Field Trimming of SSC Dipoles

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Abstract

The beneficial effect of compensating the sextupole field error of each SSC dipole magnet is investigated using computer tracking. To measure optical quality the by-now-standard "smear" is used, but only for comparing different accelerators (e.g. SSC-Tevatron). The arbitrarily defined "linear aperture" is not used. It is argued on economic grounds that the erect (and possibly also the skew) sextupole field error should be adjusted approximately to zero for each magnet individually, using full length trim coils.

Introduction and Proposal

For most existing accelerator magnets there has been no need to incorporate trim coils to improve field uniformity. When such elements have been present[1] they have not been critical and have had negligible influence on the magnet design and cost. In the SSC design so far trim coils, though present, have implicitly been assigned a similar second-class status. Yet the possibility exists that overall magnet costs could be reduced by placing greater reliance on field trimming.

It is only a slight exaggeration to say that the value in dollars of an SSC dipole magnet is equal to $(a_2^2+b_2^2)^{-1}$ where a_2 and b_2 are

the conventional sextupole field errors and the units have been chosen appropriately. The basis for this statement is that the "value" of the whole ring is roughly proportional to the linear aperture which varies inversely with the rms sextupole strength. The SSC is the first accelerator for which this is true, because nonlinear field errors have not previously been dominant. (The term "linear aperture" will be defined and discussed below. Other than in this preliminary discussion it will not be used.)

It is not necessary to subscribe fully to the slightly outrageous statements in the previous paragraph to be persuaded of the extreme importance of dipole field quality for the SSC. It is straightforward but expensive to improve uniformity by enlarging the magnet coils, but if a method exists which gives greater improvement at lower cost and at a comparable level of confidence, it should obviously be reflected in the optimal design. The purpose of this note is to pursue this line of reasoning.

The importance of reliable measurement and compensation of field errors has certainly already been stressed in the Conceptual Design Report (CDR).[2] I will argue, though, that to minimize the SSC cost it is appropriate to have a more precise and more local correction scheme than is presently contemplated. To motivate this investigation one need only make reference to the recent DOE review of the CDR.[3] It was their recommendation that the option be retained of increasing the magnet physical aperture by 25%, at the anticipated incremental cost of $160 million, in order to increase the linear aperture. It will be shown that a much greater improvement in the linear aperture can be obtained, at a small fraction of that cost, by correcting the

quadratic field errors on a magnet-by-magnet basis. This would be done using sextupole windings running the full length of each dipole with the possibility being retained of independently setting the current in each trim coil.

As far as magnet construction is concerned, what is being suggested is reasonably compatible with current plans -- bore tube correction windings are already needed to compensate for persistent currents. What is new is the promotion of these trim coils from their present level (i.e., a nuisance to be added on as cheaply as possible) to first-class status as an integral part of the magnet, as sturdy and essential as any other part. They would be calibrated during the measurement phase to determine permanent settings. Included in this recommendation is that other issues such as sorting and compensation of other multipoles, both random and systematic, will have to be rethought with the phase advance per cell and, to a lesser extent, the cell length having important influences.

In the earliest accelerators (cyclotrons) it was unnecessary to consider even field gradients in the dipole magnet, but as apertures became relatively smaller it became necessary to control these quadrupole field errors. It should not be surprising that this evolution has, for the first time with the SSC, led to the need for controlling the next field errors a_2 and b_2. At the same time we can be hopeful that higher multipoles will not demand as close attention. The likelihood of this can be enhanced by design choices.[4]

The question of which multipoles deserve local compensation is an important one -- the surface will only be scratched here. Dipole errors b_0 and a_0 cause closed orbit errors which are assumed to be compensated by steering correctors located in the spool pieces beside the

lattice quads. These are local, though not precisely superimposed on the dipole, and their main purpose is to compensate for quadrupole location errors, not bend errors in the dipoles. It has been assumed that skew quad errors a_1 will be ameliorated by sorting.[5] Erect quad errors have largely been neglected since they leave the equations of motion linear and can be remotely compensated. Both a_1 and b_1 deserve further study. A likely ingredient of the plan being proposed here is that they both would be better compensated by sorting than has been assumed so far.

