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THE RESONANCE CORRECTION SCHEME FOR THE AGS BOOSTER

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ABSTRACT

We describe the resonance correction scheme that will be implemented on the AGS-Booster. This scheme will correct: (1) the quadrupole stop bandwidth resonances $2\nu_x=9$ and $2\nu_y=9$; (2) the skew quadrupole coupling and sum resonances $\nu_x-\nu_y=0$ and $\nu_x+\nu_y=9$; and (3) the sextupole third integer resonances $3\nu_x=13$, $\nu_x+2\nu_y=13$, $3\nu_x=14$ and $\nu_x+2\nu_y=14$. Additionally, the tune and the chromaticity remain unchanged.

The configuration we chose depended partly on the hardware available. That is, 48 quadrupole correctors in each of the main quadrupoles, 24 skew quadrupole correctors located in some of the correction trim coil assemblies and 48 sextupole correctors in each of the main sextupoles. Due to the strength limitations of these correctors the configuration we chose must be as efficient as possible. Since, some of the correction trim coil assemblies were missing (because of injection and extraction requirements, etc.), the location of the skew quadrupole correctors was another constraint. Furthermore, the number of power supplies required must be kept to a minimum to reduce the total cost.

Introduction.

The AGS-Booster is required to accelerate high intensity protons, polarized protons and heavy ions in order to extend the capabilities of the AGS. These requirements lead to a fast cycling machine with a large space charge tune shift, especially with the high intensity protons[1].

This large tune shift can cause particles to cross several second and third order resonances as seen from the tune diagram given in Fig. 1. Thus, in order to reduce the possibility of beam loss, we need to correct the following three classes of resonances: (1) the quadrupole stop bandwidth resonances $2\nu_x=9$ and $2\nu_y=9$; (2) the skew quadrupole coupling and sum resonances $\nu_x-\nu_y=0$ and $\nu_x+\nu_y=9$; and (3) the sextupole third order resonances $3\nu_x=13$, $\nu_x+2\nu_y=13$, $3\nu_x=14$ and $\nu_x+2\nu_y=14$. We do not expect any problems with skew sextupole resonances or resonances that are induced by off momentum particles, however these can be dealt with if it proves necessary after commissioning.

In order to devise a correction scheme, we need to relate the corrector strength with the resonance strength[2-8]. To do this, we define the following functions related to the phase advance:

$$\mu_x(s) = \int_0^s \frac{dt}{\beta_x(t)} - \frac{2\pi}{C}\nu_x s, \qquad \mu_y(s) = \int_0^s \frac{dt}{\beta_y(t)} - \frac{2\pi}{C}\nu_y s$$

where $\beta_x(s)$ and $\beta_y(s)$ are the betatron functions, ν_x and ν_y are the tunes, C is the circumference and s is the azimuthal position in the accelerator. Using a thin lens approximation, the resonance strengths can be approximated as a sum over each corrector strength with coefficients depending on the β and μ functions at the centers of each corrector.

Next, we consider the correctors. The AGS-Booster consist of six superperiods and each superperiod contains eight correction trim coil assemblies of which four of these assemblies will contain the skew quadrupole correctors. Furthermore, each of the Boosters 48 quadrupoles contain trim coils for half integer stop bandwidth correction and the 48 sextupoles contain trim coils for third integer resonance correction. Using these correctors we want to generate resonances that cancels those resonances excited by the errors.

Due to the superperiodicity of the AGS-Booster, the β and μ functions and the lattice are periodic with the azimuth s. Thus, the sums to find the resonance strengths can be simplified. Firstly, we define

$$t_q = t_{(p=1)q}$$

then

$$t_{pq} = t_q + (p-1)C/6$$

which represents the position of the q'th corrector in the p'th superperiod. Secondly, we introduce the coefficients $f_p^{(n)}$ in which

$$K_{pq} = f_p^{(9)} K_q^{(9)},$$

$$M_{pq} = f_p^{(0)} M_q^{(0)} + f_p^{(9)} M_q^{(9)},$$

$$S_{pq} = f_p^{(14)} S_q^{(14)} + f_p^{(13)} S_q^{(13)}$$

are the strengths of the correctors (i.e. quadrupoles, skew quadrupoles and sextupoles respectively) so that the sum over the superperiods, p, can be factored. Separating the sums over the superperiods leads to the following factor

$$\eta(f_p^{(m)}, n) = \sum_{p=1}^{6} f_p^{(m)} e^{i\pi n(p-1)/3} .$$

By choosing $f_p^{(m)} = \cos[m\pi(p-1)/3]$, we can select which harmonics of the resonances we wish to excite (within the alias of the fourier series). Thus, for a given harmonic number, m, we will excite the harmonics $6k\pm m$ for any integer k.

The resonance strengths, given in the next three sections, can now be expressed in terms of "normalized" corrector strengths $K_q^{(n)}$, $M_q^{(n)}$ and $S_q^{(n)}$ for each harmonic, n.

To estimate the maximum corrector strengths required, we used the following model. We simulated the errors as kicks where we assumed a gaussian distribution of errors with a 2.5σ cut, eddy current sextupoles[9] of $.20T/m^2$ (at injection with 200Mev protons) and the main sextupoles corrected the chromaticity to zero in the presence of the eddy current sextupoles.

Quadrupole Resonance Correction.

