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Resonance Correction for the SSC–LEB

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ABSTRACT

The SSC–LEB is a fast cycling low energy booster for the SSC complex. It will have a large space charge tune spread causing the beam to cross several imperfection resonances. Because of the eddy current sextupoles, some of these imperfection resonances may be strong. We propose a scheme for resonance correction in the SSC–LEB and estimate the strength of the correctors required. We find the strength of the quadrupole correctors, $\langle B'\ell/B\rho\rangle_{rms} \leq 0.00043$ m^{-1}; skew quadrupole correctors, $\langle B'\ell/B\rho\rangle_{rms} \leq 0.00055$ m^{-1}; sextupole correctors, $\langle B''\ell/B\rho\rangle_{rms} \leq 0.0025$ m^{-2} and skew sextupole correctors, $\langle B''\ell/B\rho\rangle_{rms} \leq 0.00063$ m^{-2}.

Introduction

The low energy booster for the SSC, denoted SSC–LEB, will accelerate protons from 0.6 GeV to 11 GeV (or alternatively from 1 GeV to 11 GeV). In order to meet the SSC requirements, the SSC–LEB will be fast cycling. These as well as other requirements lead to the following proposed lattice[1] for the SSC–LEB consisting of 112 degree cells, 9 cells per superperiod with 4 missing dipoles and 6 superperiods. The operating tunes are $\nu_x = 16.85$ and $\nu_y = 16.75$. Additionally, this lattice will have a large space charge tune spread[2] of $\Delta\nu_x$, $\Delta\nu_y \simeq -0.4$ and strong nominal eddy current sextupoles[3] of $b_2 \simeq 0.156$ m^{-2}.

Due to the large tune spread several imperfection resonances may be crossed. Furthermore, the strong eddy current sextupoles may excite strong imperfection resonances. These imperfection resonances must be corrected to reduce beam loss. We propose a resonance correction scheme that will correct the imperfection resonances crossed in the tune diagram shown in Fig. 1. The resonances to be corrected are:

(i) Quadrupole

$$2\nu_x = 33$$

$$2\nu_y = 33$$

[1] H. Foelsche and Y.Y. Lee, private communication.

[2] G. Parzen, "Space Charge Effects in the Low Energy Booster", BNL Report, AD/AP–17 (1990).

[3] S.Y. Lee, private communication.

(ii) Skew Quadrupole

$$\nu_x + \nu_y = 33$$

(iii) Sextupole

$$3\nu_x = 50$$

$$\nu_x + 2\nu_y = 50$$

(iv) Skew Sextupole

$$3\nu_y = 50$$

$$\nu_y + 2\nu_x = 50$$

We do not anticipate the need to correct the imperfection resonances excited by the higher order multipoles (i.e., octupoles, dodecapoles, etc.) in the SSC–LEB. Furthermore, a more careful analysis will be required to determine whether any resonances induced by off–momentum particles will need to be corrected.

In the next section we derive the resonance strengths as a function of the correctors and errors. Following this, we consider the placement of correctors in the SSC–LEB and give the strategy to determine the corrector strengths. Finally, we estimate the maximum strength required by the correctors and give a conclusion.

Theory

We assume, the particles motion can be determined using the following Hamiltonian[4,5]

$$H = \frac{p_x^2}{2} + \frac{p_y^2}{2} + \left[K(s) + \frac{1}{\rho^2(s)}\right]\frac{x^2}{2} - K(s)\frac{y^2}{2} + \\ + M(s)xy + \frac{S_R(s)}{6}(x^3 - 3xy^2) + \frac{S_S(s)}{6}(y^3 - 3yx^2)$$

where x and y are the transverse coordinates of the particles; p_x and p_y are the conjugate momenta; s is the independent variable (i.e. the azimuth along the accelerator); $\rho(s)$ is the radius of curvature due to dipole fields; $K(s)$ and $M(s)$ are the regular and skew quadrupole strengths; and $S_R(s)$ and $S_S(s)$ are regular and skew sextupole strengths.

[4] H. Goldstein, Classical Mechanics, (Addison–Wesley Publishing Company, 1965).

[5] E. Courant and H. Snyder, "Theory of the Alternating Gradient Synchrotron", Ann. Phys. 3, 1 (1958).

In order to find the resonance strengths we must perform two canonical transformations on the Hamiltonian.[4–6] The first, converts the Hamiltonian to action–angle variables denoted as (J_x, Φ_x) and (J_y, Φ_y). This can be done with the following generation function

$$F(x, y, \Phi_x, \Phi_y, s) = -\frac{x^2}{2\beta_x(s)}\left[\tan\Phi_x - \frac{\beta_x'(s)}{2}\right] - \frac{y^2}{2\beta_y(s)}\left[\tan\Phi_y - \frac{\beta_y'(s)}{2}\right]$$

where primes denote d/ds and $\beta_x(s)$ and $\beta_y(s)$ are solutions of

$$1 = \frac{\beta_x(s)\beta_x''(s)}{2} - \frac{\left[\beta_x'(s)\right]^2}{4} + \left[K(s) + \frac{1}{\rho^2(s)}\right]\beta_x^2(s)$$

$$1 = \frac{\beta_y(s)\beta_y''(s)}{2} - \frac{\left[\beta_y'(s)\right]^2}{4} - K(s)\beta_y^2(s) \quad .$$