For typical transverse particle amplitudes the deflections due to the sextupole errors a_2 and b_2 are appreciably less than the constant and linear errors mentioned in the previous paragraph. The need for correcting them comes from the linear aperture requirement. Based on Tevatron and early SSC magnet construction experience the rms variation of a_2 is expected to be considerably less than that of b_2, but not small enough to be declared negligible.[6] It is easy to see that there can be no systematic $\bar{a}_2$ but it is more subtle why its random component should also be less. One can fear being surprised by unexpectedly large variation in a_2. (A related surprise is documented in the CDR,[7] in a comparison between LBL and BNL prototypes. They obtain opposite results regarding the relative importance of a_1 and b_1.) For this note it has been assumed that coils are present for trimming both a_2 and b_2, but the main improvement is presumably due to b_2 since it is larger to start with.

For typical amplitudes the nonlinear deflections due to higher multipoles are much smaller than those due to a_2 and b_2. (If this were not true the magnet coil would certainly have to be enlarged.) There are, however, certain

chromatic effects of higher systematic multipoles that fit into the class, mentioned above, of things which have to be rethought. These cause global effects which, compared to random effects, are inexpensive to compensate. Whether or not it is necessary and/or desirable for these compensation coils to share the same bore tube locations as the sextupole windings will not be addressed.

From now on we will concentrate on b_2 and a_2, or rather just on b_2, leaving it intentionally vague as to whether the very tight tolerances assumed on a_2 are met by manufacturing control or by dedicated trim coils, or possibly by sorting.

It goes without saying that the b_2 trim coils cannot be set to an accuracy better than b_2 can be measured. Accuracies at least as good as ±0.2 units are required.[8] (That is 2 parts in 10^5.) Such accuracies are thought to be achievable[9] but because the importance is unprecedented the onus must be left with the magnet factory to demonstrate on a day-to-day basis that such accuracy has been achieved and is being maintained. This should include (I believe) the requirement that every such measurement be performed by two independent methods. This will enforce, on a magnet-by-magnet basis, a quality control on the field uniformity commensurate with its importance. The redundancy will also protect against uncertainty in the interpretation of systematic month-by-month and factory-to-factory variations. Such drifts, which can perhaps be expected at the ±1 unit level, could compromise sorting schemes.

It is the need for redundancy that favors a design in which the sextupole trim coils run the full length of the dipole unit. Then for every sextupole

determination, using coils of any length whatever, the redundant measurement will consist of measuring the trim coil current which nulls out the effect. (If a short coil measurement coil is used it will be necessary to average the readings taken at many points along the magnet as it is the field error integrated over the longitudinal coordinate which is of primary importance for accelerator operation.) It is also true that full length trim coils give the optimal compensation but this does not decisively rule out the use of shorter coils as a somewhat lumpy compensation scheme is thought to be tolerable.

Powering the Trim Coils

As has been described each dipole unit is equipped with a sextupole trim coil that, when powered to a pre-measured value, cancels the quadratic variation of the magnetic field, thereby adjusting b_2 to be close to zero. One (unnecessarily flexible) scheme for powering these coils would be to have one power supply for each coil. This would require five times as many supplies as are presently needed for steering correctors. In the CDR the cost of correction power supplies makes up 0.6% of the total magnet cost. Assuming equal unit cost for a steering supply and a sextupole supply, the cost of this scheme could increase the magnet cost by as much as 3% (i.e. $36M). Though much cheaper than the aperture enlargement mentioned earlier this will be seen to give a much greater improvement factor.

There are also ways of powering the trim coils far more cheaply though less flexibly. One such scheme is illustrated in Fig. 1. There are several

