BNL-101729-2014-TECH

RHIC/AP/74;BNL-101729-2013-IR

? Spreads Due to Systematic Field Errors Including b3, b4, and a1

G. Parzen

January 1989

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

AD/RHIC-AP-74

ν Spreads Due to Systematic Field Errors Including b_3, b_4, and a_1

G. Parzen

BNL

January 5, 1989

b_4 effects

Systematic b_4 due to iron saturation at high fields

$$b_4' = 6 \times 10^{-4}$$
$$b_4 = 1.54 \times 10^{-5} / cm^{-4}$$

Reference: AD/RHIC-28, Dell, Hahn, Parzen, Ruggiero

ν- Shifts

For each magnet type

$$\Delta\nu_x = \frac{1}{\pi}\frac{N}{\rho} L\, b_4 \left\{ \beta_x (X_p\delta)^3 + .75\, \beta_x^2 X_p\delta\, \varepsilon_x - 1.5\, \beta_x \beta_y (X_p\delta)\, \varepsilon_y \right\}$$

$$\Delta\nu_y = \frac{1}{\pi}\frac{N}{\rho} L\, b_4 \left\{ -\beta_x (X_p\delta)^3 - 1.5\, \beta_x\beta_y\, \varepsilon_x X_p\delta + .75\, \beta_y^2 X_p\delta\, \varepsilon_y \right\}$$

$$\delta = \Delta P/p$$

$\Delta\nu$ depends on δ, ε_x, ε_y — may take as many as 6 power supplies to control the 6 different terms in $\Delta\nu_x$, $\Delta\nu_y$. With 2 power supplies, $\Delta\nu$ can be reduced by about a factor of 2.

b_4 effects and Correction

$b_4' = 6, \quad b_4 = 1.54\,E{-}5\ \mathrm{cm}^{-4}, \quad \gamma = 100$

	Old RF	New RF $\varepsilon_{x_0} = 10$	$\varepsilon_{x_0} = 60$
σ_x (mm)		1.7	2.4
$\varepsilon_{x,N}$	30	35	69
$\varepsilon_x = 6\sigma_x^2/\beta_x$	.3	.35	.69
$\varepsilon_{6\sigma} = 6\,\varepsilon_x$	1.8	2.1	4.1
$\sigma_p\,/10^{-3}$	1.04	1.58	.993
$\frac{\Delta p}{p}/10^{-3} = 2.5\,\frac{\sigma_p}{10^{-3}}$	2.6	3.95	2.5
$\Delta\nu\,/10^{-3}$ To be Corrected	11	21	22
$\Delta\nu\,/10^{-3}$ Corrected	5	10	11
$b_4 L\ (m^{-3})/10^3$ Correction ~~needed~~	12.5	12.7	12.4

$\Delta\nu_{spread} \equiv 2 \times \Delta\nu$ because $\Delta\nu \approx \Delta p/p$

$\Delta\nu_{spread} = 40 \times 10^{-3}$ uncorrected

$= 20 \times 10^{-3}$ corrected

For $\varepsilon_{2.5\sigma} = .35$, $\Delta p/p = 2\sigma_p = 3.2 \times 10^{-3}$

$\Delta\nu$ spread $= 8.2 \times 10^{-3}$ uncorrected

$\Delta\nu$ spread $= 4 \times 10^{-3}$ corrected

$\Big\}\ \varepsilon_{x_0} = 10$

About same result for $\varepsilon_{x0} = 60$

b_3 effects

There is no known source of systematic b_3. Fermilab experience indicates that construction procedures introduce an average b_3 which is not zero; and

$$b_{3,av} \simeq \frac{1}{3}\, b_{3,rms} ,$$

where $b_{3,rms}$ is the rms random b_3.

In Dipoles $b_{3,rms} = 8.1 \times 10^{-6}\ \mathrm{cm}^{-3}$

QF, QD $b_{3}\ rms = 1.5 \times 10^{-5}\ \mathrm{cm}^{-3}$

ν-shifts (Reference AD/RHIC-22, H. Hahn)

For each Magnet type

$$\Delta\nu_x = \frac{3}{4}\,\frac{NL}{\pi\rho}\, b_3 \left\{ \beta_x (X_p\delta)^2 + \frac{1}{4}\beta_x^2 \varepsilon_x - \frac{1}{2}\beta_x\beta_y\varepsilon_y \right\}$$

$$\Delta\nu_y = \frac{3}{4}\,\frac{NL}{\pi\rho}\, b_3 \left\{ -\beta_x (X_p\delta)^2 - \frac{1}{2}\beta_x\beta_y\varepsilon_x + \frac{1}{4}\beta_y^2 \varepsilon_y \right\}$$

b_3 effects

(4)