From the generating function we find

$$x = \sqrt{2J_x\beta_x} \quad \cos\Phi_x$$
$$y = \sqrt{2J_y\beta_y} \quad \cos\Phi_y \quad .$$

Note, the emittances of the beam, $E_x = 2\pi J_x$ and $E_y = 2\pi J_y$, are proportional to the actions. If there are no non–linearities present then the emittances (as well as the actions) are invariants of the motion.[5]

From the generating function F, the new Hamiltonian becomes:

$$\begin{aligned} H_1 = {} & \frac{J_x}{\beta_x} + \frac{J_y}{\beta_y} + \delta K(J_x\beta_x\cos^2\Phi_x - J_y\beta_y\cos^2\Phi_y) + \\ & + 2M\sqrt{J_xJ_y\beta_x\beta_y}\cos\Phi_x\cos\Phi_y + \frac{S_R}{3}\sqrt{2J_x\beta_x} \\ & (J_x\beta_x\cos^2\Phi_x - 3J_y\beta_y\cos^2\Phi_y)\cos\Phi_x + \frac{S_S}{3}\sqrt{2J_y\beta_y} \\ & (J_y\beta_y\cos^2\Phi_y - 3J_x\beta_x\cos^2\Phi_x)\cos\Phi_y \end{aligned}$$

where δK consists of the quadrupoles corrector field strengths and the stray quadrupole fields.

A second canonical transformation is required to eliminate the time dependence in the first two terms of H_1. We do this with the following generating function

$$G(\Phi_x, \Phi_y, I_x, I_y, s) = I_x(\Phi_x - \mu_x(s)) + I_y(\Phi_y - \mu_y(s))$$

[6] R.D. Ruth, "Single–Particle Dynamics in Circular Accelerators", (SLAC Summer School 1985), AIP Conference Proceedings, 153, 150–235 (1987).

where I_x and I_y are the new action variables

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

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

and

$$\nu_x = \frac{1}{2\pi}\int_0^C \frac{dt}{\beta_x(t)} \quad , \quad \nu_y = \frac{1}{2\pi}\int_0^C \frac{dt}{\beta_y(t)}$$

with C being the circumference of the accelerator. Note, $\mu_x(s)$ and $\mu_y(s)$ are periodic functions of s with periods of C/P where P is the periodicity of the lattice.

The new action–angle variables are related to the old variables as follows:

$$\begin{aligned} I_x &= J_x \quad , & I_y &= J_y \\ \Psi_x &= \Phi_x - \mu_x(s) \quad , & \Psi_y &= \Phi_y - \mu_y(s) \quad . \end{aligned}$$

where Ψ_x and Ψ_y are the new angle variables.

The transformed Hamiltonian, H_2, becomes

$$\begin{aligned} H_2 = \frac{2\pi}{C}\Bigg\{ & \nu_x I_x + \nu_y I_y + 2Re\Bigg[\sum_{n=-\infty}^{\infty}[2I_x(A_{1n}e^{i2\Psi_x} + A_{2n}) + \\ & + 2I_y(A_{3n}e^{i2\Psi_y} + A_{4n}) + 2\sqrt{I_x I_y}(A_{5n}e^{i(\Psi_x+\Psi_y)} + \\ & + A_{6n}e^{i(\Psi_x-\Psi_y)}) + (2I_x)^{3/2}(A_{7n}e^{i3\Psi_x} + 3A_{8n}e^{i\Psi_x}) + \\ & + 2\sqrt{2I_x}I_y(A_{9n}e^{i(\Psi_x+2\Psi_y)} + 2A_{10n}e^{i\Psi_x} + A_{11n}e^{i(\Psi_x-2\Psi_y)}) + \\ & + (2I_y)^{3/2}(A_{12n}e^{i3\Psi_y} + 3A_{13n}e^{i\Psi_y}) + 2\sqrt{2I_y}I_x \\ & (A_{14n}e^{i(\Psi_y+2\Psi_x)} + 2A_{15n}e^{i\Psi_y} + A_{16n}e^{i(\Psi_y-2\Psi_x)})] \\ & e^{-i2\pi ns/C}\Bigg]\Bigg\} \end{aligned}$$

where

$$A_{1n} = \frac{1}{8\pi}\int_0^C \delta K(t)\beta_x(t)e^{i[2\mu_x(t)+2\pi nt/C]}dt$$

$$A_{2n} = \frac{1}{8\pi}\int_0^C \delta K(t)\beta_x(t)e^{i\ 2\pi nt/C}dt$$

$$A_{3n} = \frac{1}{8\pi}\int_0^C \delta K(t)\beta_y(t)e^{i[2\mu_y(t)+2\pi nt/C]}dt$$

