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Skew Quadrupole Corrections for the SNS Ring

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1 Introduction

The Accumulator Ring [1] for the proposed Spallation Neutron Source (SNS) is designed to operate with horizontal and vertical tunes (Q_x and Q_y) between 5 and 6. Several second and third-order resonance lines cross this region, and, because the ring will operate at very high intensities for which stringent limits on losses will be imposed, the possibility of beam loss due to excitation of these resonances must be considered. Although the space-charge tune spread of the beam is expected to be small (at most 0.1), a number of resonance lines are sufficiently close to the nominal working point ($Q_x = 5.82$, $Q_y = 5.80$) to be of concern. Other lines in the region may also be of concern if one wants to have room to maneuver the tunes. In this report we focus on the $Q_x + Q_y = 11$, $Q_x + Q_y = 12$, and $Q_x - Q_y = 0$ resonances which are excited by skew quadrupole fields in the ring.

2 The Ring Lattice and Correction Elements

The ring lattice [2, 3, 4] consists of four superperiods, each containing a 90° arc and a long straight section. The four superperiods are labeled A, B, C, D and run sequentially along the beam direction from the beginning of one arc to the next. The order of magnets in each superperiod X is DHX1, QVX1, DHX2, QHX2, ..., DHX8, QHX8, QVA9, QHX10, QVX11, QHX12, where D and Q denote dipoles and quadrupoles, and H and V refer to the horizontal and vertical planes. The long straight section in superperiod X runs from QHX8 through QHX12.

To compensate for the small unavoidable field imperfections and magnet alignment errors that can lead to resonance excitation, the ring will have a set of correction elements consisting of horizontal and vertical dipoles, skew quadrupoles, sextupoles, skew sextupoles and octupoles. Trim windings on the lattice quadrupoles will allow for any necessary quadrupole corrections. Correction dipoles and skew quadrupoles will be mounted downstream of the position monitor at each quadrupole with the dipole and skew quadrupole windings wound on the same core. We shall use QSX1, QSX2, ..., QSX11, QSX12 to label the skew quadrupoles downstream of quadrupoles QVX1, QHX2, ..., QVX11, QHX12 respectively. In the calculations carried out for this report, the skew quadrupoles were taken to be thin elements located at the downstream ends of the quadrupoles; the integrated strength of each skew quadrupole was taken to be 10 Gauss per Amp.

3 Skew Quadrupole Strings

For the correction of random skew quadrupole errors that can excite the $Q_x - Q_y = 0$, $Q_x + Q_y = 11$, and $Q_x + Q_y = 12$ resonances, it is necessary to connect the skew quadrupoles together in series strings that produce azimuthal harmonics 0, 11, and 12. Strings that produce azimuthal harmonic 6 are also needed to correct distortions of the dispersion that can occur as the machine tunes approach 6. Thus we define the following strings:

$$\mathrm{QS0} = \mathrm{QSX8} + \mathrm{QSX9} + \mathrm{QSX10} + \mathrm{QSX11}$$

$$\mathrm{QS6Y} = \mathrm{QSA3} - \mathrm{QSB3} + \mathrm{QSC3} - \mathrm{QSD3}$$

$$\mathrm{QS6Z} = \mathrm{QSA5} - \mathrm{QSB5} + \mathrm{QSC5} - \mathrm{QSD5}$$

$$\mathrm{QS11Y} = \mathrm{QSA4} - \mathrm{QSC4}, \qquad \mathrm{QS11Z} = \mathrm{QSB4} - \mathrm{QSD4}$$

$$\mathrm{QS12} = \mathrm{QSA1} + \mathrm{QSB1} + \mathrm{QSC1} + \mathrm{QSD1}$$

$$- \mathrm{QSA7} - \mathrm{QSB7} - \mathrm{QSC7} - \mathrm{QSD7}$$

Here the + and − signs indicate the relative polarities of the skew quadrupoles in each string.