The strengths for the quadrupole stop bandwidth resonances in terms of the "normalized" corrector strengths (the integrated quadrupole strength/$B\rho$, m^{-1}), $K_q^{(n)}$, are[5]

(*i*) $2\nu_x = 9$

$$A_9 = \frac{i}{4\pi}\,\eta(f_p^{(9)},9)\sum_{q=1}^{8} K_q^{(9)}\beta_x(t_q)e^{i[2\mu_x(t_q)+18\pi t_q/C]},$$

(*ii*) $2\nu_y = 9$

$$B_9 = \frac{i}{4\pi}\,\eta(f_p^{(9)},9)\sum_{q=1}^{8} K_q^{(9)}\beta_y(t_q)e^{i[2\mu_y(t_q)+18\pi t_q/C]},$$

Given the resonance strengths A_9 and B_9, we want to find the "normalized" corrector strengths $K_q^{(9)}$ for q=1,2,3,...,8. Thus we have 4 conditions with 8 unknowns. Gardner has found that the following additional 4 conditions[10]

$$K_1^{(9)}=K_7^{(9)}, \qquad K_2^{(9)}=K_8^{(9)},$$

$$K_3^{(9)}=-K_5^{(9)}, \qquad K_4^{(9)}=-K_6^{(9)}.$$

minimize the corrector strengths required.

Once we find the "normalized" corrector strengths, we can determine actual corrector strengths with $f_p^{(9)}$ given in the following table:

p	$f_p^{(9)}$
1	1
2	-1
3	1
4	-1
5	1
6	-1

Since $f_p^{(9)}$ are either 1 or -1, we can group the quadrupole correctors into four families. Thus, only four power supplies are required as shown in Fig. 2. Furthermore, the tunes are unaffected by the quadrupole correctors and only resonances of the 9'th harmonic and its aliases (i.e. 3rd, 15'th, 21'st, etc.) are excited.

In the control room, a program will be used to solve for the quadrupole corrector strengths, K_{pq}, given the resonance strengths A_9 and B_9. We tested this program on a Booster lattice which contained the following errors

(1) σ=.6mm Horizontal displacements of eddy current sextupoles

(2) σ=.3mm Horizontal displacements of the main sextupoles

(3) σ=.06% Error in the gradients of the main quadrupoles.

From 20 different random seeds we found the worst case tune shifts to be

$$\delta\nu_x \le .00143 \quad \text{and} \quad \delta\nu_y \le .00136$$

Furthermore, we find the limit on the corrector strength over all 20 seeds is

$$|K_{pq}| \le .000218 \ \mathrm{m}^{-1}.$$

A distribution of the maximum corrector strength with random seed is given in Fig. 3 in which

$$|K_{pq}| \le .08\% \text{ of the main quadrupole strength}$$

for .50375m long correctors.

Skew Quadrupole Resonance Correction.

The strengths for the skew quadrupole coupling and sum resonances in terms of the "normalized" corrector strengths (the integrated skew quadrupole strength/Bρ, m^{-1}), $M_q^{(n)}$, are[6]

(*i*) $\nu_x - \nu_y = 0$

$$A_0 = \frac{i}{4\pi}\,\eta(f_p^{(0)},0)\sum_{q=1}^{4} M_q^{(0)}\beta_x^{1/2}(t_q)\beta_y^{1/2}(t_q)e^{i[\mu_x(t_q)-\mu_y(t_q)]},$$

(*ii*) $\nu_x + \nu_y = 9$

$$B_9 = \frac{i}{4\pi}\,\eta(f_p^{(9)},9)\sum_{q=1}^{4} M_q^{(9)}\beta_x^{1/2}(t_q)\beta_y^{1/2}(t_q)e^{i[\mu_x(t_q)+\mu_y(t_q)+18\pi t_q/C]},$$

Given the resonance strengths A_0 and B_9, we want to find the "normalized" skew quadrupole corrector strengths $M_q^{(0)}$ and $M_q^{(9)}$ for q=1,2,3,4. Thus we have four conditions and 8 unknowns. The corrector strengths can be minimized with the following additional 4 conditions

$$M_1^{(0)}=M_7^{(0)}, \qquad M_2^{(0)}=M_8^{(0)},$$

$$M_1^{(9)}=M_7^{(9)}, \qquad M_2^{(9)}=M_8^{(9)}.$$

The skew quadrupole corrector strengths can be found from the "normalized" corrector strengths using $f_p^{(0)}$ and $f_p^{(9)}$ shown in following table:

p	$f_p^{(0)}$	$f_p^{(9)}$
1	1	1
2	1	-1
3	1	1
4	1	-1
5	1	1
6	1	-1

With this choice of $f_p^{(n)}$, the skew quadrupole correctors can be grouped into four families. Two of the families will reside in superperiods 1, 3 and 5 while the other two families will occupy superperiods 2, 4 and 6. Thus, only four power supplies are needed as shown in Fig. 4. Additionally, the correction scheme for $\nu_x-\nu_y=0$ resonance will excite the alias harmonics ..., -12, -6, 6, 12, etc. and the $\nu_x+\nu_y=9$ resonance excites ..., -3, 3, 15, 21, etc. as well.

A program, required in the control room, will be used to calculate the skew quadrupole corrector strengths, M_{pq}, given the resonance strengths A_0 and B_9. We tested this program on a Booster lattice with the following errors

(1) $\sigma = .3$mm Vertical displacements of the main sextupoles

(2) $\sigma = .6$mm Vertical displacements of the eddy current sextupoles

(3) $\sigma = .6$mrad Rotations of the main quadrupoles.

