.0	0.7	1.0
3	0.0	0.1	0.2	0.0	0.1	0.3
5	1.0	0.0	0.6	0.0	0.1	0.1
9	-0.1	0.0	0.0	0.0	0.0	0.0

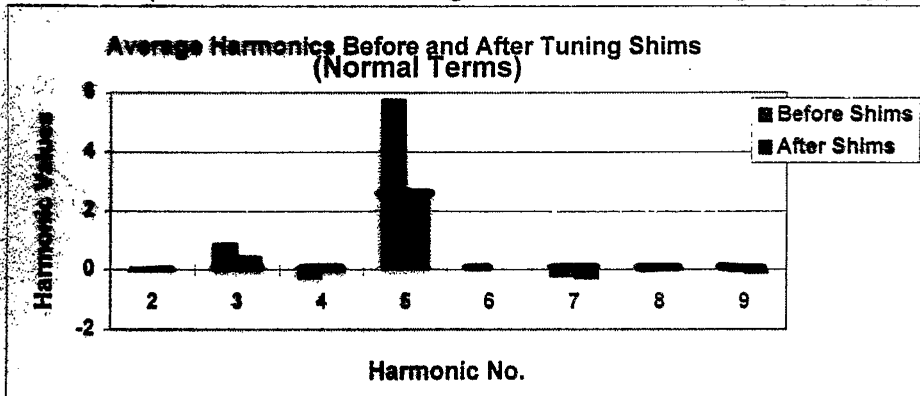
desired

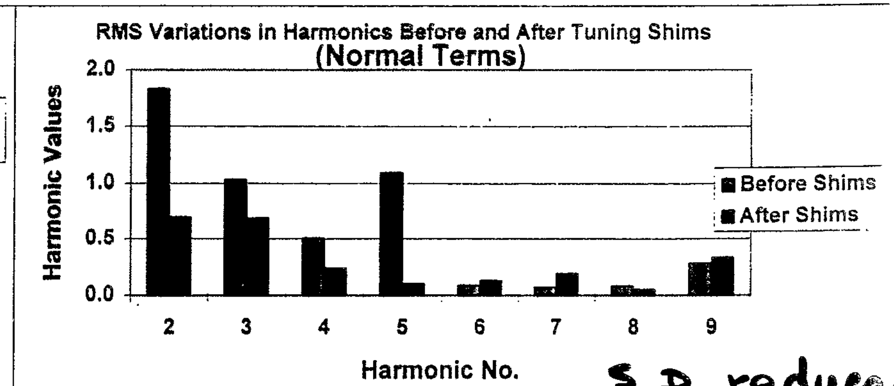
(1) uncertainty in measurement & shimming.

(2) dependence on quench & thermal cycle

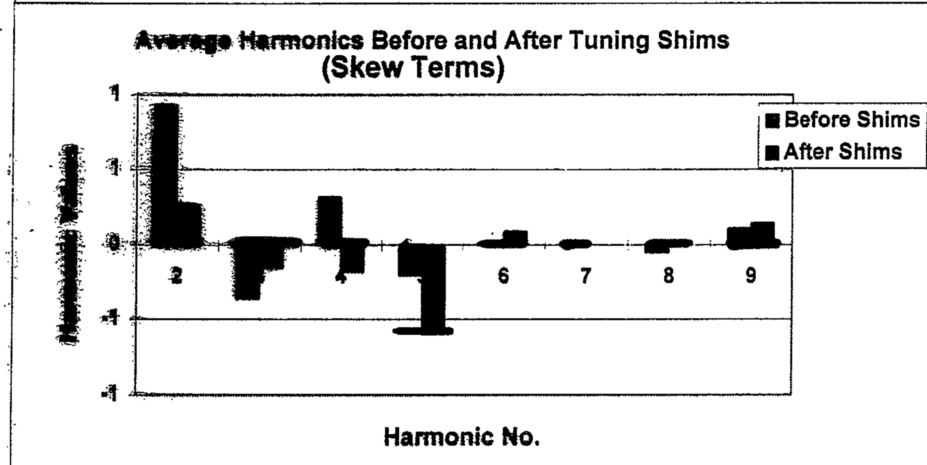
R. Gupta

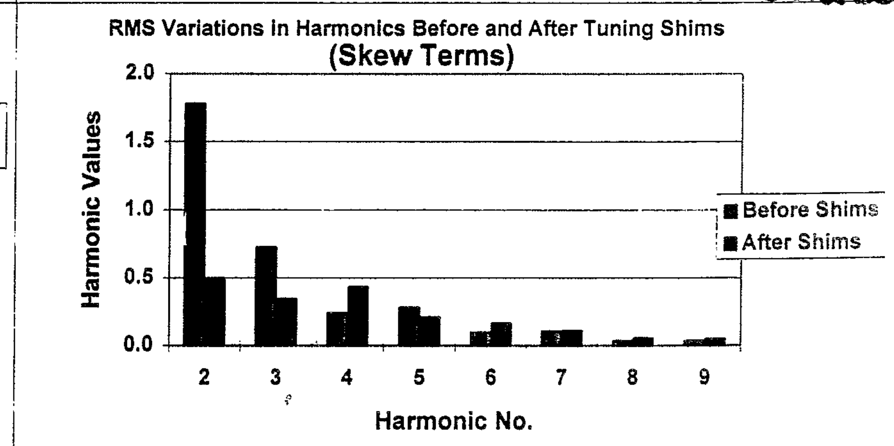
Average and RMS values of harmonics before and after tuning shims in RHIC 13 cm quadrupoles :
(The harmonics are given at 5 kA during up ramp)