The notation QSXn used for the elements of the QS0 string indicates that for each n, the string contains the four skew quadrupoles QSAn, QSBn, QSCn, QSDn. The string therefore consists of four groups of four magnets spaced one superperiod apart, and, since magnets separated by azimuthal angles of π and $\pi/2$ are excited with the same polarity, the string produces only azimuthal harmonics 0, 4, 8, 12, 16, and so on.

The skew Quadrupoles in the QS6Y and QS6Z strings are also spaced one superperiod apart, but those separated by azimuthal angles of π and $\pi/2$ are excited with the same and opposite polarities respectively; each string therefore produces only azimuthal harmonics 2, 6, 10, 14, 18, and so on. Note that since the betatron phase advance between magnets QSX3 and QSX5 is approximately $\pi/2$, the QS6Y and QS6Z strings provide orthogonal correction of the real and imaginary parts of the excitation coefficient for dispersion distortion.

The skew quadrupoles in the QS11Y and QS11Z strings are spaced two superperiods apart and those separated by an azimuthal angle of π are excited with opposite polarities; each string therefore produces only harmonics 1, 3, 5, 7, 9, 11, and so on. At the 11th harmonic, the two strings provide orthogonal correction of the real and imaginary parts of the $Q_x + Q_y = 11$ resonance excitation coefficient.

Similarly, the group of 4 skew quadrupoles, QSX1, in the QS12 string produces only azimuthal harmonics 0, 4, 8, 12, 16, and so on; the same is true of QSX7 group.

Note that if the uncoupled horizontal and vertical tunes are close to 6, then the betatron phase advances between QSX8 and QSX10 in the QS0 string are nearly $\pi/2$ and it follows that the contribution of the QSX8 magnets to the excitation of the $Q_x + Q_y = 12$ resonance is nearly cancelled by that of the QSX10 magnets. The same is true of QSX9 and QSX11. Thus, the QS0 string has little effect on the $Q_x + Q_y = 12$ resonance when the uncoupled tunes are both close to 6. Similarly, the betatron phase advances between QSX1 and QSX7 in the QS12 string are both nearly $3\pi/2$, and since these magnets are excited with opposite polarities it follows that the QS12 string will excite the $Q_x + Q_y = 12$ but not the $Q_x - Q_y = 0$ resonance.

4 Correction of Dispersion and the $Q_x - Q_y = 0$ and $Q_x + Q_y = 12$ Resonances

To test the ability of the QS6Y and QS6Z strings to correct distortions of the dispersion (due to skew quadrupole errors), we use the Ealign command of the MAD code [5] to generate Gaussian distributions of quadrupole alignment errors in the ring. Specifically, the alignment error for each quadrupole is taken to be a rotation—i.e. a roll—of the quadrupole about the longitudinal axis. This produces a skew quadrupole error proportional to the roll angle. We take the RMS deviation of the distribution of roll angles to be 1.0 milliradians and impose a cutoff of 2.5 standard deviations. Figure (1) shows the lattice parameters obtained from an error distribution with a seed of 7777. Here the uncoupled tunes have been adjusted to be $Q_x = Q_y = 5.992$, and, because the tunes are close to six, we see significant distortion of the horizontal dispersion (lower solid curve) and the vertical dispersion (lower dashed curve). Using the Match module [6, 7] of the MAD program with appropriate constraints on the dispersion, we find that we can correct the distortion with the current in string QS6Y set to 3.51 and that in string QS6Z set to -2.79 Amps. Figure (2) shows the resulting lattice parameters with these corrections.

Because the uncoupled tunes are equal in this case, the skew quadrupole errors introduced by the rolled quadrupoles can also excite the $Q_x - Q_y = 0$ resonance. To correct for this effect we adjust the current in the QS0 string so that the two normal-mode tunes given by the MAD program are as close to 5.992 as possible. For the error distribution generated with a seed of 7777, we find that a current of 2.4 Amps is required in the QS0 string.