From 20 random seeds, we found the worst case stop-bandwidth to be

$$\delta(\nu_x - \nu_y) \le 3.6\times10^{-3} \quad \text{and} \quad \delta(\nu_x + \nu_y) \le 1.9\times10^{-5}$$

(not necessarily the same random seed). Furthermore, the limit on the strength for this model was found to be

$$|M_{pq}| \le .000414 \text{ m}^{-1}.$$

This model leads to a distribution of corrector strengths over the 20 random seeds tried shown in Fig. 5. For correctors of 20cm length this translates to

$$|M_{pq}| \le .36\% \text{ of the main quadrupole strength.}$$

Sextupole Resonance Correction.

The strengths for the sextupole third integer resonances in terms of the "normalized" corrector strengths (the integrated sextupole strength/Bρ, m^{-2}), $S_q^{(n)}$, are[7]

(*i*) $3\,\nu_x = m$

$$A_m = \frac{i}{48\pi}\,\eta(f_p^{(m)}, m) \sum_{q=1}^{8} S_q^{(m)} \beta_x^{3/2}(t_q) e^{i[3\mu_x(t_q) + 2\pi m t_q / C]},$$

(*ii*) $\nu_x + 2\,\nu_y = m$

$$B_m = \frac{i}{16\pi}\,\eta(f_p^{(m)}, m) \sum_{q=1}^{8} S_q^{(m)} \beta_x^{1/2}(t_q) \beta_y(t_q) e^{i[\mu_x(t_q) + 2\mu_y(t_q) + 2\pi m t_q / C]},$$

where m is either 13 or 14.

Once we know the resonance strengths A_{13}, B_{13}, A_{14} and B_{14} that need to be excited we want to find the required corrector strengths S_{pq}. There are 8 conditions to be satisfied from the 4 resonances and there are 16 unknowns,

$S_q^{(13)}$ and $S_q^{(14)}$ for q=1,2,3,...,8. Hence we need 8 additional conditions in order to find the corrector strengths. Gardner minimized the required corrector strengths, with the following 8 conditions[10]

$$S_1^{(13)}=-S_3^{(13)}, \quad S_2^{(13)}=-S_4^{(13)}, \quad S_5^{(13)}=-S_7^{(13)}, \quad S_6^{(13)}=-S_8^{(13)},$$

$$S_1^{(14)}=-S_3^{(14)}, \quad S_2^{(14)}=-S_4^{(14)}, \quad S_5^{(14)}=-S_7^{(14)}, \quad S_6^{(14)}=-S_8^{(14)}.$$

The required corrector strengths can now be found from the "normalized" corrector strengths with $f_p^{(13)}$ and $f_p^{(14)}$ given in the following table

p	$f_p^{(13)}$	$f_p^{(14)}$
1	1	1
2	1/2	-1/2
3	-1/2	-1/2
4	-1	1
5	-1/2	-1/2
6	1/2	-1/2

With this choice of f_p's, the sextupole correctors can be grouped into 8 families. Four of the families will reside on superperiods 1, 3 and 5 with the half of the strength in superperiods 3 and 5. Similarly, four additional families will reside in superperiods 2, 4 and 6 with half of the strength in superperiods 2 and 6. Thus, we need 8 power supplies (with the capability of driving some of the correctors at half the strength) for this sextupole corrector scheme as shown in Fig. 6. Additionally, the chromaticity remains unchanged. Note, this correction will excite the following alias harmonics:

(*i*) Harmonic 13

...., -5, -1, 1, 5, 7, 11, 17, 19, ...

(*ii*) Harmonic 14

...., -4, -2, 2, 4, 8, 10, 16, 20, ...

A program, that will be used in the control room, will calculate the sextupole corrector strengths, S_{pq}, given the resonance strengths A_{13}, B_{13}, A_{14} and B_{14}. To test this program, we simulated random sextupoles in the AGS-Booster with the following errors

(1) $\sigma=4\%$ of the systematic eddy current sextupole strengths

(2) $\sigma=.04\%$ of the main sextupoles strengths

After trying 20 different random seeds we found the worst case stop bandwidths to be

(*i*) Harmonic 13

$$\delta(3\nu_x)\le 4.86\times 10^{-4} \quad \text{and} \quad \delta(\nu_x+2\nu_y)\le 6.84\times 10^{-4}$$

(*ii*) Harmonic 14

$$\delta(3\nu_x)\le 6.01\times 10^{-4} \quad \text{and} \quad \delta(\nu_x+2\nu_y)\le 9.29\times 10^{-4}$$

Additionally, the the maximum strength required for correcting all of the above cases is

$$|S_{pq}| \le .0162 \text{ m}^{-2}.$$

A distribution of the strengths from this model is given in Fig. 7. This leads to (for 10cm long correctors)

$$|S_{pq}| \le 3.5\% \text{ of the main sextupole strengths.}$$

Conclusion

We present a scheme for correcting: (1) half integer stop bandwidth resonances excited by stray quadrupole fields; (2) sum and coupling resonances excited by stray skew quadrupole fields; and (3) third integer stop bandwidth resonances excited by stray sextupole fields. This scheme has gone through several iterations in order to meet the current hardware configuration requirements of the AGS-Booster.

As the Booster progresses toward commissioning there will be advances (such as direct correction of the eddy current sextupoles[9], etc.) which may have implications that lead to some further adjustments to the above scheme before it is finally implemented.