S.D. reduced





	b2	b3	b4	b5	b6	b7	b8	b9			a2	a3	a4	a5	a6	a7	a8	a9
[redacted]	-0.06	0.88	-0.31	5.77	0.07	-0.24	-0.01	0.06	Before	Average	0.92	-0.36	0.32	-0.20	0.01	0.01	-0.05	0.11
[redacted]	-0.04	0.42	-0.09	2.55	0.00	-0.31	0.02	-0.13	After	Average	0.26	-0.16	-0.18	-0.60	0.09	0.00	0.02	0.14
[redacted]	1.83	1.03	0.50	1.09	0.09	0.07	0.08	0.28	Before	Sigma	1.78	0.73	0.24	0.28	0.10	0.11	0.04	0.04
[redacted]	0.70	0.69	0.24	0.10	0.13	0.19	0.05	0.33	After	Sigma	0.50	0.34	0.43	0.21	0.16	0.11	0.06	0.05

[redacted] 1. Harmonics corrected with tuning shims are a2 through a5 and b2 through b5.
2. a5 and b5 are custom otimized for each magnet. The above statistics is only for Q1 magnet a5 and b5 are generally within 0.1 unit of desired value.
3. a4 and b4 numbers are not reliable due to tilt in measurin (Warm measurements may be used instead).

— : target value for shimming

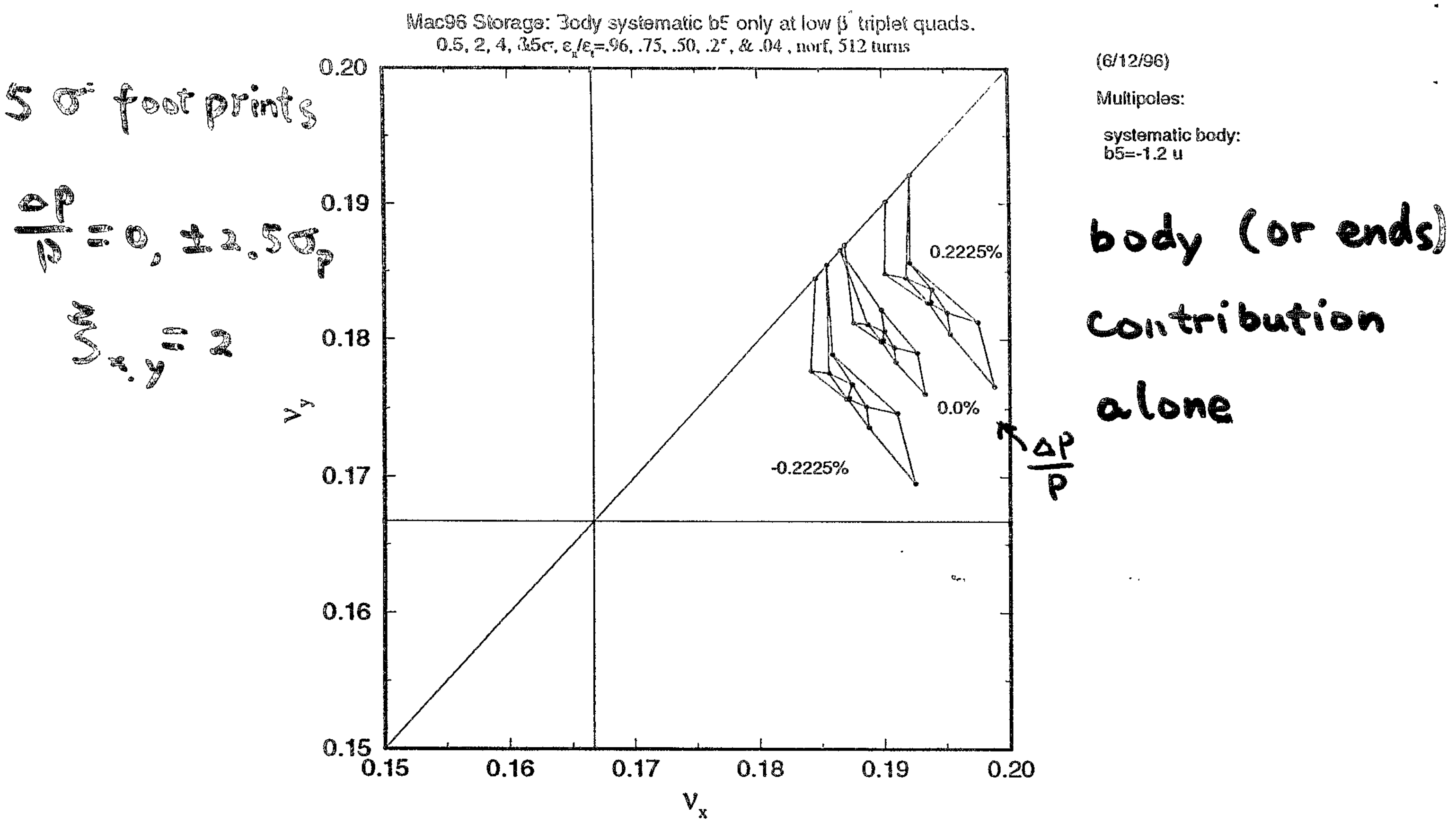


Figure 2: Effects of systematic body b_5 or ends B_5 at the triplet quads.