$$A_{4n} = \frac{1}{8\pi}\int_0^C \delta K(t)\beta_y(t)e^{i\ 2\pi nt/C}dt$$

$$A_{5n} = \frac{1}{4\pi}\int_0^C M(t)\sqrt{\beta_x(t)\beta_y(t)}e^{i[\mu_x(t)+\mu_y(t)+2\pi nt/C]}dt$$

$$A_{6n} = \frac{1}{4\pi}\int_0^C M(t)\sqrt{\beta_x(t)\beta_y(t)}e^{i[\mu_x(t)-\mu_y(t)+2\pi nt/C]}dt$$

$$A_{7n} = \frac{1}{48\pi}\int_0^C S_R(t)\beta_x^{3/2}(t)e^{i[3\mu_x(t)+2\pi nt/C]}dt$$

$$A_{8n} = \frac{1}{48\pi}\int_o^C S_R(t)\beta_x^{3/2}(t)e^{i[\mu_x(t)+2\pi nt/C]}dt$$

$$A_{9n} = \frac{1}{16\pi}\int_0^C S_R(t)\beta_x^{1/2}(t)\beta_y(t)e^{i[\mu_x(t)+2\mu_y(t)+2\pi nt/C]}$$

$$A_{10n} = \frac{1}{16\pi}\int_0^C S_R(t)\beta_x^{1/2}(t)\beta_y(t)e^{i[\mu_x(t)+2\pi nt/C]}dt$$

$$A_{11n} = \frac{1}{16\pi}\int_0^C S_R(t)\beta_x^{1/2}(t)\beta_y(t)e^{i[\mu_x(t)-2\mu_y(t)+2\pi nt/C]}dt$$

$$A_{12n} = \frac{1}{48\pi}\int_0^C S_S(t)\beta_y^{3/2}(t)e^{i[3\mu_y(t)+2\pi nt/C]}dt$$

$$A_{13n} = \frac{1}{48\pi}\int_0^C S_S(t)\beta_y^{3/2}(t)e^{i[\mu_y(t)+2\pi nt/C]}dt$$

$$A_{14n} = \frac{1}{16\pi}\int_0^C S_S(t)\beta_x(t)\beta_y^{1/2}(t)e^{i[\mu_y(t)+2\mu_x(t)+2\pi nt/C]}dt$$

$$A_{15n} = \frac{1}{16\pi}\int_0^C S_S(t)\beta_x(t)\beta_y^{1/2}(t)e^{i[\mu_y(t)+2\pi nt/C]}dt$$

$$A_{16n} = \frac{1}{16\pi}\int_0^C S_S(t)\beta_x(t)\beta_y^{1/2}(t)e^{i[\mu_y(t)-2\mu_x(t)+2\pi nt/C]}dt$$

are the resonance strengths, except A_{2n} and A_{4n} which leads to tune shifts.

The goal is to include a system of correctors such that the appropriate resonance strengths, A_{kn}, are brought to zero to reduce beam loss. This can be done by using the correctors to excite resonance strengths that are opposite those excited by the errors. In the next section we propose a correction scheme for the SSC–LEB lattice that can excite $A_{1,33}$, $A_{3,33}$, $A_{5,33}$, $A_{7,50}$, $A_{9,50}$, $A_{12,50}$ and $A_{14,50}$ resonance strengths.

The Correction Scheme

In order to devise a correction scheme, we must first decide where we can physically put the correctors inside the machine. One approach, (patterned after the AGS–Booster[7]) is to place the quadrupole correctors as trim coils in the main quadrupoles, the sextupole correctors as trim coils in the main sextupoles and the skew quadrupole and skew sextupole correctors on a correction trim coil assembly next to the quadrupoles.

This leaves us with up to 18 quadrupole correctors per superperiod of which we will use 16. Similarly we will use 16 sextupole correctors. Finally, we assume the correction trim coil assembly will be a separated function magnet with respect to the skew quadrupole, and skew sextupole correctors (but may be combined with the orbit correction dipole kickers as in the AGS–Booster[7]). Hence, we choose 8 skew quadrupole and 8 skew sextupole correctors per superperiod.

We can relate the corrector strengths to the resonance strengths by approximating the integrals, given in the previous section, with the thin lens approximation. For the $2\nu_x = n$ resonance (i.e. A_{1n} integral) we have

$$A_{1n} = \frac{1}{8\pi}\sum_{p=1}^{6}\sum_{q=1}^{16} K_{pq}\beta_x(t_{pq})e^{i[2\mu_x(t_{pq})+2\pi n t_{pq}/C]}$$

where K_{pq} is the integrated quadrupole strength of the q'th corrector in the p'th superperiod and t_{pq} is the azimuth at the center of this corrector.

The sum over the superperiods can be factored by defining

$$K_{pq} = f_p K_q$$

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

and

[7] "Booster Design Manual," BNL Report No. 27, 1988.