References

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[9] Booster Design Manual, (Rev. 1, October 1988)

[10] C. J. Gardner, "Effective Placement of Stopband Correction Elements in an AGS Lattice", AD Tech Note, AGS/AD/Tech. Note No. 321

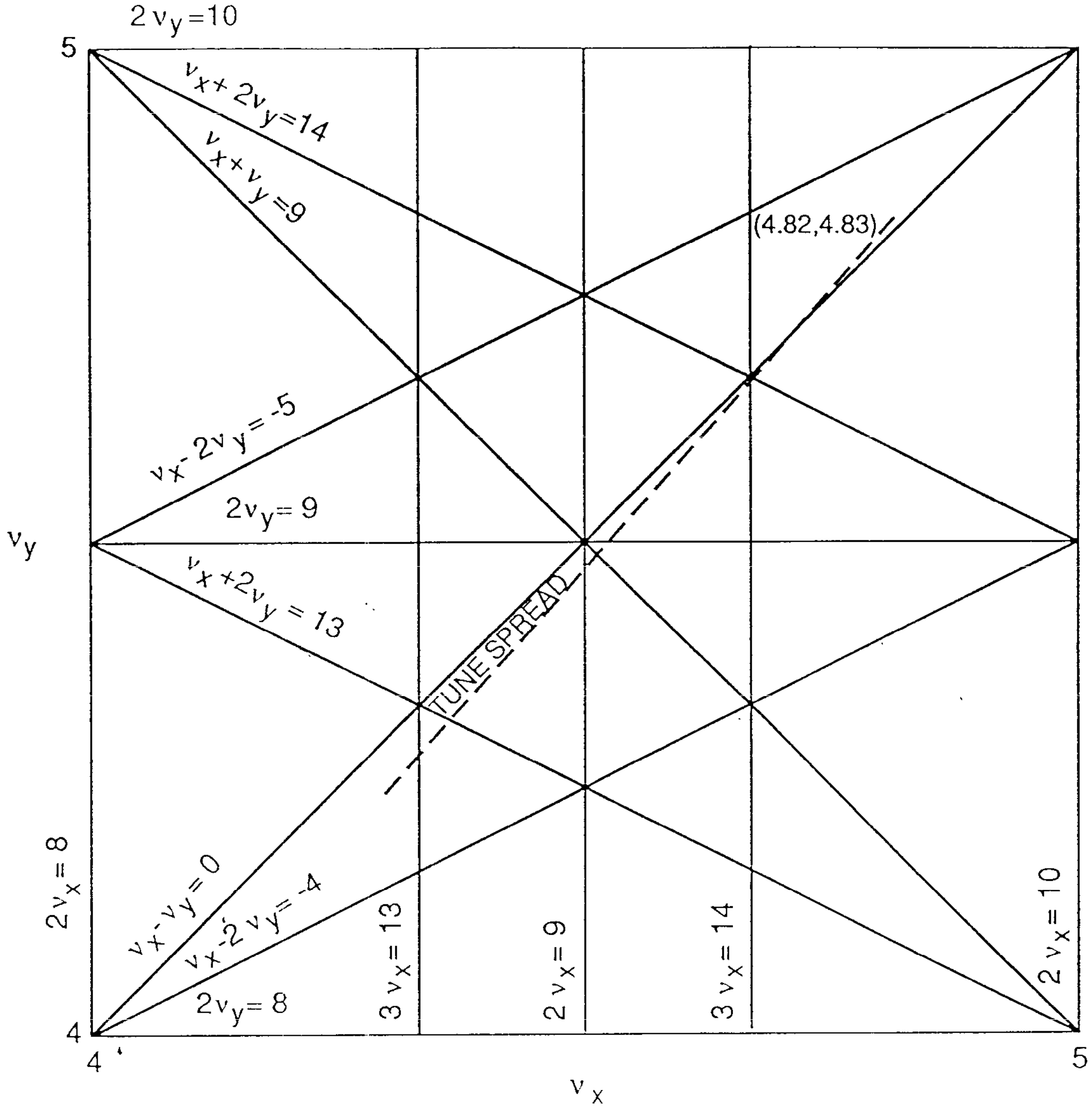

Fig. 1. The Tune diagramm with the expected tune spread from space charge[1]