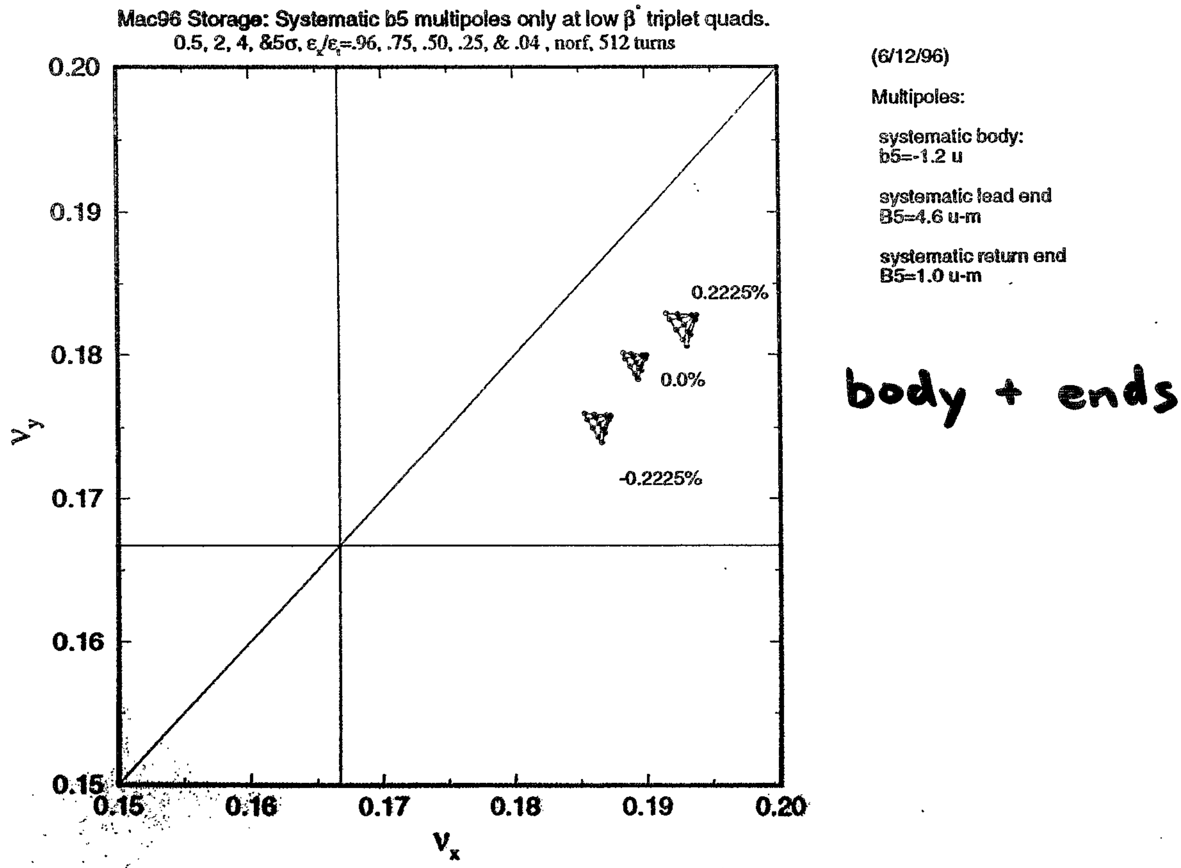


Figure 3: Effects of body-ends compensation on systematic b_5 for the triplet quads.

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irprod.dat

Priority	Magnet	LECor	NLECor	LEDx	LEDy	LEDroll	NLEDx	NLEDy	NLEDroll	Model
1	QRI103									101
2	QRI104									104
3	QRI120									105
4	QRI121									108
5	QRJ102									
6	QRJ114									
7	QRJ116									
8	QRJ117									
9	QRK101		CRI101	0.0	0.0	0.0	0.0	0.0	0.0	112
10	QRK103									
11	QRK107									
12	QRK108									
14			CRI102							109
15		CRK102								120
16		CRK103								117
17	DRZ101									203
18	DRZ103									201

(17 rows affected)

C Q match

⇒ non-golden

* C Q sorting and offset minimization

Triplet correctors:

- One horizontal and one vertical dipole correctors are located near focusing and defocusing quads of each IR triplet.

  closed orbit

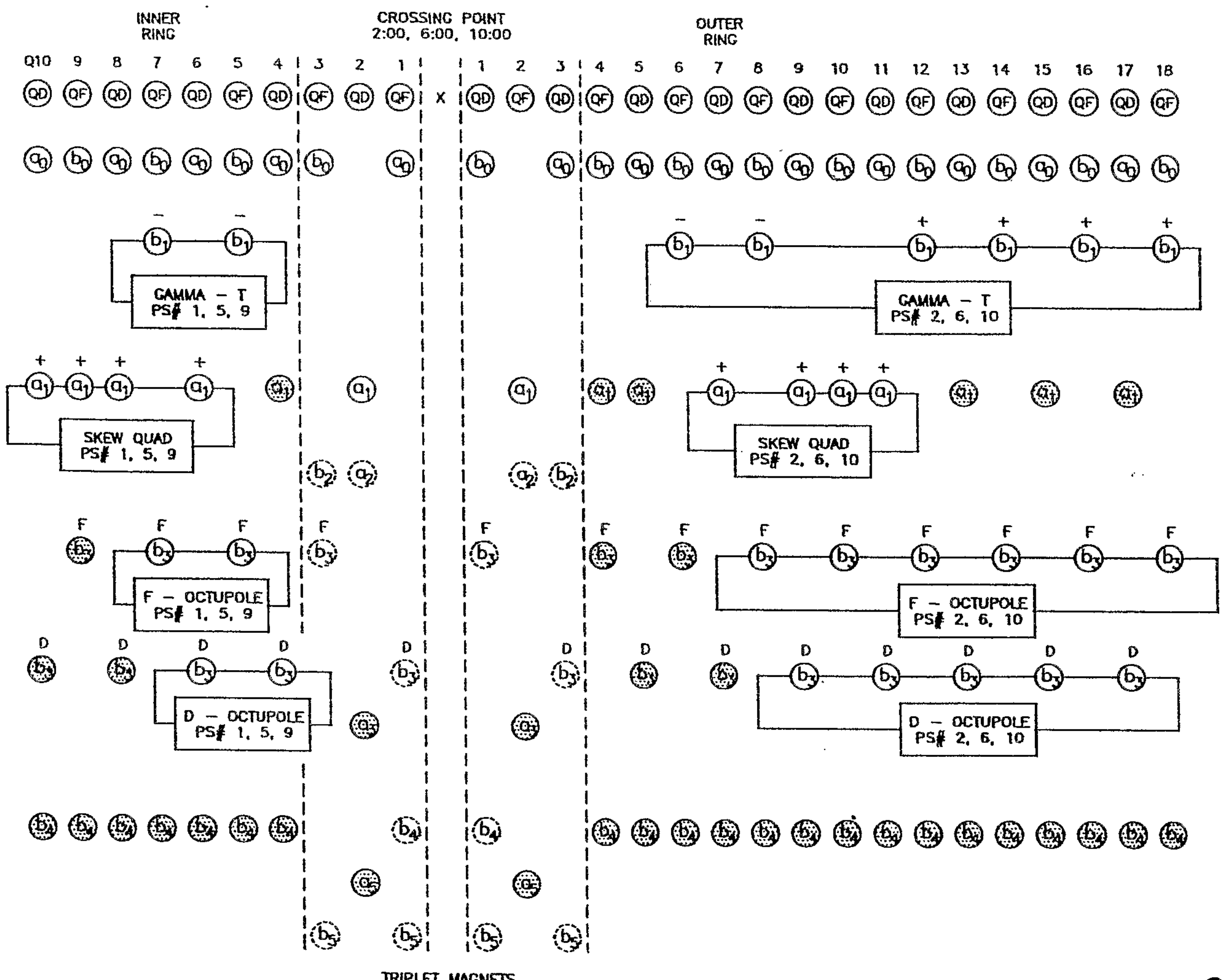
- Local decoupling can be done using dual-plane BPMs, including the two at every triplet.