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

where K_q are the normalized corrector strengths. Then we have

$$A_{1n} = \frac{1}{8\pi}\eta(f_p, n)\sum_{q=1}^{16} K_q \beta_x(t_q) e^{i[2\mu_x(t_q)+2\pi n t_q/C]}$$

where

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

The choice of the f_p parameters determines which harmonics n, this corrector system excites. For example, $f_p^{(m)} = \cos[\pi m(p-1)/3]$ would excite only the harmonics $n = 6k \pm m$ where k is an arbitrary integer.

Similarly, the $2\nu_y = n$ resonances are excited with the resonance strength.

$$A_{3n} = \frac{1}{8\pi}\eta(f_p, n)\sum_{q=1}^{16} K_q \beta_y(t_q) e^{i[2\mu_y(t_q)+2\pi n t_q/C]} \ .$$

Choosing $f_p = \cos[11\pi(p-1)]$, we can excite $2\nu_x = 33$ and $2\nu_y = 33$ plus the following alias harmonics

$$\ldots 15 \ \ 21 \ \ 27 \ldots 39 \ \ 45 \ \ 51 \ldots$$

which shouldn't cause any trouble.

Next, we must find the strengths of the normalized correctors strengths K_q so that we excite the resonance strengths $A_{1,33}$ and $A_{3,33}$. Since we have 16 unknowns of K_q and 4 conditions to satisfy we need an additional 12 conditions. These conditions should be chosen to minimize the strength requirements of the K_q.[8] By examining the angles ($\phi_q = 2\pi t_q/C$) for each corrector, shown in Table 1, we choose the following 12 conditions

$$K_1 = K_4 = K_{11} = K_{14}$$

$$K_2 = K_5 = K_{15} = K_{18}$$

$$K_6 = K_9 = K_{16} = K_{17}$$

$$K_3 = K_7 = K_{10} = K_{13} \ .$$

[8] C.J. Gardner, "Effective Placement of Stopband Correction Elements in an AGS Lattice," BNL Report, AGS/AD/Tech. Note 321.

Fig. 2 shows the resulting configuration.

The other correctors can be treated in the same way. The skew quadrupole resonance excites the harmonic 33 with resonance strength $A_{5,33}$. This harmonic is the same as

Table 1

Location	ϕ_q	$33\phi_q$	$50\phi_q$
1	0	0	0
2	3.33	110	116.7
3	6.67	220	333.3
4	10.	330	140
5	13.33	80	306.7
6	16.67	190	113.3
7	20	300	280
8	23.33	50	86.7
9	26.67	160	253.3
10	30	270	60
11	33.33	20	226.7
12	36.67	130	33.3
13	40.	240	200
14	43.33	350	6.7
15	46.67	100	173.3
16	50	210	340
17	53.33	320	146.7
18	56.67	70	313.3

for the quadrupole case leading to the same f_p and alias harmonics. Thus, we have 2 conditions with 8 unknowns. From Table 1 we choose the following 6 conditions

$$M_2 = M_5 = M_{12} = M_{18}$$

$$M_3 = M_{10} = M_{16} = M_{17} \quad .$$

Fig. 3 shows the skew quadrupole corrector configurations.

Additionally, we must correct the resonances excited by the sextupole fields. The resonance strengths are $A_{7,50}$ and $A_{9,50}$, leading to 4 conditions. Here we have chosen $f_p = \cos[50\pi(p-1)/3]$ which has the following values:

Table 2

p	f_p
1	1
2	-1/2
3	-1/2
4	1
5	-1/2
6	-1/2

This configuration excites the following alias harmonics

$$\ldots 28 \;\; 32 \;\; 34 \;\; 38 \;\; 40 \;\; 44 \;\; 46 \ldots 52 \;\; 56 \;\; 58 \;\; 62 \;\; 64 \;\; 68 \;\; 70 \ldots$$

We may have to be careful with the alias harmonics 32 and 34, since off momentum particles can induce quadrupoles like resonances. However, we don't expect this to be a problem.

Since there are 16 unknowns and 4 conditions we require 12 additional conditions. From Table 1 we choose

$$S_{R_1} = S_{R_3} = S_{R_{14}} = S_{R_{16}}$$

$$S_{R_4} = S_{R_6} = S_{R_8} = S_{R_{10}}$$

$$S_{R_2} = S_{R_{13}} = S_{R_{15}} = S_{R_{17}}$$

$$S_{R_5} = S_{R_7} = S_{R_9} = S_{R_{18}}$$

Fig. 4 shows the sextupole corrector configuration.

Finally, there are two skew sextupole resonances that we plan to correct, $A_{12,50}$ and $A_{14,50}$. We use the same f_p as with the sextupole correctors, which excites the same alias harmonics. There are 8 skew sextupole correctors and 4 conditions to satisfy. Using Table 1 we choose the following 4 additional conditions:

$$S_{S_1} = S_{S_{14}} \qquad S_{S_{13}} = S_{S_{15}}$$
$$S_{S_6} = S_{S_8} \qquad S_{S_7} = S_{S_9} \;\; .$$

Fig. 5 shows the resulting skew sextupole corrector configuration.