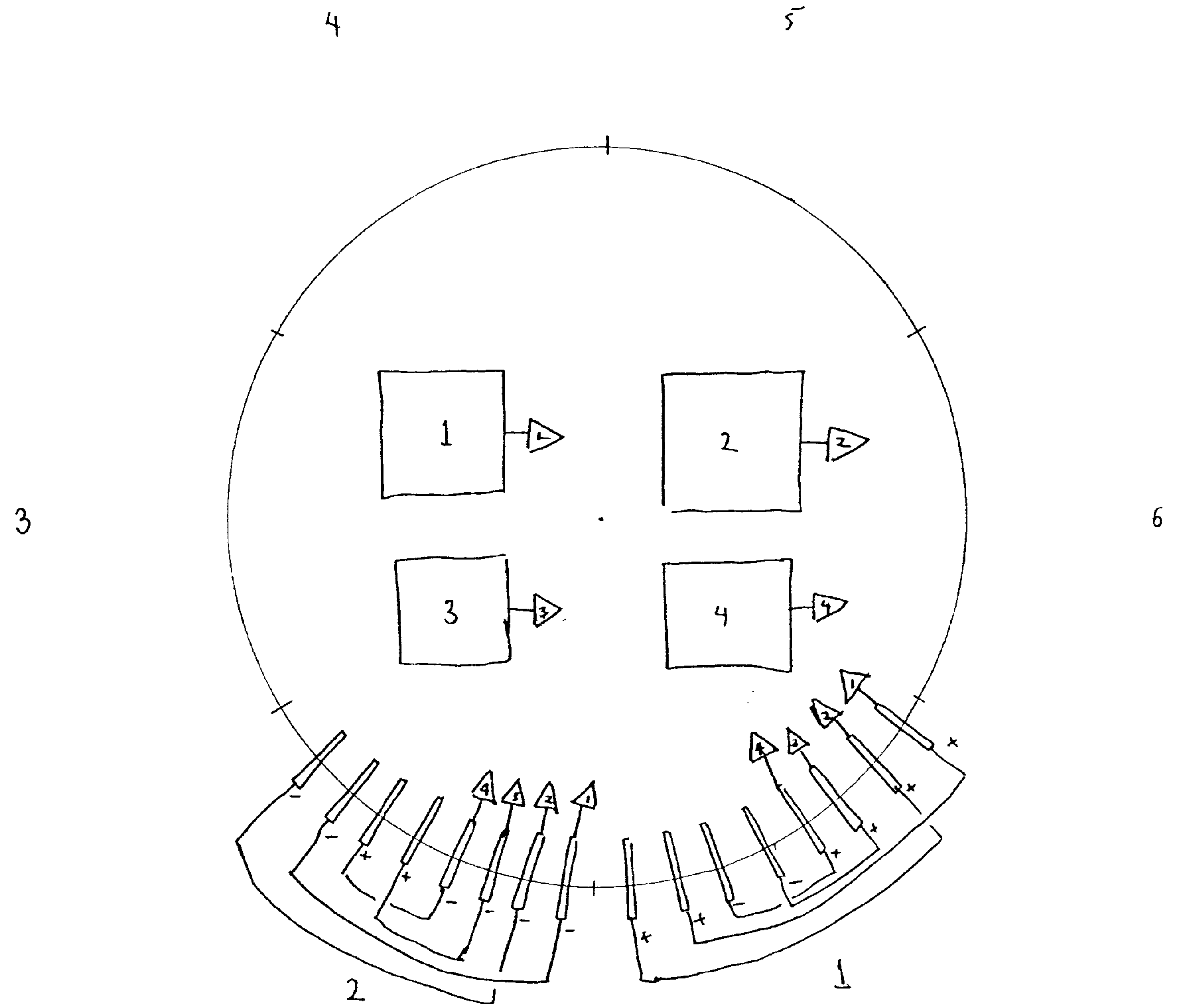

Fig 2. Power supply configuration for the Quadrupole correctors. Note, superperiod pairs (3,4) and (5,6) are identical to (1,2). The + and − signs indicate the direction of current through the coils.

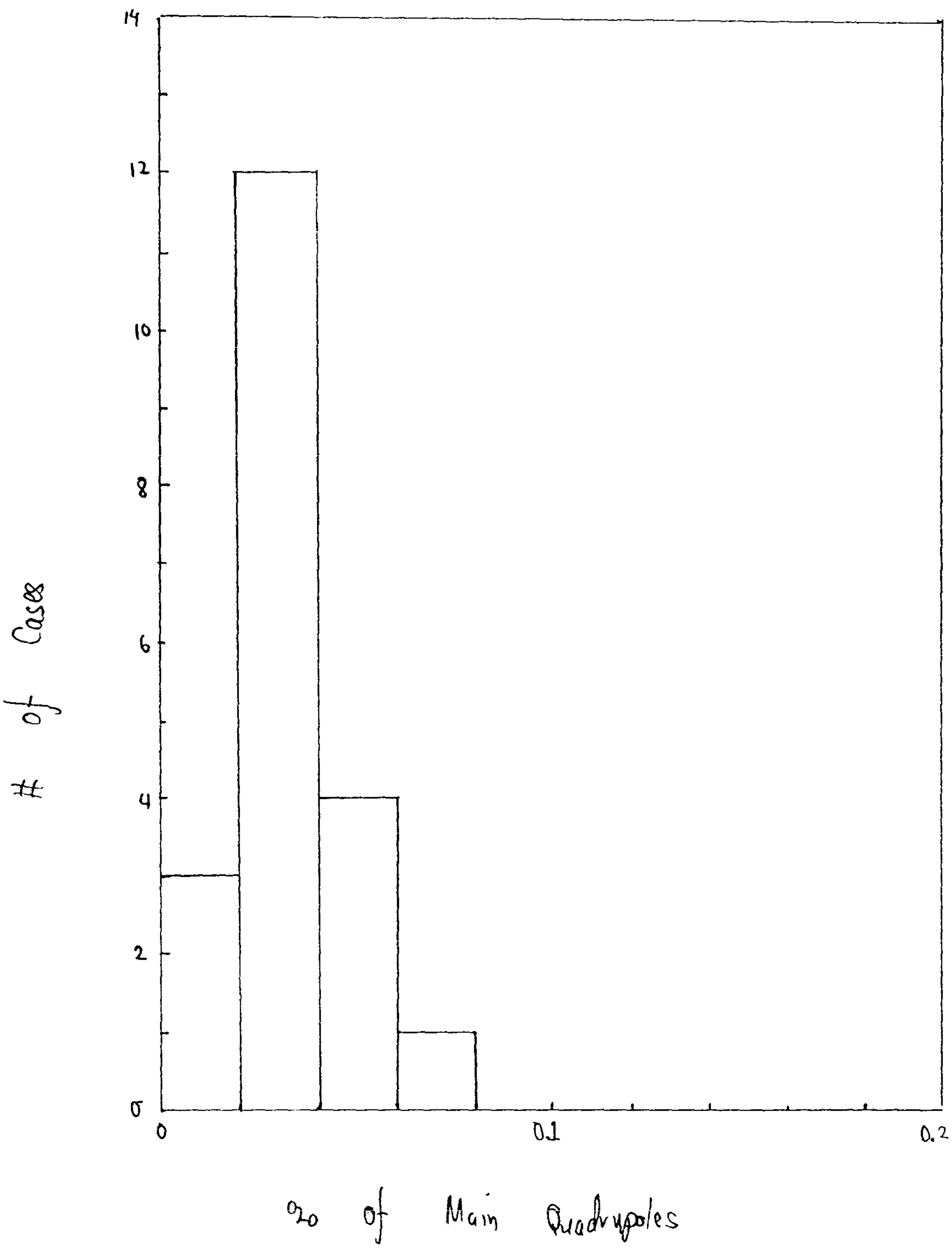

Fig. 3 The distribution of the maximum corrector strength against the number of cases for the quadrupole correctors.