  coupling

- Local higher-order correctors are dead-reckoned, based on cold measurement of every triplet quad.

  b_3 , b_5 , b_2 , etc.

- It would be very helpful to develop and implement higher-order corrections based on live beam measurement, to overcome the dependence on thermal cycles.



arc ←

arc →

triplet

shaded: no power supplies connected

Fig. 2-14. Corrector supplies at 2, 6 and 10 o'clock.

Table 3: The IR triplet correction strategy.

Order, n	Normal, b_n	Skew, a_n
0	C1 or C3	C3 or C1
1	individually powered	C2
2	S, C3	S, C2
3	B, S, C1, C3	S, C2
4	S, C1	S
5	B+, S+, C1, C3	B+, S, C2
7	B	
9	B	

B: coil cross-section iteration

B+: coil cross-section iteration plus body-ends compensation

S: using tuning shims

S+: using tuning shims on random b_5 after body-ends compensation

C1, C2, C3: correction available at C1, C2, or C3 corrector

* Dipole D0

- For $\beta^* = 1$ m IRs, beam size is large at D0 ($\beta \sim 600$ m); field quality is important.

- Tight geometry $\Longrightarrow$ challenge on cross-section design:

  cross-ring talk vs. iron saturation

  ? unknown

- Inadequate iron $\Longrightarrow$ excessive b_2 saturation in early D0s.

- These early D0s have been/will be designated as non-golden magnets used in higher β^* IRs

  cross-section iteration results in tolerable b_2 and b_4

- Triplet correctors are planned to be used for b_2 correction of D0s.

  only one b_2 corrector per triplet; less effective than pairs (b_3 & b_5)

  two b_2 correctors per IR can be used for semi-local correction

- Early D0s with large b_2 saturation can not be used at low-β^* IRs.