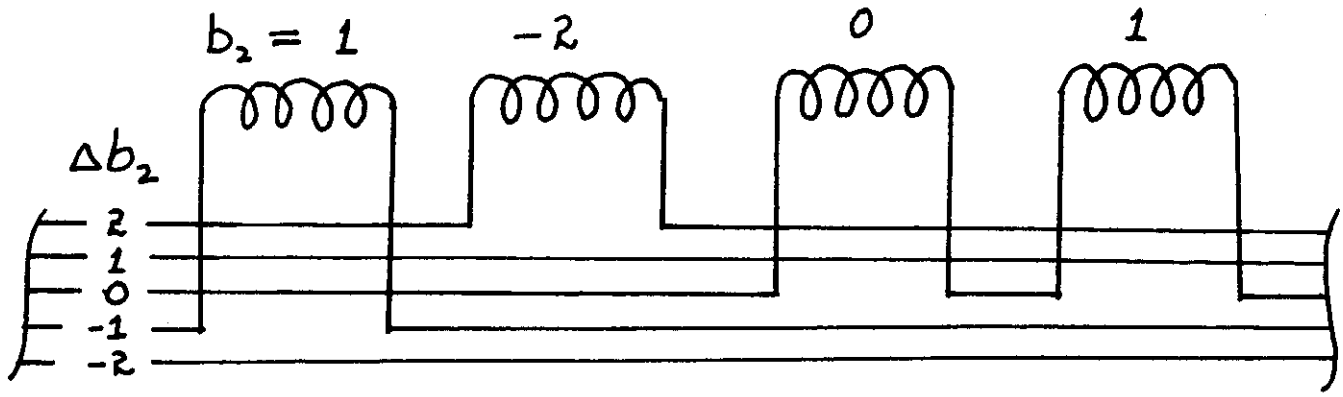

Fig. 1 Illustration of the use of multiple trim buses for "binned" compensation. The b_2 sextupole coils are shown.

(say eight) current buses, each carrying a slightly different current. For a sextupole trim coil belonging to a magnet with a certain b_2 value, a particular current is needed to cancel it. The bus carrying the closest current is selected and routed through the coil. Sample numerical values are given in Fig. 1 to illustrate the scheme. This could be called a "binned" compensation scheme to distinguish it from other schemes (e.g. "sorting") that have the same general purpose. With eight circuits it is estimated that the rms variation of a given multipole will be reduced by a factor of five. For this note an improvement factor of four has been assumed.

Quantifying the Optical Quality of the Entire Lattice

In analysing the effect of field errors a concept which has been prominent in SSC design so far is that of "linear aperture". To determine it the "smear" is first defined as the fractional variation of the Courant-Snyder

invariant -- with no field errors this would, true to its name, not vary. For reasons which are hard to reconstruct, but which can be plausibly rationalized, a smear value of ±10% has been taken to assure acceptable linearity and that has been taken as the condition for whether or not a particle lies within the "linear aperture". This is to be compared with the "needed aperture" which is the largest transverse amplitude that will be encountered in routine operations. It encapsulates experience with existing machines, extrapolated to the SSC.

Though the term "linear aperture" has a handy engineering purpose I will avoid using it and thereby avoid introducing the artificial ±10% value. I will, however, continue to use "smear" to quantify optical quality for purposes of comparing different lattices and different accelerators (in particular the SSC and the Tevatron). Even though "smear" has been referred to earlier in this paper as "by-now standard" there are appreciable inconsistencies in its definition among different labs, among different members of the CDG, and even between different papers by the same author (me). This is at least partly due to the fact that it is, theoretically, a somewhat "grubby" quantity having non-trivial dependence on initial conditions. Here only motion with equal horizontal and vertical emittance will be considered (this is standard, though not easily justifiable) while the maximum radial distance from the origin at a maximum beta point in the lattice is taken as the aperture measure (this is not standard, though it should be). As mentioned above these details don't really matter as long as the smear is calculated consistently for any lattices being compared as will be true here.

The figure-of-merit to be used in comparing different lattices will be the smear of a particle at the edge of the needed aperture. Any "needed" particle will be inside the needed aperture and will necessarily have a smear value smaller than the figure of merit. Using this terminology it will be possible, starting with experimental observation on an existing machine (the Tevatron) to make inferences for the SSC which are far more reliable than would be true for purely theoretical tracking results.

This approach assumes that the needed aperture is unambiguously known. For the SSC it is 4.9 mm.[10] This depends somewhat on cell length and phase advance per cell. We will ignore such variation and, as a round number, take 5 mm as the needed aperture. It is dominated at injection energy by three roughly equal components: natural beam size, closed orbit errors and injection errors. Of these, only the first can be easily scaled to relate two different accelerators. It varies as $(\beta/E)^{1/2}$ where β is the lattice function and E is the energy. The other two contributions are less dependent on energy and make up a smaller fraction of the needed aperture for the Tevatron than for the SSC. But there are other small contributions and numerically the needed aperture for the Tevatron is about 7 mm which is consistent with the 5 mm SSC number and the $(\beta/E)^{1/2}$ scaling. I will assume that scaling relation as far as needed aperture at injection is concerned.

Tracking Results

Using TEAPOT,[11] particles were tracked to give the smear as a function of transverse amplitude for the following five different lattices: SSC, 60° cells, with and without sextupole compensation, Fig. 2; SSC, 90° cells, with and without sextupole compensation, Fig. 3; and Tevatron cells with their measured rms errors, Fig. 4. In every case purely repetitive FODO cells were used with no intersection regions or other inserts. In these figures the smear is plotted as a function of amplitude for each of 5 or 6 randomly generated machines. The assumed rms multipole errors are listed in Table 1. The dipole and quadrupole errors were taken to be zero and are not listed.