The two other curves shown in Figures (1) and (2) are horizontal (solid curve) and vertical (dashed curve) envelope parameters whose square roots are proportional to the maximum extent of the beam particle oscillations. These are similar to the beta functions for uncoupled motion as discussed in Ref. [8]. As the tunes approach the $Q_x + Q_y = 12$ resonance, we expect some distortion of these parameters due to skew quadrupole errors. To correct for this, we adjust the current in the QS12 string to minimize the distortion. For the error distribution generated with a seed of 7777, we find that a current of 0.5 Amps is required in the QS12 string. Figure (3) shows the resulting lattice parameters with this additional correction. In this case there was, in fact, very little distortion of the envelope parameters, and so the current required in the QS12 string is rather small. The effect of deliberately mistuning the QS12 string is shown in Figure (4). The results of carrying out the above analysis for several different seeds are summarized in Table I.

Table I: Dispersion and Coupling Corrections
$Q_x = Q_y = 5.992$ (Currents in Amps)

Seed	IQS6Y	IQS6Z	IQS0	IQS12
7777	3.51	−2.79	2.4	0.5
6777	2.28	−0.65	0.0	−0.5
5777	−4.74	−1.59	−3.2	−6.0
4777	−2.34	2.16	−0.2	−0.5
3777	1.47	−0.77	0.9	−1.0
2777	−1.99	−4.36	0.1	−1.0
1777	3.86	−2.09	2.0	−4.0
0777	0.65	−1.13	0.7	−0.5

5 $Q_x + Q_y = 11$ Resonance Correction

As the tunes approach the $Q_x + Q_y = 11$ resonance, skew quadrupole errors that produce an 11th azimuthal harmonic will cause some distortion of the beam envelope functions. To correct for this effect we use the strings QS11Y and QS11Z. As before, we use the Ealign command of the MAD code to generate Gaussian distributions of quadrupole alignment errors (rolls about the longitudinal axis of the quadrupole) in the ring. We take the RMS deviation of the distribution of roll angles to be 1.0 milliradians and impose a cutoff of 2.5 standard deviations. Figure (5) shows the lattice parameters obtained from an error distribution with a seed of 7777. Here the uncoupled tunes have been adjusted to be $Q_x = Q_y = 5.508$. We find that currents of 11 and 6 Amps are required in the QS11Y and QS11Z strings to minimize the envelope distortion. To correct for the excitation of the $Q_x - Q_y = 0$ resonance, we find that 2 Amps are required in the QS0 string. Figure (6) shows the resulting lattice parameters with these corrections. The results of carrying out the analysis for several different seeds are summarized in Table II.

Table II: $Q_x + Q_y = 11$ Corrections $Q_x = Q_y = 5.508$ (Currents in Amps)			
Seed	IQS11Y	IQS11Z	IQS0
7777	11.0	6.0	2.0
6777	8.0	3.0	0.0
5777	7.0	−2.0	−2.7
4777	8.0	4.0	−0.3
3777	1.0	−4.0	0.7
2777	−3.0	−2.0	0.0
1777	7.0	2.0	1.8
0777	−8.0	−5.0	0.7

6 Comments

The results of the previous sections indicate that skew quadrupoles similar to those employed in the AGS Booster should be adequate for the SNS Ring. (The skew quadrupoles in the Booster have an integrated strength of 5.45 Gauss per Amp and are powered with bipolar 25 Amp power supplies. An integrated strength of 10 Gauss per Amp was assumed for the calculations reported here.) Although a correction scheme consisting of 6 strings of magnets has been considered here, only one of these is really necessary if one stays close to the nominal operating point ($Q_x = 5.82$, $Q_y = 5.80$). This is the QS0 string which allows one to correct or adjust the coupling between the two planes. The other strings are necessary only if one wants to move the tunes close to the $Q_x + Q_y = 11$ and $Q_x + Q_y = 12$ resonances where distortions of the beam envelope parameters and dispersion can become significant.