  large action kick causes dynamic aperture problem

$$\frac{\Delta J}{J} \sim 0.013 \quad \text{for } 5\sigma \text{ particle}$$

- With new expected values, field quality is tolerable

  changes chromaticity by 0.6 units; manageable

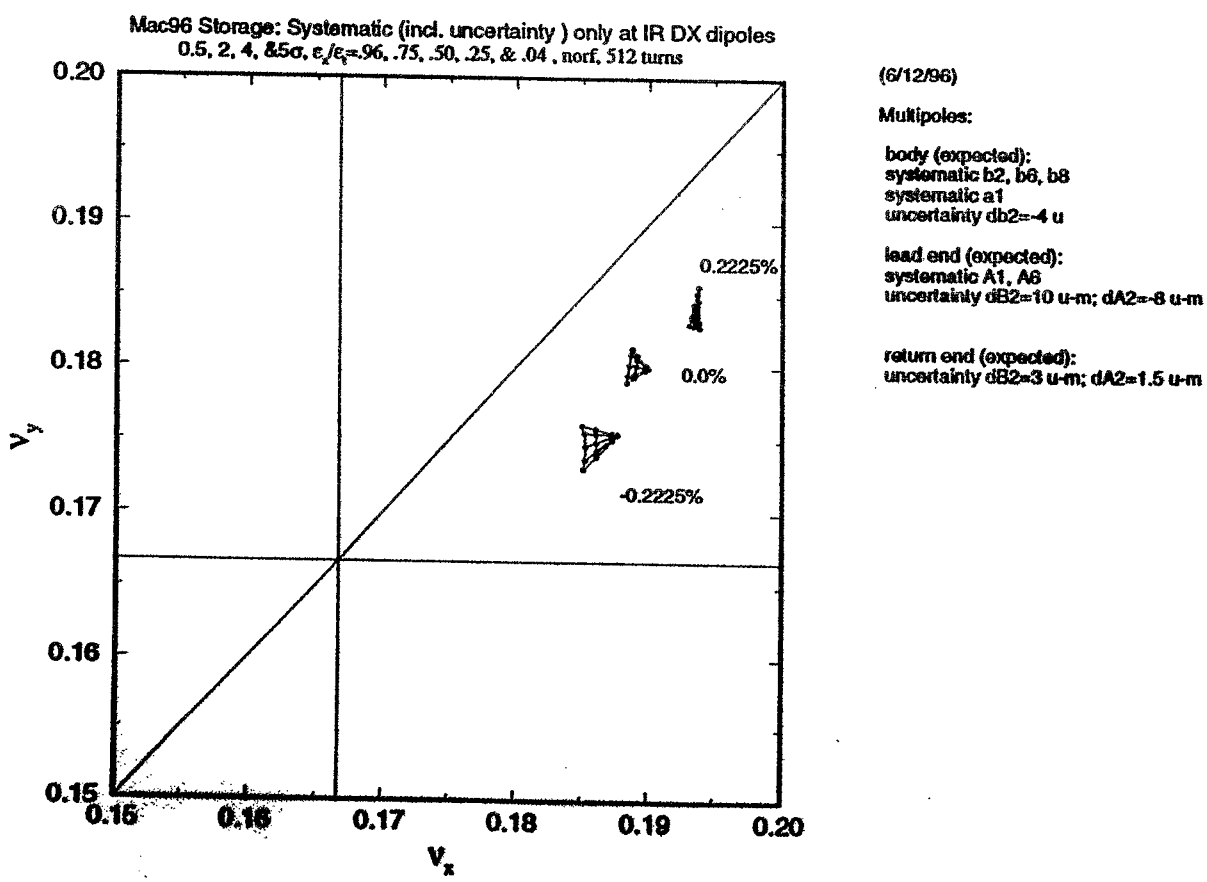


Figure 5: Effects of systematic b_2 in IR D0 dipoles.

R. Gupta
etc.

Table 4: Measured harmonics in D0 magnet DRZ103.

early Dφ
(non-golden)

Order, n	Normal, b_n
2	5.2
4	-0.2
6	0.9
8	-0.2

Table 5: New expected values for D0 integral harmonics at storage.

iterated
cross-section

Order, n	$\langle b_n \rangle$	db_n
2	1.0	1.0
4	0.2	0.2
6	0.8	0.1
8	-0.2	0.05

Expected D0 Harmonics

(used in tracking)

BODY HARMONICS, TOP ENERGY, 5 kA

[<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	.8	-2.5	1.0	1.3
2	-3.0	3.0	2.3	.0	.4	.5
3	.0	.2	.3	.0	.3	1.0
4	.4	.5	.6	.0	.06	.2
5	.0	.03	.1	.0	.1	.26
6	.6	.5	.1	.0	.03	.1
7	.0	.03	.1	.0	.03	.1
8	.0	.3	.1	.0	.03	.1
9	.0	.03	.1	.0	.03	.1
10	.0	.2	.1	.0	.03	.1

cross talk

LEAD END INTEGRATED HARMONICS, (Unit-m), STORAGE (5 kA)

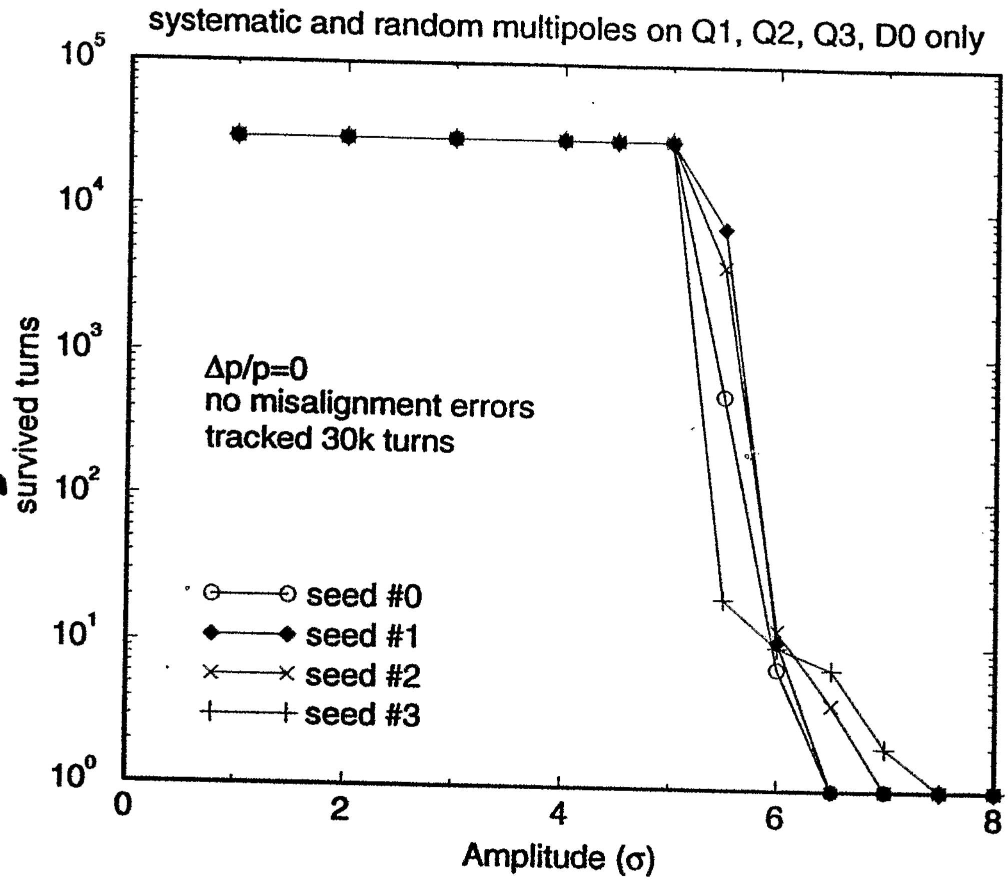
n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	-1.0	1.0	1.0	1.0	2.0	1.0
2	14.0	2.0	2.0	-10.0	2.0	1.0
3	.3	.2	.2	.0	1.0	1.0
4	1.0	1.0	.2	2.0	.5	.3
5	.0	.2	.2	.0	1.0	.2
6	1.0	.2	.1	-.9	.2	.2
7	.0	.1	.1	.0	.1	.1
8	-.2	.1	.1	.2	.1	.1
9	.0	.1	.2	.0	.1	.1
10	.0	.1	.1	-.1	.1	.1

RETURN END INTEGRATED HARMONICS, (Unit-m), STORAGE (5 kA)