The main information in these graphs is the smear, read off at the amplitude value corresponding to the needed aperture. The different curves give an indication of the range of expected values; the mean and the rms spreads are indicated on the graphs.

The following observations are based on figures 3, 4 and 5.

i) The case intended to represent the CDR is 60°, uncompensated, Fig. 2a. The average smear is 8.8% at the needed aperture. In the old language one would say that this is a just barely satisfactory situation in that the needed aperture is a bit smaller than the linear aperture.

ii) In Fig. 2(b) the result of the sextupole compensation, which has been described previously, is indicated. The fourfold reduction in a_2 and b_2 reduces the smear from 8.8±4.7% to 3.2±1.2%. Except for the altered values of a_2 and b_2 the machines are the same. Before-after comparisons can be made using the number labels in the graphs.

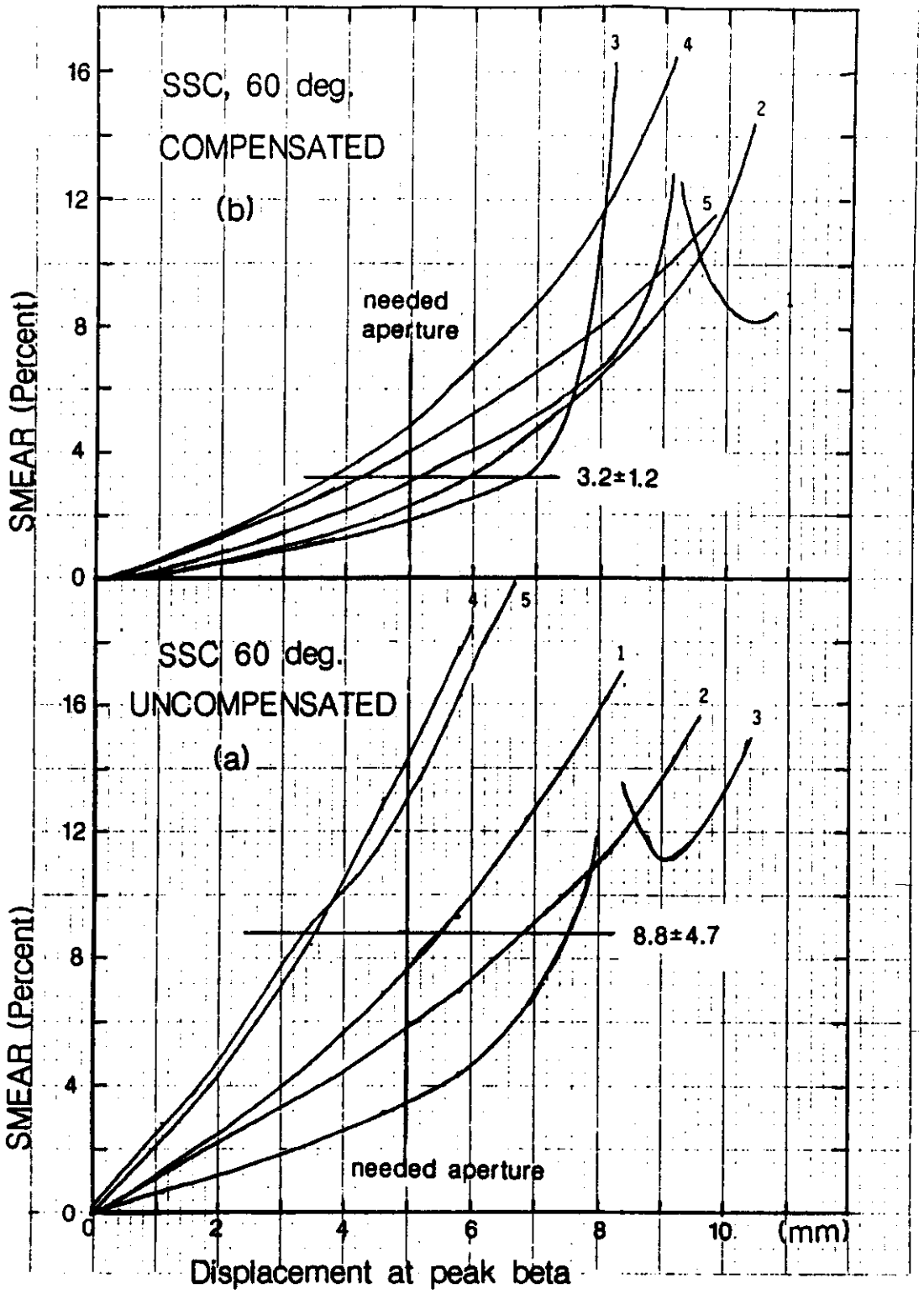

Fig. 2. Smear vs. amplitude for the SSC 60° lattice, before and after local compensation of sextupole field errors.