7 Acknowledgement

As always, I would like to thank Jim Niederer for his help and advice in using the MAD code.

8 References

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Figure 1: Coupled Lattice Parameters

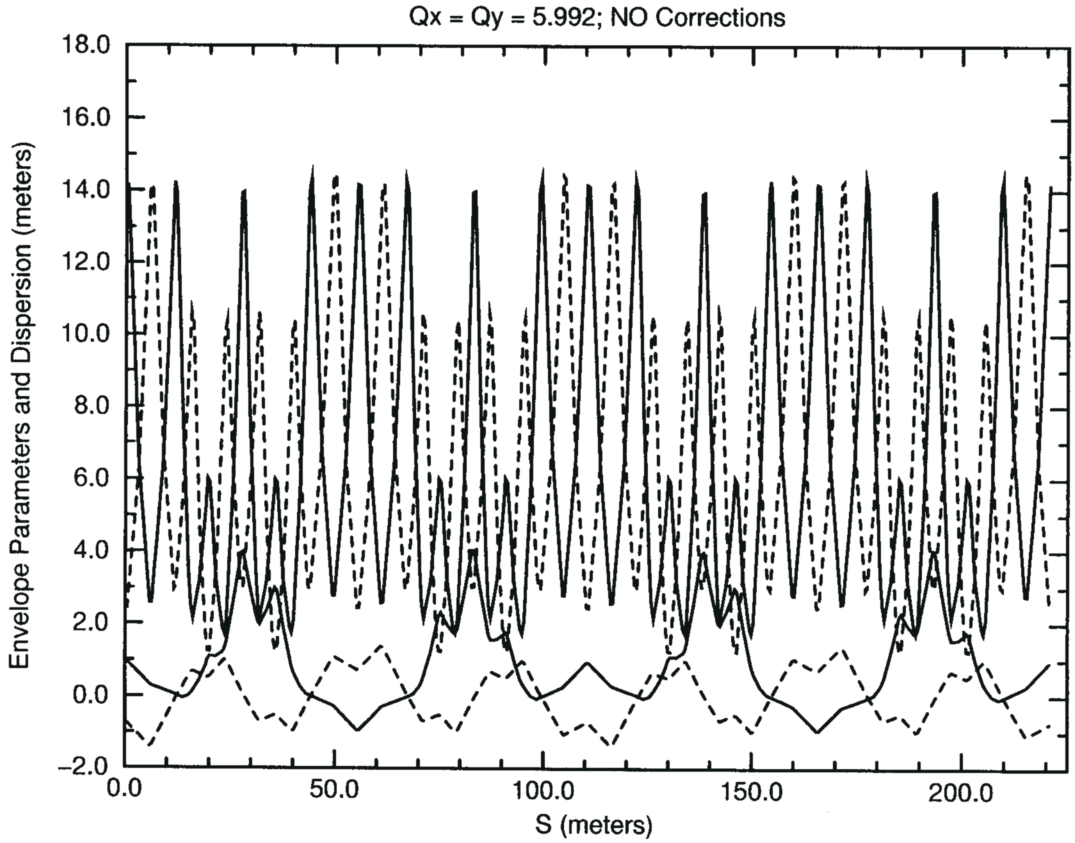

Figure 2: Coupled Lattice Parameters

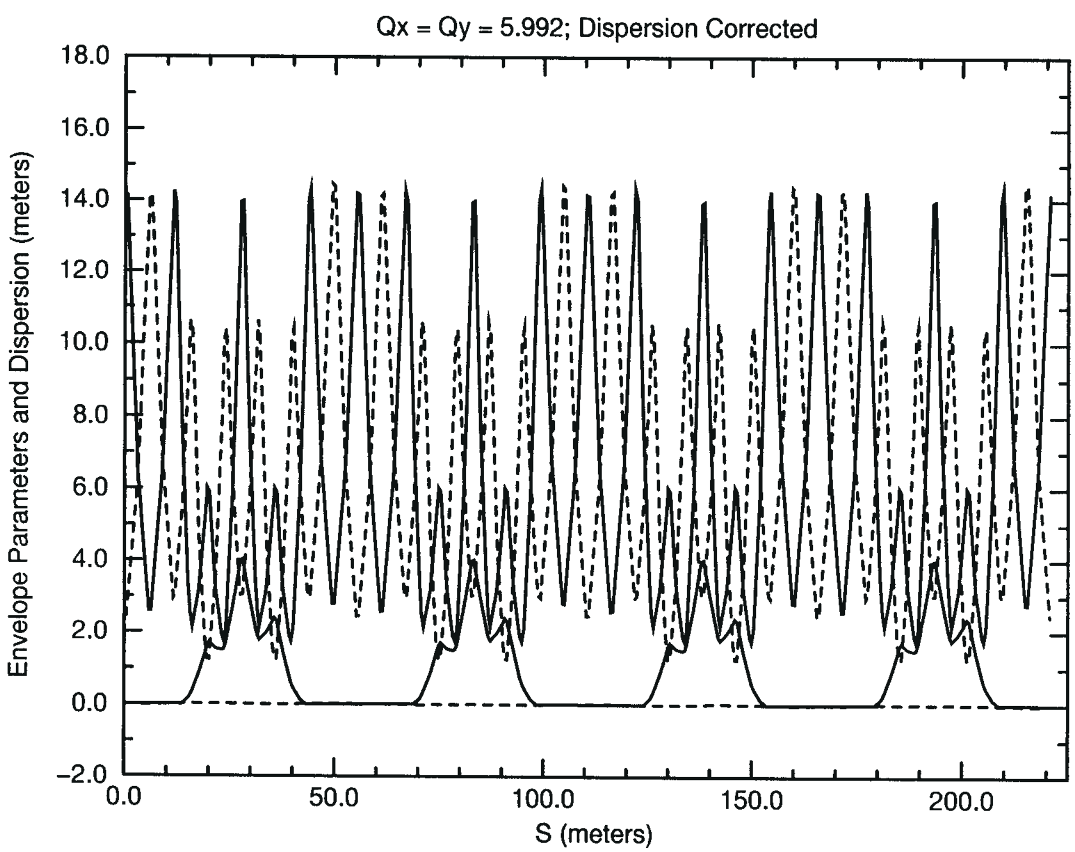