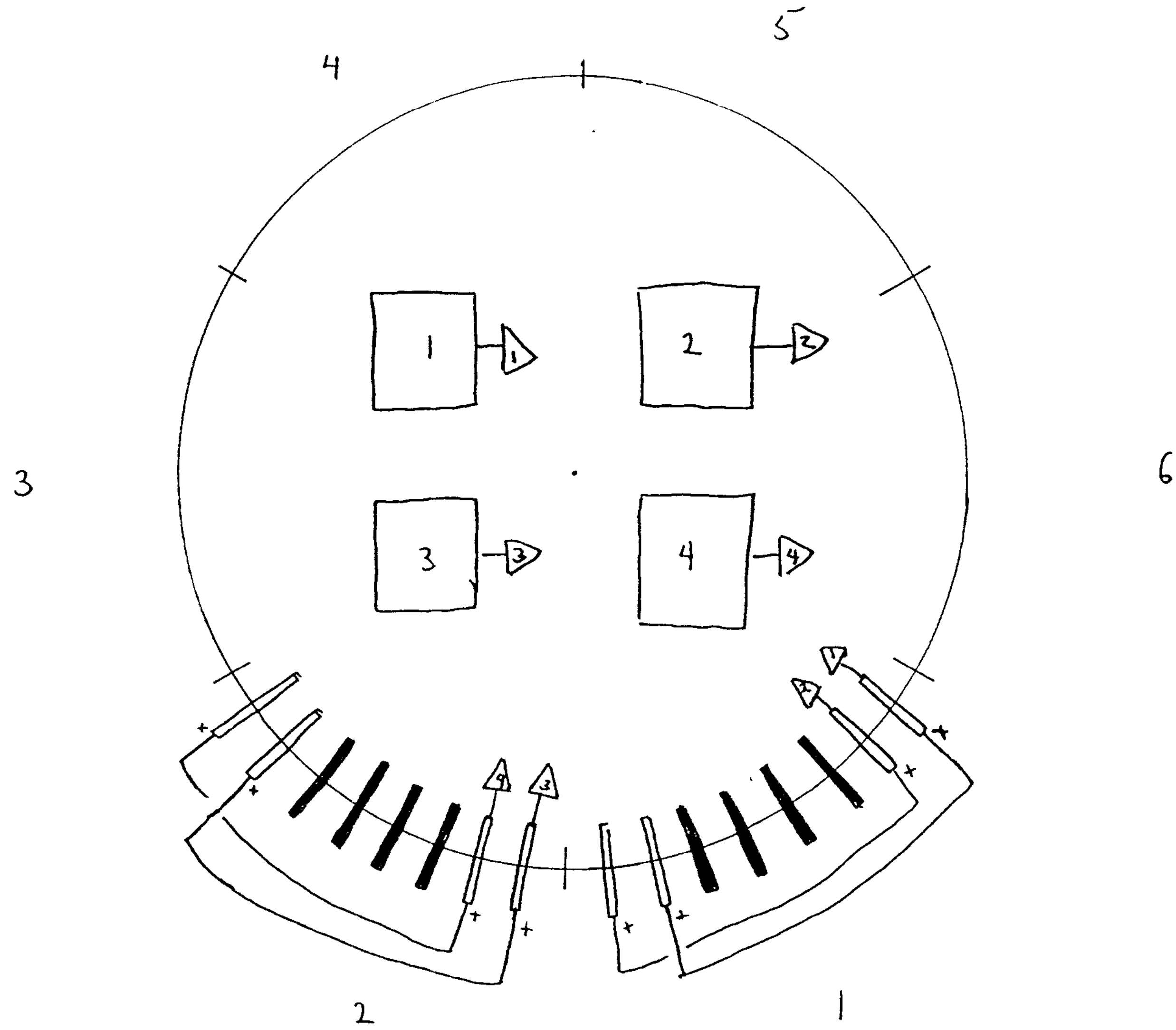

Fig. 4 The power supply configuration for the skew quadrupole correctors. Note, superperiods pairs (3, 4) and (5, 6) are connected identically as (1, 2). The + and − signs indicate the direction of current through the coils. Additionally, there are only 4 skew quadrupole correctors per superperiod.