Corrector Strengths

To estimate the corrector strengths we use the following identity

$$R = R_c + R_e$$

where R is the total resonance strength, R_c is the resonance strength excited by the correctors and R_e is the resonance strength excited by the errors.

If the correctors are chosen properly then R is brought to zero leaving

$$R_c = -R_e$$

or

$$\sum_i \ell_i C_i \beta_x^{m/2}(t_i)\beta_y^{n/2}(t_i)e^{ip\phi_i} = -\sum_j \overline{\ell}_j E_j \beta_x(\overline{t}_j)\beta_y^{n/2}(\overline{t}_j)e^{ip\overline{\phi}_j}$$

where $\ell_i C_i$ are the integrated corrector strengths, t_i represents the corrector azimuths, ϕ_i gives the angles at the correctors, $\overline{\ell}_j E_j$ are integrated stray field strengths, $\overline{t}_j$ are the azimuths of the stray fields and $\overline{\phi}_j$ are the angles at the stray fields. The resonance being corrected is $m\nu_x + n\nu_y = p$.

The strengths of the correctors can be estimated from the strengths of the error fields using Parseval's identity.[9] However, since ϕ_i or $\overline{\phi}_j$ are not necessarily equally spaced, the summations are not necessarily a fourier series. Thus, Parseval's identity gives only an approximation to the strengths required, leading to

$$\sum_i \ell_i^2 C_i^2 \beta_x^m(t_i)\beta_y^n(t_i) \simeq \sum_j \overline{\ell}_j^2 E_j^2 \beta_x^m(\overline{t}_j)\beta_y^n(\overline{t}_j) \quad .$$

If the variation in the beta functions are small then

$$\sum_i \ell_i^2 C_i^2 \simeq \sum_j \overline{\ell}_j^2 E_j^2 \quad .$$

Finally, the root mean square integrated corrector strength becomes

$$\langle \ell C \rangle_{rms} \cong \sqrt{\frac{1}{N_c}\sum_j \overline{\ell}_j^2 E_j^2}$$

[9] G.P. Tolstov, Fourier Series, (Dover Publications, Inc., 1962).

where N_c is the total number of correctors.

In estimating the strength of the quadrupole correctors, we assume the following errors

(i) Gradient errors of main quadrupoles, $\frac{\Delta K}{K} < 10^{-3}$

(ii) Horizontal displacements of the main sextupoles, $\Delta_x \leq 0.3$ mm

(iii) Horizontal displacements of the nominal eddy current sextupoles, $\Delta_x \leq 0.6$ mm then

$$\langle K_{pq} \rangle_{rms} \leq 0.000427 \text{ m}^{-1}$$

where we assumed the main sextupoles have the strengths $B''\ell/B\rho = 0.74669$ (focusing), -1.5347 (defocusing). Furthermore, the greatest contribution is due to the main sextupoles.

For the skew quadrupole correctors, we assume the following errors:

(i) Rotation errors in the main quadrupoles of $\Delta\theta \leq 0.3$ mrad

(ii) Vertical displacements of the main sextupoles, $\Delta_y \leq 0.3$ mm

(iii) Vertical displacements of the nominal eddy current sextupoles, $\Delta_y \leq 0.6$ mm then

$$\langle M_{pq} \rangle_{rms} \leq 0.000549 \text{ m}^{-1}$$

As with the quadrupole correctors, the greatest contribution is due to the main sextupoles.

The strength required for the sextupole correctors can be estimated with the following models for errors:

(i) Errors in the main sextupole fields, $\Delta S/S < 10^{-3}$.

(ii) Errors in the eddy current sextupoles, $\Delta S_R \leq 10\%$ of nominal eddy current sextupole strength.

then

$$\langle S_{R_{pq}} \rangle_{rms} \leq 0.00253 \text{ m}^{-2}$$

where the greatest contribution is due to the eddy current sextupoles.

Finally, we consider the strength of the skew sextupole correctors. Given the following errors

(i) Rotations of the main sextupoles, $\Delta\theta \leq 0.3$ mrad

(ii) From eddy current sextupoles, $\Delta S_S \leq 1\%$ of the nominal eddy current sextupole strength

then

$$\langle S_{S_{pq}} \rangle_{rms} \leq 0.000625 \text{ m}^{-2}$$

with the main sextupoles giving the greatest contribution.

Conclusion

We presented a resonance correction scheme for the SSC–LEB and estimated the strength of the correctors required. This analysis suggest alternatives to the above scheme. Since the skew sextupole corrector strengths are small, we could reduce the number of skew sextupole correctors to 4 per superperiod or none at all. Furthermore, at full intensity proton beams, the space charge tune spread[2] can be greater than 0.4 which would cause some of the particles to cross the sextupole and skew sextupole resonances with harmonic 49. In this case we would need twice the number of power supplies for the sextupole correction scheme. A more complete analysis will be required to address these questions and others mentioned in this paper.