Figure 3: Coupled Lattice Parameters

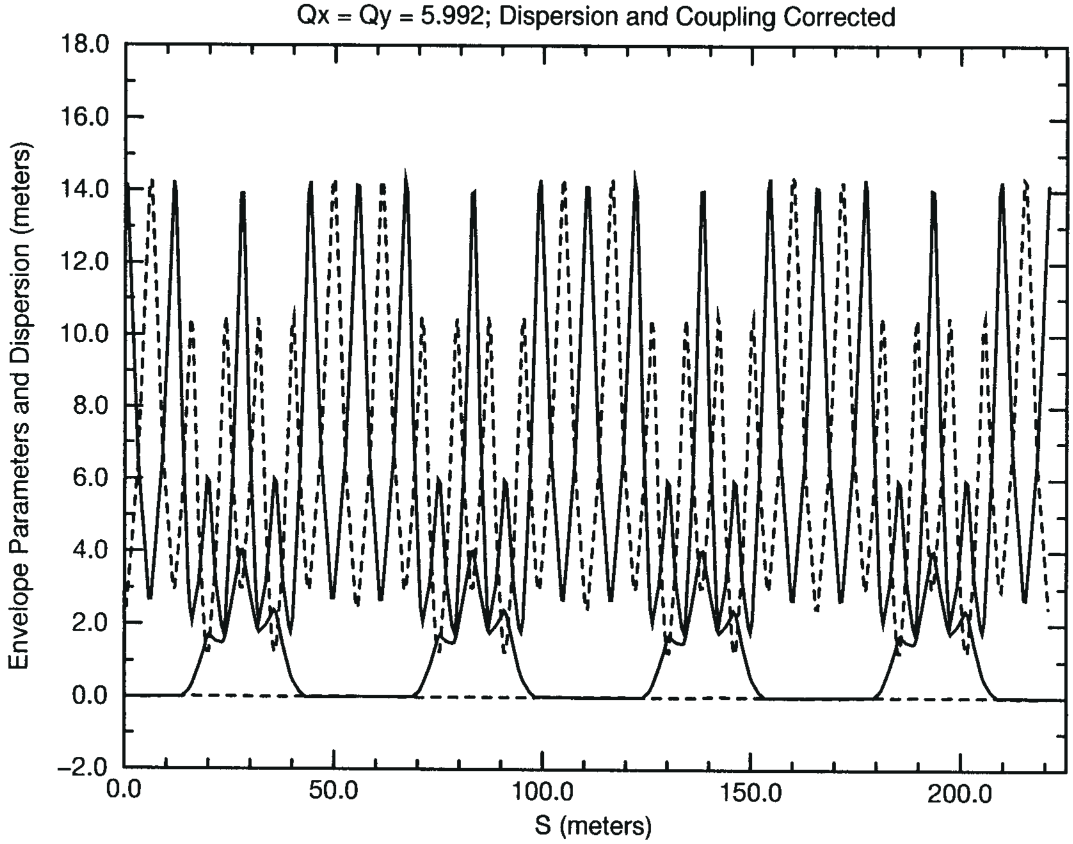

Figure 4: Coupled Lattice Parameters

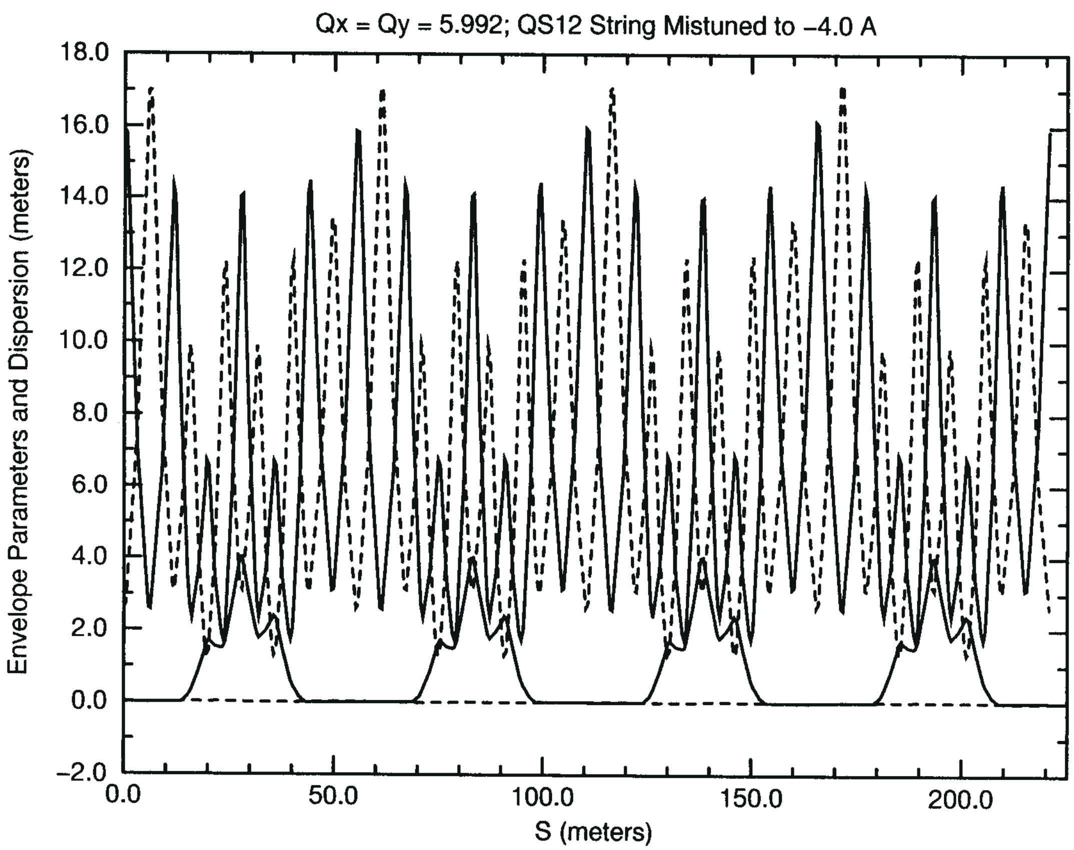

Figure 5: Coupled Lattice Parameters