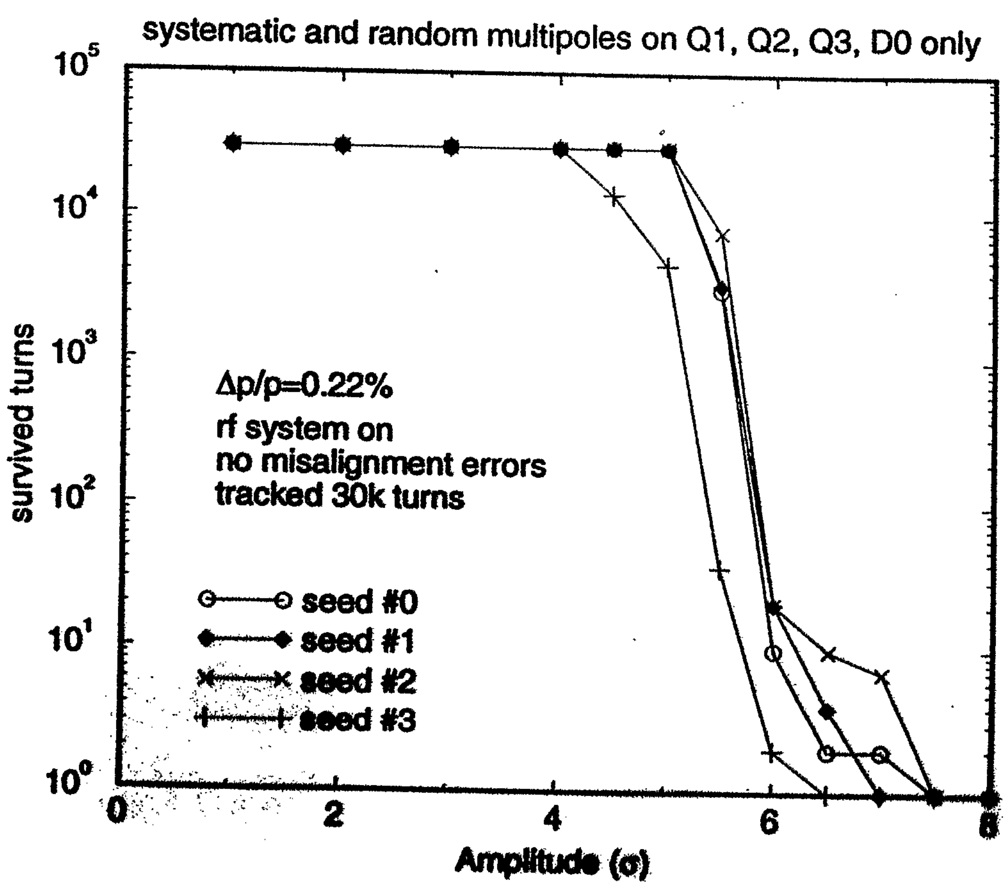
n	<Bn>	d(Bn)	sig(Bn)	<An>	d(An)	sig(An)
1	.0	1.0	1.0	.0	.5	1.0
2	5.0	2.0	1.0	.0	.5	1.0
3	.0	.2	.1	.0	.3	.5
4	1.0	1.0	.2	.0	.1	.1
5	.0	.1	.1	.0	.1	.2
6	-.1	.1	.1	.0	.05	.1
7	.0	.1	.1	.0	.05	.1
8	.0	.1	.1	.0	.05	.1
9	.0	.1	.1	.0	.05	.1
10	-.2	.1	.1	.0	.05	.1

* Tune footprints and dynamic apertures

on momentum



off momentum ($2.5\ \sigma_p$)



* Dipole DX

- Since DX translates to accommodate for different collision scenarios, excessive beam orbit offset for proton-gold operation is no longer an issue.

- As far as field quality is concerned, gold-gold storage is relatively the most demanding scenario.

  6σ beam plus orbit offset at 63% coil radius;

  $\beta \sim 200$ m

- Expected uncertainty in body and end systematic b_2:

  insignificant effects in beam dynamics (chromaticity, tune foot-prints, dynamic aperture)

  feed-down easily correctable

- Field quality is not a problem.

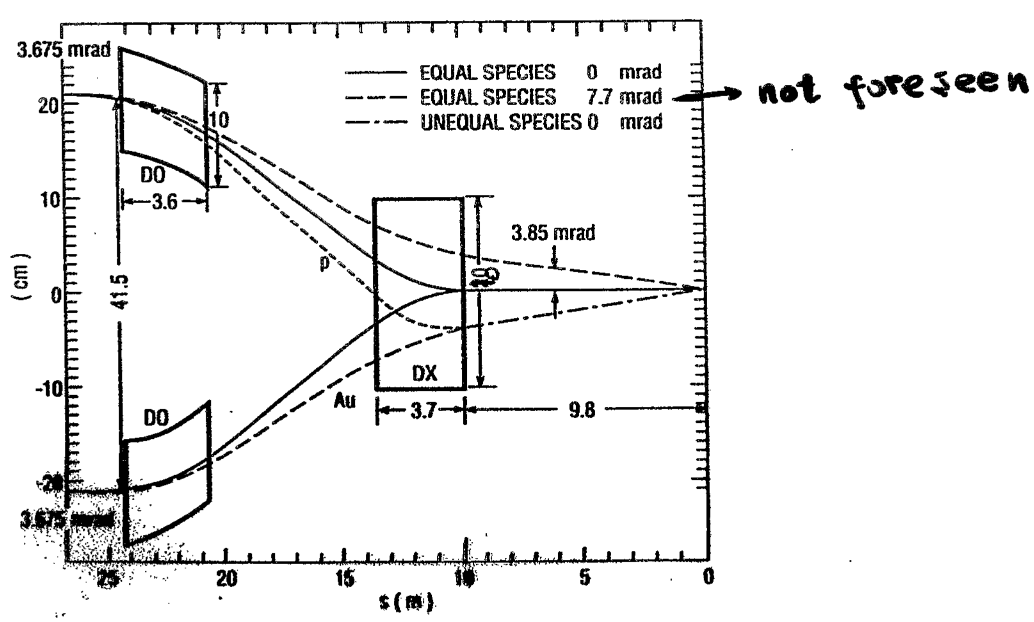


Fig. 11-7. Beam crossing geometry (magnetic lengths are shown)

Table 6: Expected values of harmonics for DX dipoles at storage.