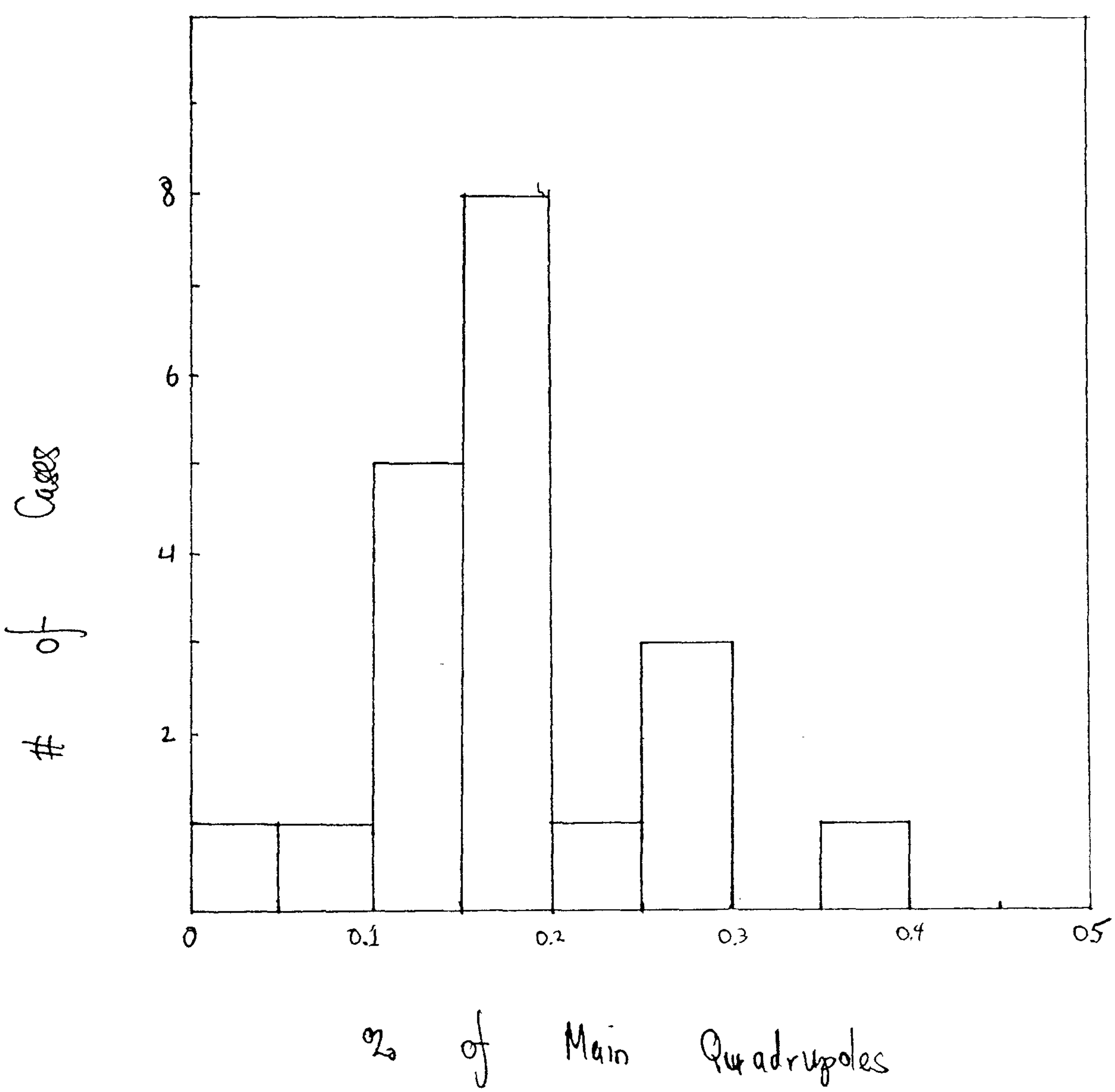

Fig. 5. The distribution of the maximum skew quadrupole corrector strength over the 20 cases tried.