Qx = Qy = 5.508; Only Qx – Qy = 0 Corrected

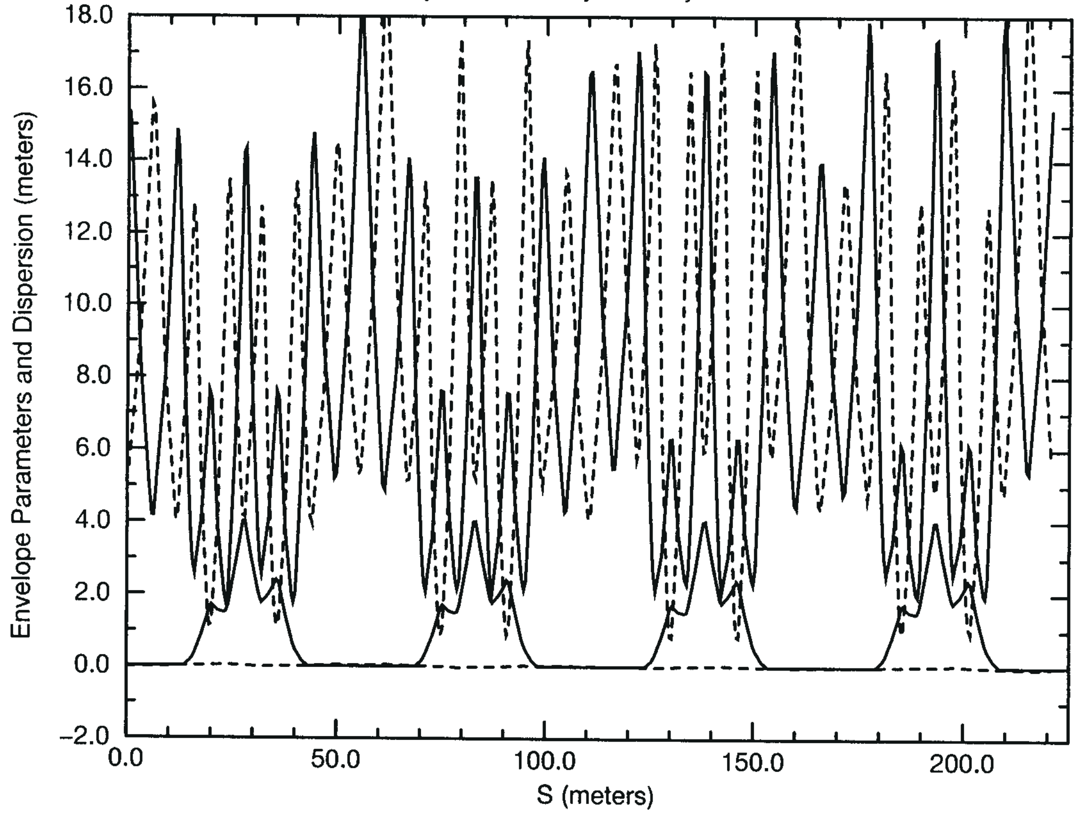

Figure 6: Coupled Lattice Parameters

Qx = Qy = 5.508; Envelope Distortion Corrected