Order, n	Normal			Skew		
BODY	$\langle b_n \rangle$	$d(b_n)$	$\sigma(b_n)$	$\langle a_n \rangle$	$d(a_n)$	$\sigma(a_n)$
1	0.0	0.4	0.5	-2.5	1.3	0.9
2	−0.6	4.0	1.6	0.0	0.4	0.3
4	0.0	1.0	0.4	0.0	0.06	0.13
6	0.05	0.2	0.1	0.0	0.03	0.1
8	−0.08	0.1	0.1	0.0	0.03	0.1
10	−0.04	0.05	0.1	0.0	0.03	0.1
12	−0.07	0.05	0.05	0.0	0.01	0.05
LEAD END	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
1	0.0	1.0	2.0	0.0	2.0	2.0
2	0.0	10.0	4.0	-1.5	8.0	2.0
4	0.0	1.0	0.4	0.4	1.5	0.6
6	0.0	1.0	0.2	−0.1	0.8	0.4
RETURN END	$\langle B_n \rangle$	$d(B_n)$	$\sigma(B_n)$	$\langle A_n \rangle$	$d(A_n)$	$\sigma(A_n)$
1	0.0	1.0	2.0	0.0	0.5	2.0
2	0.0	3.0	2.0	0.0	1.5	2.0
4	0.0	0.5	0.4	0.0	0.2	0.2

no probler

* Other insertion-region magnets

- Dipoles D5I, D5O, D6, and D9 are on the common power supply of the arc dipoles without shunts.

- The deviation of the measured dipole lengths from their ideal values will be compensated by the dipole correctors.

Table 7: **Relative deviations of the dipole length from their ideal values and the required corrector strength.**

Magnet	arc dipole	D5O	D5I	D6 & D9
Relative deviation ($\times 10^{-2}$)	0 ± 0.03	0.58 ± 0.03	0.04 ± 0.02	0.22 ± 0.02
Corrector strength (A)	0 ± 1.8	10.0 ± 0.6	1.8 ± 1.0	-11.2 ± 1.0

max. current available : 50 A

III. Alignment & Assembly Issues

Triplet cryostat contains 2 dipoles (D0), 6 quads (Q1, Q2, Q3) and 6 corrector packages (C1, C2, C3) of both ring.

Each dipole or quad must move freely in the longitudinal direction during a thermal cycle, and must be strictly confined in the transverse direction.

Triplet assembly procedure:

- assemble and align four corrector layers into a corrector package
- sort on corrector and quad cold mass units, and attach corrector with quad
- align and install CQ units and D0 into the common cryostat in the tunnel

* Multi-layer corrector

Table 8: Improvement of magnetic field angle using pole shims (CRI101).

Layer	Dipole	Octupole	Decapole	Dodecapole
pre-shimming				
Integ. field angle (mr)	1.8	−2.7	−1.5	−0.9
post-shimming				
Integ. field angle (mr)	−0.2	0.6	−0.3	0.5

* Corrector-quadrupole assembly

- Sort on corrector and quad cold mass, both to optimize the field quality for low-β^* IRs and to minimize the relative center offsets and roll between C and Q.

  based on cold mass magnetic measurements

- After fiducialized, use antenna probe to locate the quad and corrector center relative to the cold mass fiducials.

  both antenna and colloidal methods used in CQS

- The current plan of eliminating relative CQ magnetic center offsets and roll during assembly, is challenged by technical difficulties.

- After sextant test, there will be more freedom of sorting CQ after it is finished and remeasured.

* Ring installation

- CQ assemblies and D0s are assembled in the cryostat in the tunnel.

  Once closed, the quad center can not be independently adjusted.

- Using antenna techniques to relocate the quad and corrector center in the tunnel is desirable during final installation

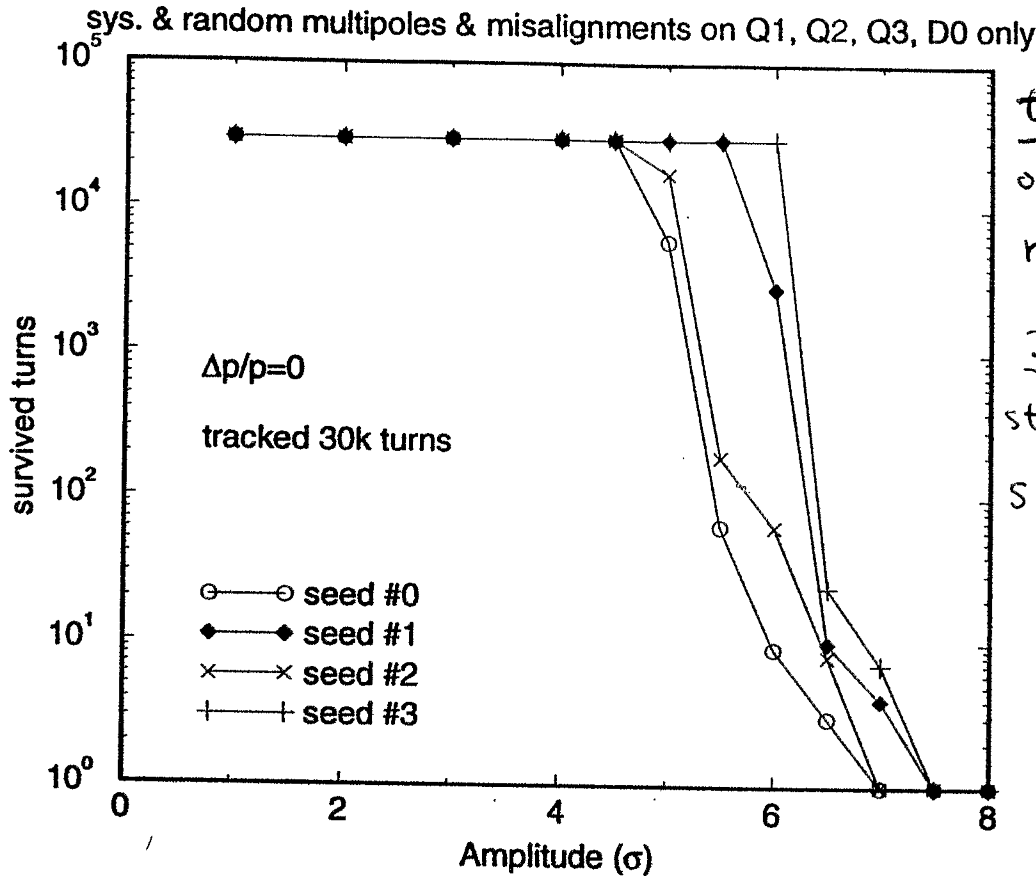
Table 9: Preliminary installation offsets (mean±S.D.) of 77 arc CQSs and 88 arc dipoles.