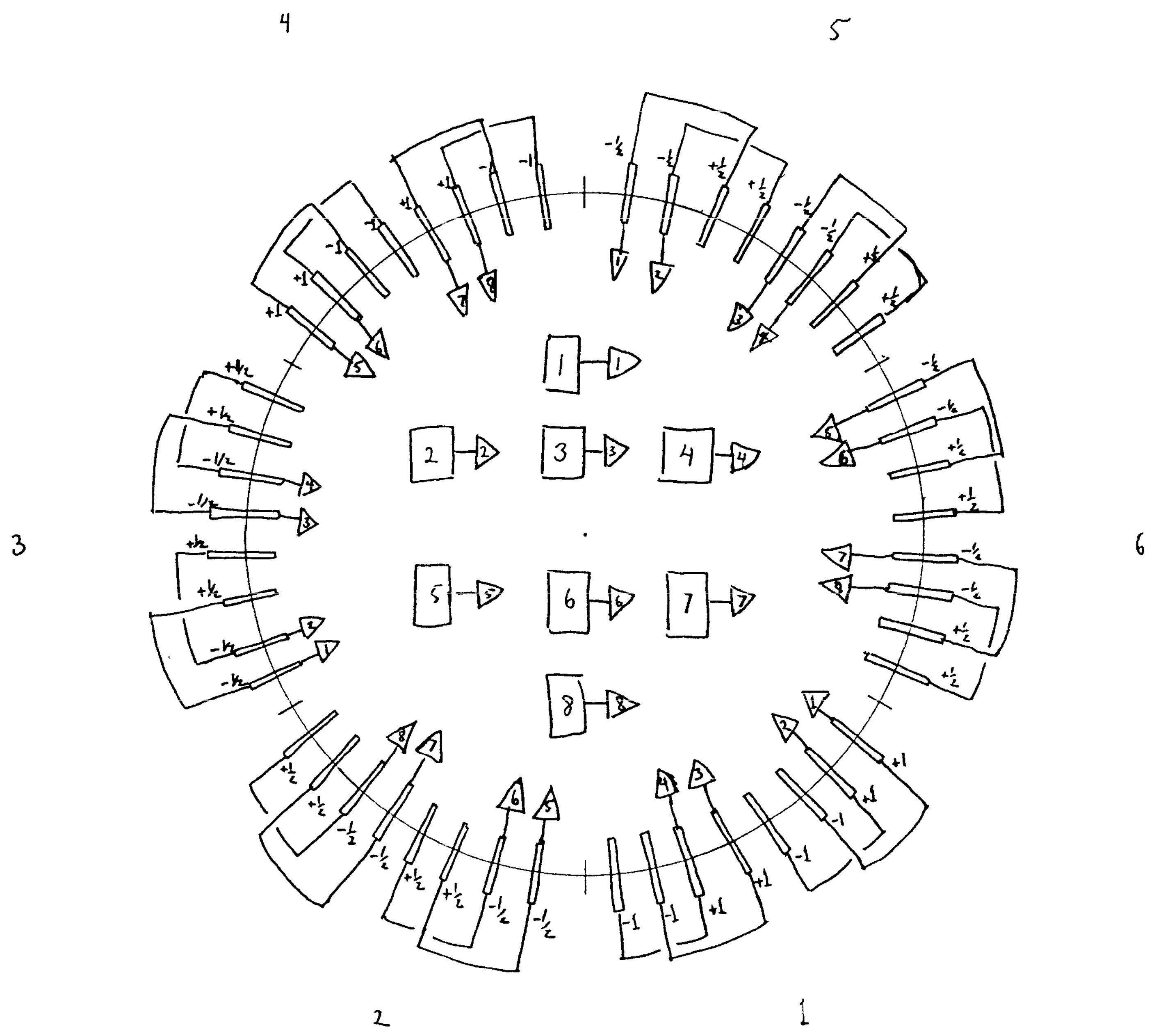

Fig. 6 The power supply configuration for the sextupole correctors. Note, some of the correctors are powered at ½ the strength.

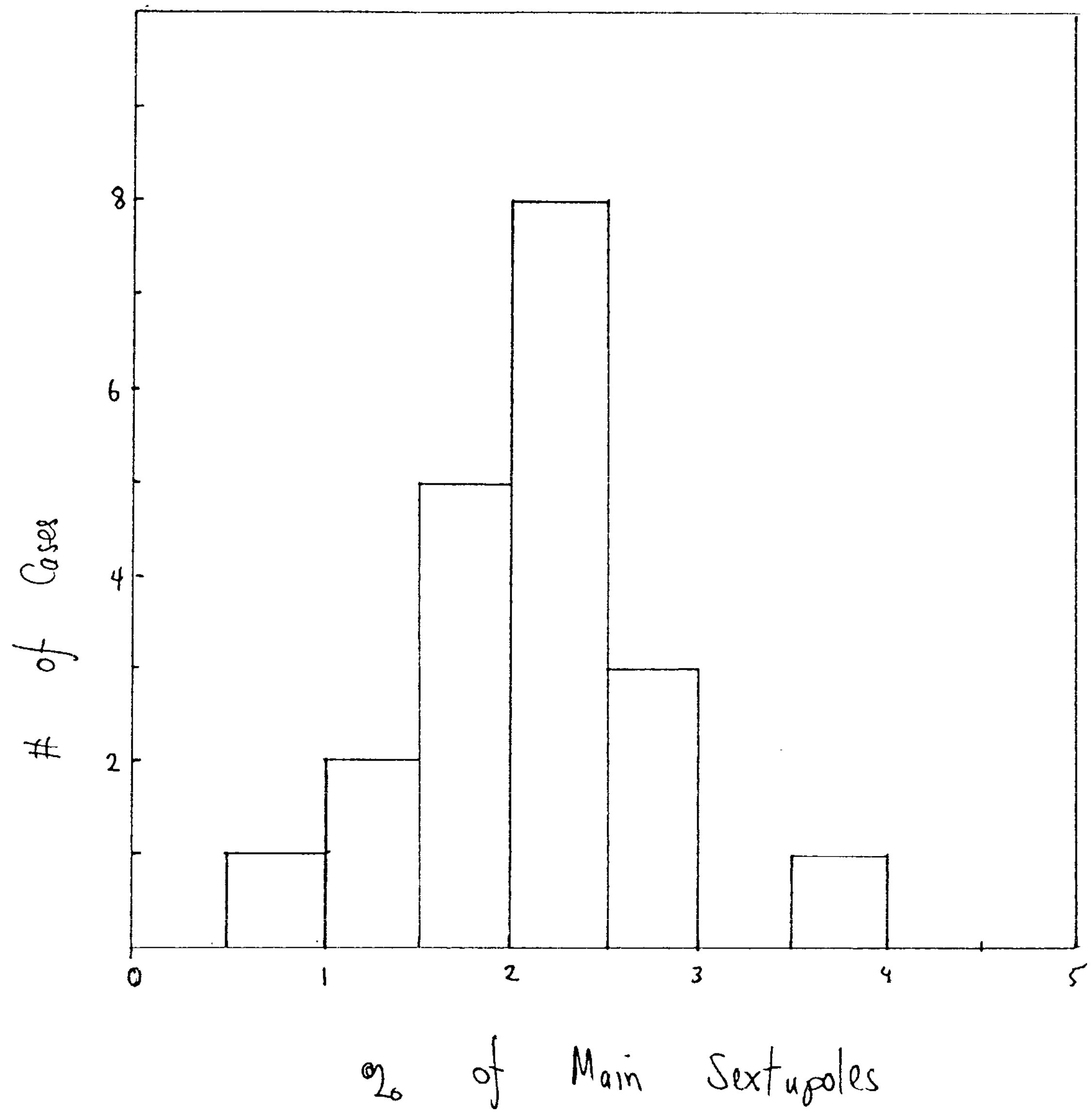

Fig. 7 The distribution of the maximum sextupole corrector strengths over the 20 cases tried