Largest $\Delta\nu$ at $\gamma = 30$; $\epsilon_{x_0} = 10$

σ_x (mm)	3.1	
$\epsilon_{x,N}$	33	
ϵ_x	1.1	
$\epsilon_{6,\sigma} = 6\,\epsilon_x$	6.6	
$\sigma_p\ /10^{-3}$	2.27	
$\frac{\Delta p}{p}/10^{-3} = \frac{2.5\sigma_p}{10^{-3}}$	5.7	
$\Delta\nu\ /10^{-3}$ To be Corrected	14.	8.6 from dipoles
$\Delta\nu\ /10^{-3}$ corrected	7	$\Delta\nu$ dipole reduced to 4
$b_3L\ (m^{-2})$ Correction needed	30	16.5 for dipoles only

$\Delta\nu_{spread} = \Delta\nu$ for octupole, $\Delta\nu \sim \Delta p/p$ to even power.

Yellow book $b_3L = 170/m^2$ at $B = 35$ KG.

For $\epsilon_{2.5\sigma} = 1.1$, $\Delta p/p = 2\sigma_p = 4.54 \times 10^{-3}$

$\Delta\nu_{spread} = 4 \times 10^{-3}$ uncorrected ($\Delta\nu = 2.3$ for dipoles)

$\Delta\nu_{spread} = 2 \times 10^{-3}$ corrected

6 σ question

Should we compute $\Delta\nu_x, \Delta\nu_y$ for $\varepsilon_{6\sigma} = 6\,\varepsilon_{2.5\sigma}$?

No obvious need for 6 σ requirement.

Requiring 6 σ provides a safety factor to allow for unknown effects. This seems worthwhile

If we reduce the 6 σ requirement (~~we~~) for $\Delta\nu$ due to b_3 b_4, we reduce the safety factor.

The 1/3 rule for ~~b3~~ systematic b_3

The next slide shows the Fermilab results that indicate

$$b_{3,av} = \frac{1}{3}\, b_{3,rms}.$$

Can we make $b_{3,av}$ smaller by watching b_3 during the magnet construction?

7

b_1, a_1

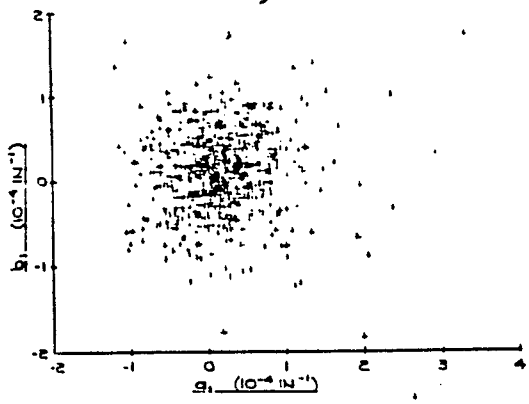

Fig. 2. a_1 and b_1 coefficients

72° for the inner coil and 36° for the outer coil. The magnitude of b_4 is also sensitive to these key angles. During collared coil fabrication we occasionally adjusted the key shims between the collars and the coils in order to maintain values of b_2 within the acceptance range of 0± 6 units at 4000 A excitation. In Figure 3 we show b_2 at 4000 A as a function of magnet number, which closely approximates the date of collared coil construction. Note that a trend toward unacceptably large values of b_2 developed

b_2

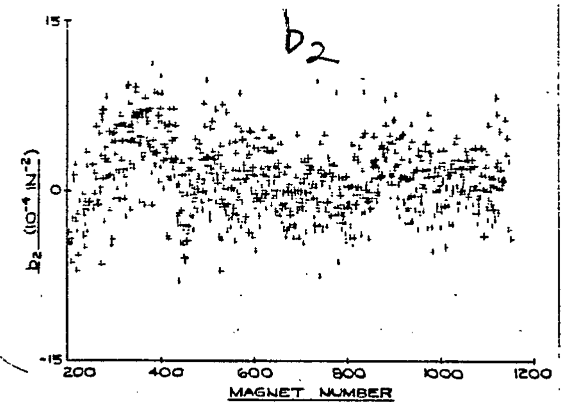

Fig. 3. b_2 coefficient at 4000 A as a function of magnet number (construction date)

during startup of the production line; the underlying construction problems were identified and brought under control after magnet number 410; and as the figure shows, thereafter we were able to maintain the average value of b_2 near zero.