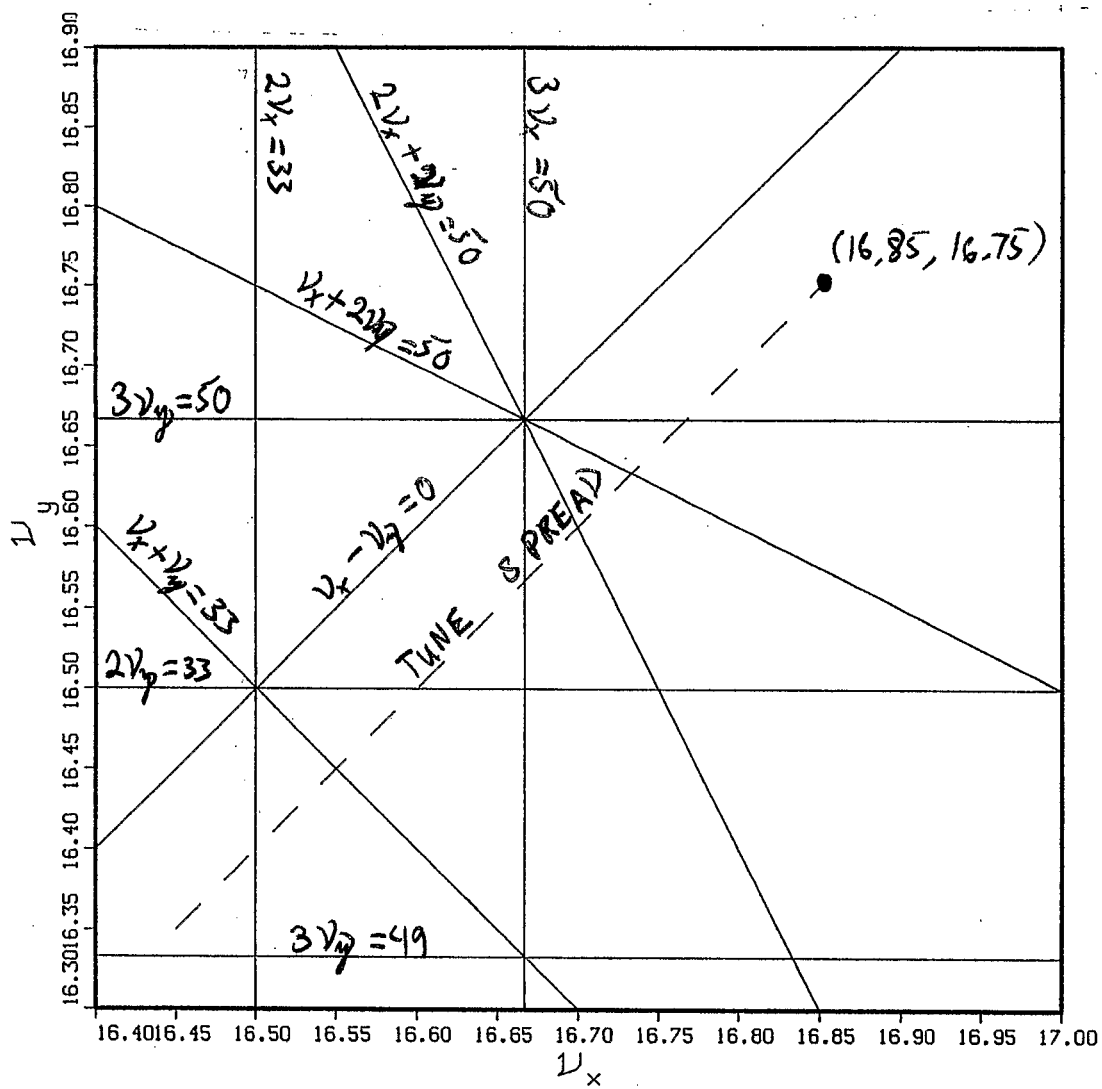

Fig. 1 The imperfection resonance tune diagram.