Direction	Units	arc dipole	CQS element
North	[mm]	-0.1 ± 0.6	0.0 ± 0.6
East	[mm]	-0.1 ± 0.5	0.0 ± 0.7
Elevation	[mm]	-0.1 ± 0.7	-0.2 ± 0.5
Radial	[mm]	0.1 ± 0.4	0.0 ± 0.4
Vertical	[mm]	-0.1 ± 0.7	-0.2 ± 0.5
Longitudinal	[mm]	0.0 ± 0.6	0.1 ± 0.4

can be reduced to ~ 0.3 mm after "smoothing" survey

* Dynamic apertures

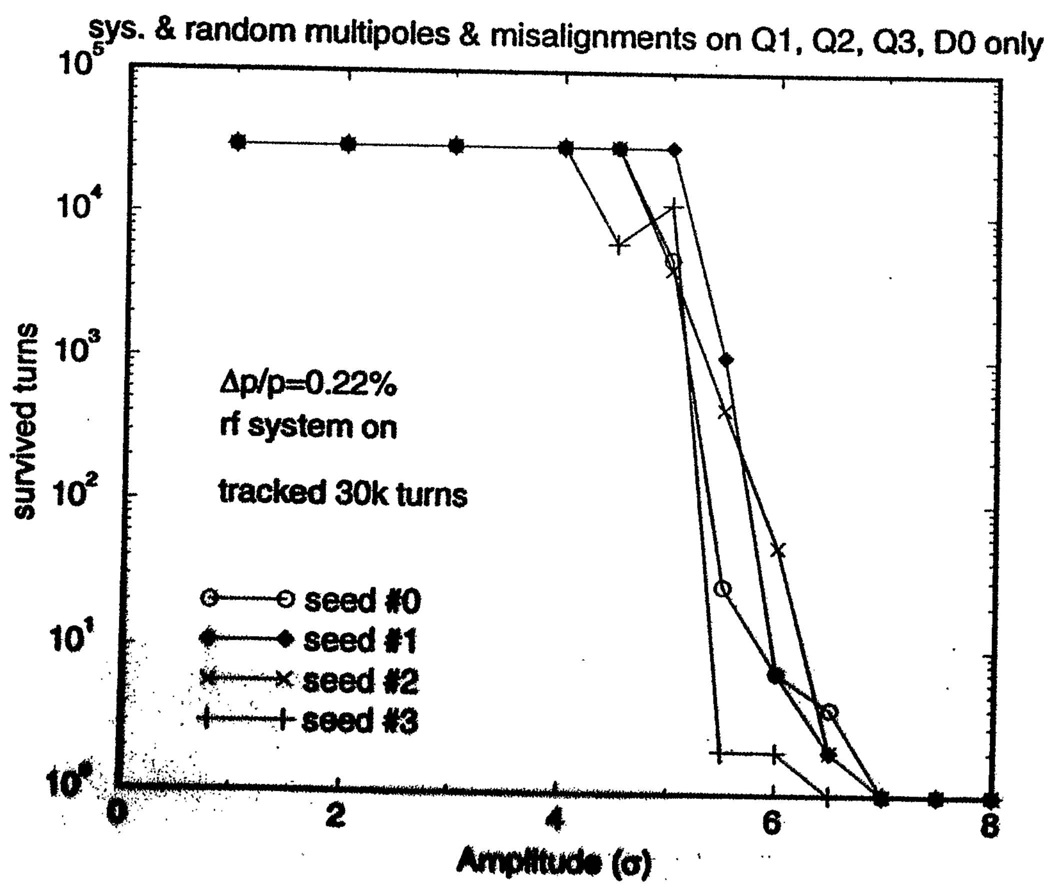
on momentum



triplet
offset ± 0.25
roll ± 0.5 m

DΦ
strength ± 0.05 %
S roll ±1 mr

off momentum ($2.5\ \sigma_p$)



IV. Summary

- The measurement data of the completed triplet quads shows that tuning shims are very effective in reducing undesired harmonics.

- Further investigation on the dependence of field harmonics on quench and thermal cycle will make local IR higher-order correction more effective.

- Golden magnet selection is necessary in minimizing the negative impact of some early production triplet quads and D0 dipoles.

- An accurate alignment of triplet quads is crucial. Further development of the antenna techniques, both for CQ cold mass and in-tunnel measurement, is highly beneficial.

- Triplet corrector packages are extremely useful at storage for orbit smoothing, decoupling, and higher-order compensation, both for triplet quads and D0.