Pole Index n	b_n Design	b_n Mean	b_n RMS	a_n Mean	a_n RMS
1		0.09	0.48	0.17	0.50
2	.04	0.95	3.12	0.10	1.16
3		-0.23	0.77	-0.07	1.46
4	1.04	-0.57	1.32	-0.10	0.46
5		-0.07	0.32	-0.07	0.55
6	4.44	5.48	0.54	-0.07	0.29
7		0.04	0.17	0.22	0.26
8	-12.09	-12.52	0.33	-0.07	0.41
9		0.02	0.23	0.28	0.38
10	3.63	3.70	0.26	0.08	0.25
11		-0.01	0.20	-0.24	0.25
12	-0.82	-0.80	0.19	-0.05	0.22

Table 1 Harmonic coefficients of the magnetic field at 4000 A in standard units for 870 dipoles

In Table 1 we show a table of values of harmonic coefficients at 4000 A excitation up to the 26-pole together with the original design estimates for b_n, n even, made for 4500 A. The n=7 data are artifacts of the data handling procedure.[3] The rms values shown for higher order a_n and b_n, n odd, probably indicate the measurement precision. The widths of the distributions of b_2, a_2, and a_3, which represent real magnet to magnet variation, are relatively large; as a consequence dipoles are assigned locations in the accelerator to reduce undesirable orbit effects that may arise from these field components.[4]

FIELD SHAPE

Another way to characterize the magnetic field is to show B_y/B_o along the x and y axes out to ± 1 inch. Figures 4 and 5 show these distributions. The mean value of B_y/B_o for the sample of 870 dipoles at each x or y is traced by the solid lines, and the dotted lines give a band containing 90% of the magnets.

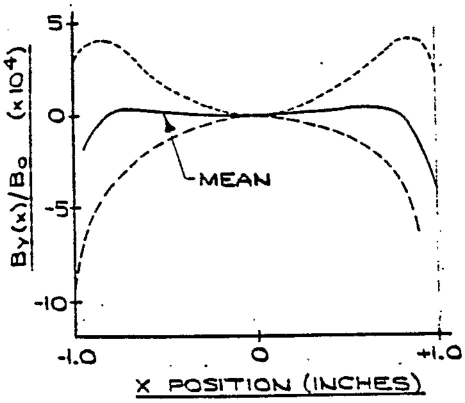

Fig. 4. B_y/B_o as a function of x at y=o

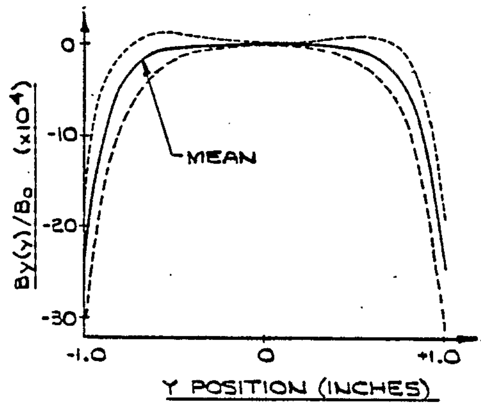

Fig. 5. B_y/B_o as a function of y at x=o

INTEGRAL FIELD

Integral field measurements were made using stretched wire loops at many magnet excitation currents. Figure 6 shows the distribution of normalized field integral at 2000 A magnet excitation as a function of magnet number.

It can be seen that the construction problems that affected b_2 also affected the integral field. These same data are shown as a histrogram in Figure 7;

IEEE, 1983 – Fermilab Dipoles

The Systematic a_1 effect

The systematic a_1 implied by the 1/3 rule gives a large $\Delta\nu$ splitting.

$a_{1,av} = \frac{1}{3}\, a_{1,rms}$ in the dipoles gives a $\Delta\nu$ splitting due to $a_{1,av}$ in the dipoles which is 2 times the $\Delta\nu$ splitting due to $a_{1,rms}$ in the dipoles

Total $\Delta\nu$ splitting, due to both dipoles and quads, is increased by factor 2.4 for $\beta^* = 6$ by the $a_{1,av} = (1/3)\, a_{1,rms}$. This will increase the a_1 correction requirement by about a factor of 2. This probably will increase the number of correction skew quads.

Another possible problem is the residual $\Delta\nu$ splitting after correction due to higher order in a_1 effects. At present it is $\Delta\nu_{splitting} = 15 \times 10^{-3}$ in the worst case. This may be increased by factor 2 by $a_{1,av} = (1/3)\, a_{1,rms}$. However, it is possible that $a_{1,av}$ does not affect the residual ν-splitting

Recommendation: Some way be found to keep $a_{1,av}$ small; $a_{1,av} \lesssim .1\, a_{rms}$ at least!

A possible solution of the problem of $a_{1,AV}$ in the dipoles, suggested by H. Hahn, is to use the skew quads in the arcs to generate an $a_{1,av}$. This would require 4 families of skew quads in each sextant instead of the presently planned 2 families

old → 2-family	1	2	-1	-2	1	2	-1	-2	1	2	-1	-2
	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙	⊙
New 4 family	1	2	3	4	1	2	3	4	1	2	3	4

⊙ indicate QD quads

This can reduce the $a_{1,av}$ in dipoles effect by about factor 5. (The imaginary part of the coupling stopband, about 20% of the Real part, cannot be canceled).

The extra families may also be useful for reducing two effects of the random a_1, the residual ν-splitting and the reduction in dynamic aperture.