Quadrupole Correctors

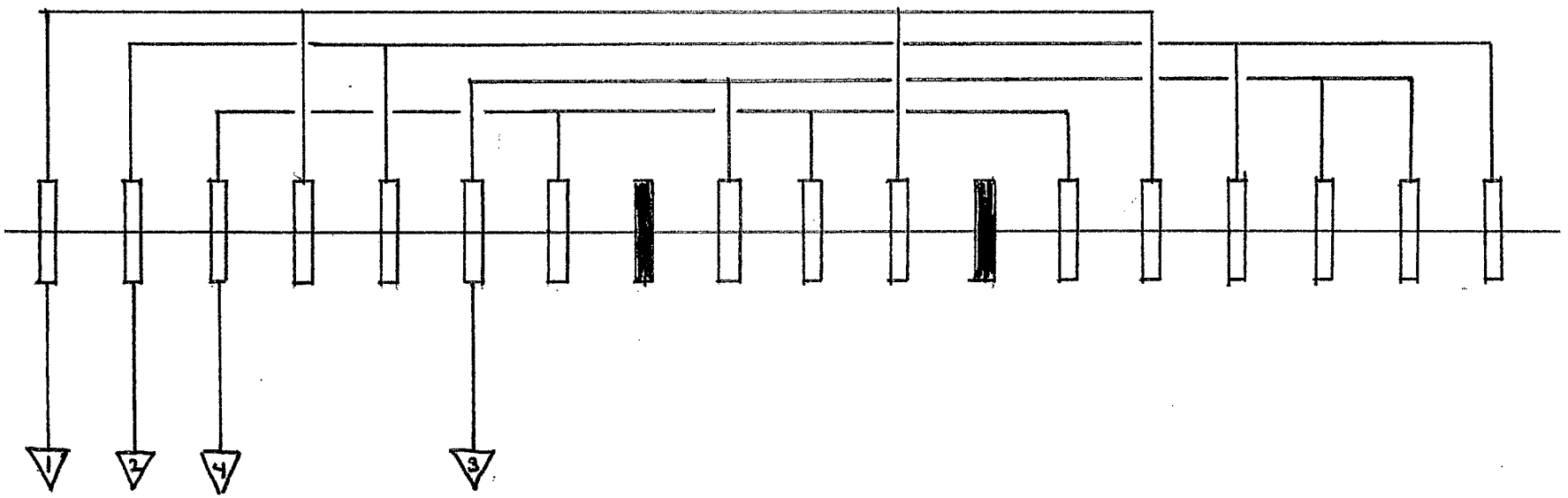

Fig. 2 Consecutive superperiods are oppositely powered. 16 correctors/superperiod.

Skew Quadrupole Correctors

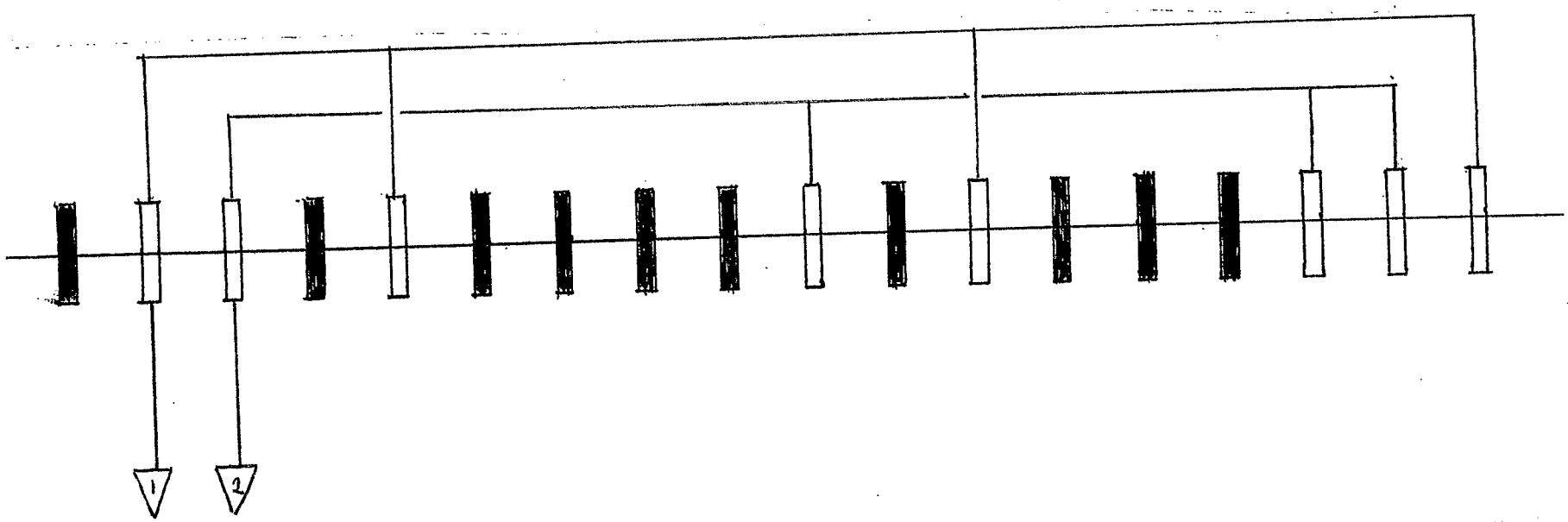

Fig. 3 Consecutive superperiods are oppositely powered. [Note, $\nu_x - \nu_y = 0$ isn't corrected.]

Sextupole Correctors

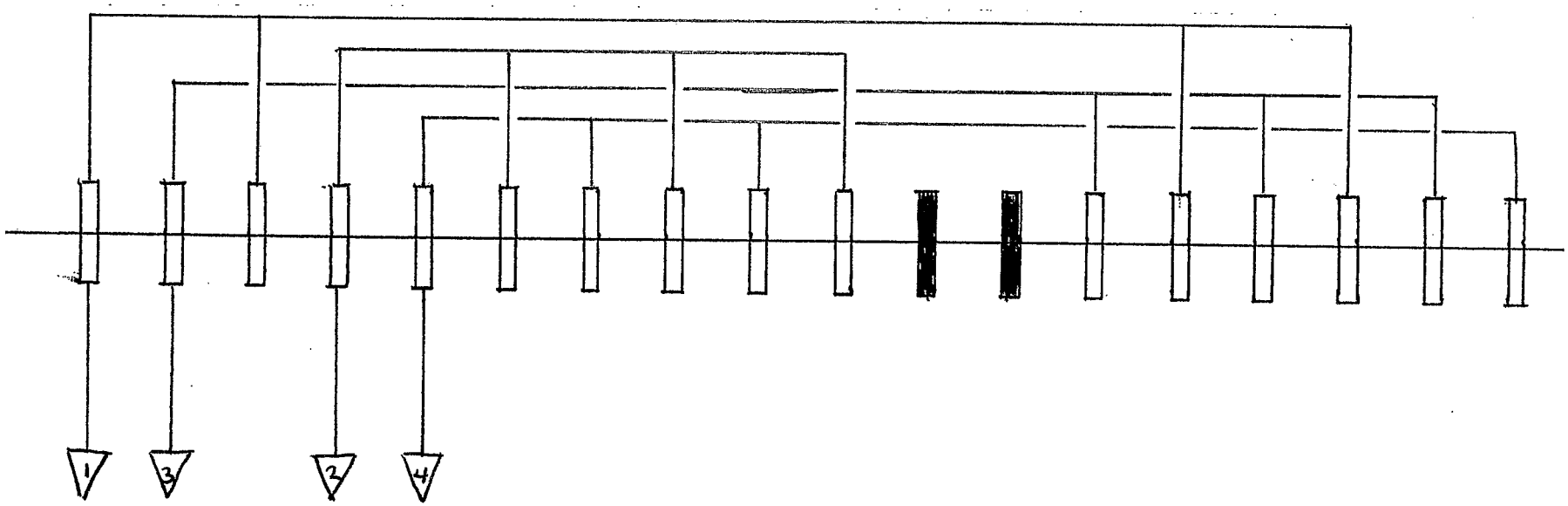

Fig. 4 The first and fourth superperiods are powered as above, however, all other superperiods are reverse wired and powered at half the strengths.

Skew Sextupole Correctors

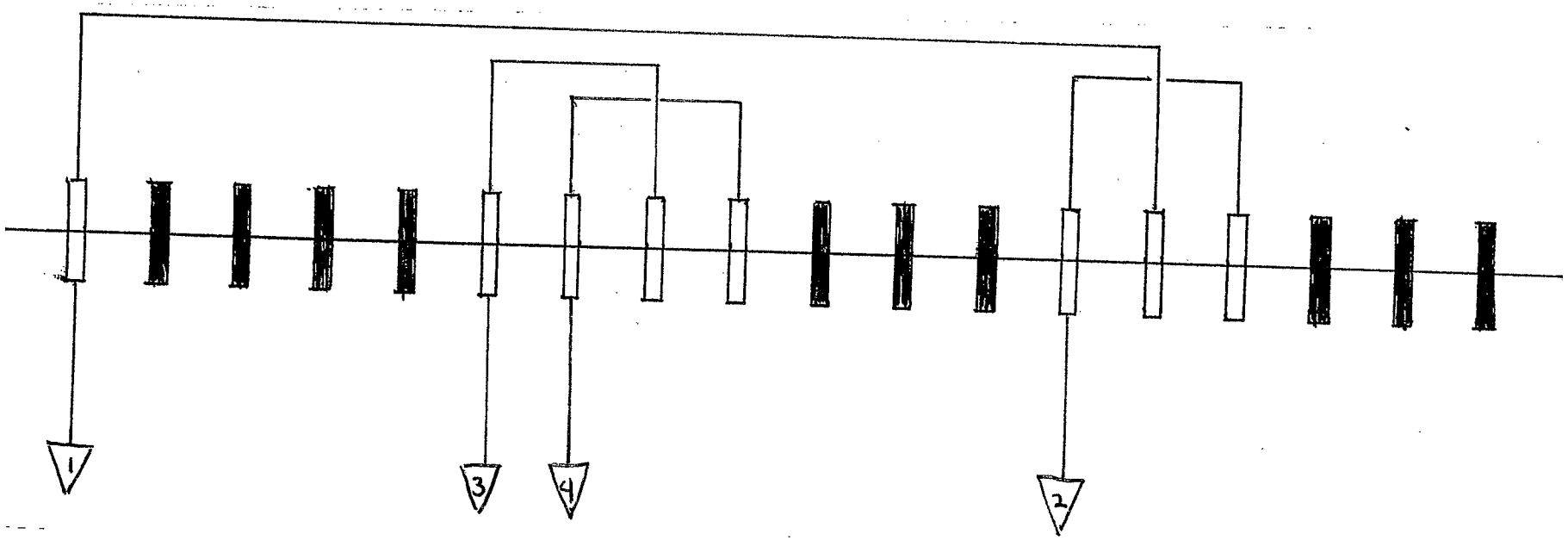

Fig. 5 The first and fourth superperiods are powered as above, but all other superperiods are oppositely powered and at half the strength.