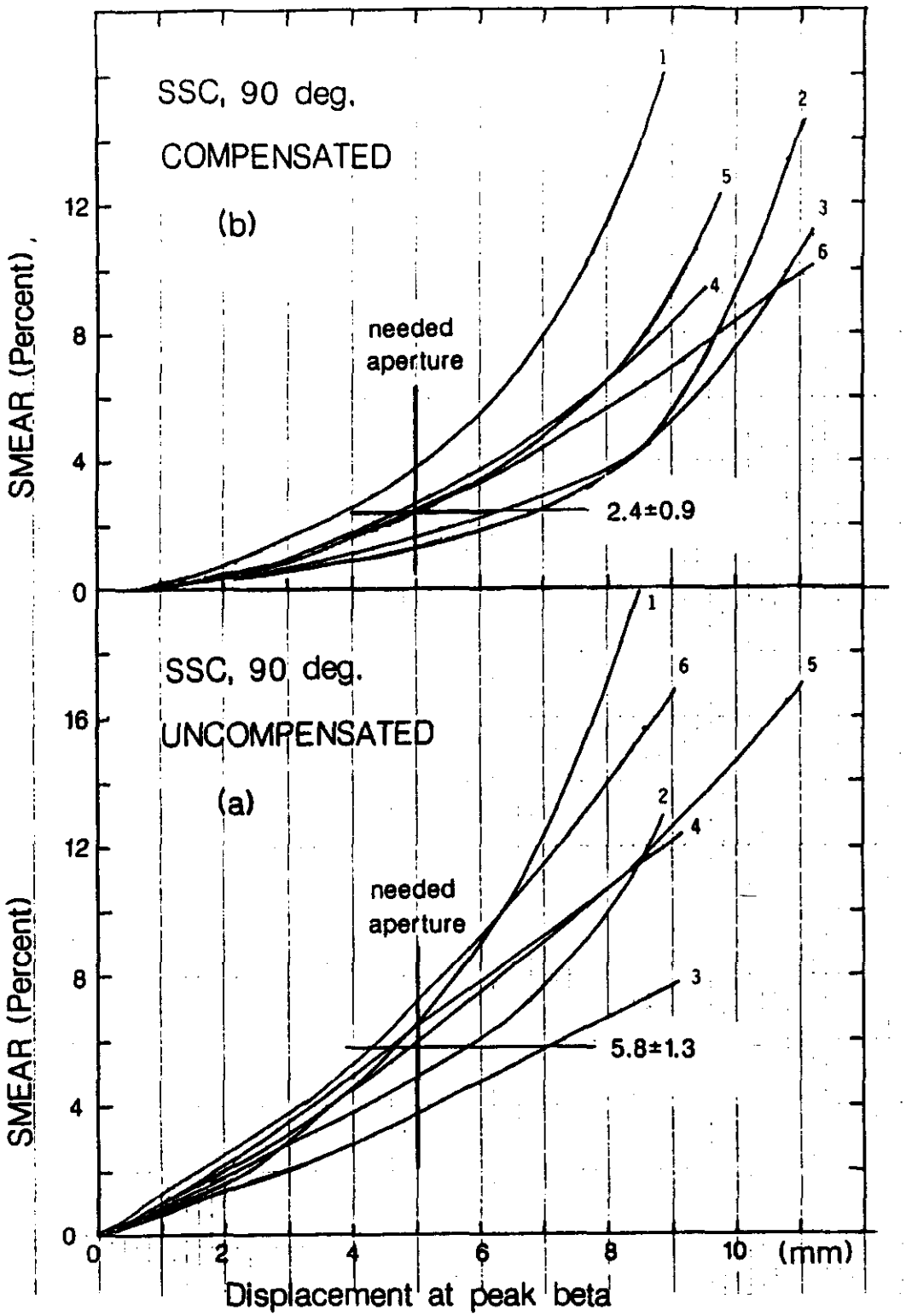

Fig. 3 Same as Fig. 2 but with 90° phase advance per cell.

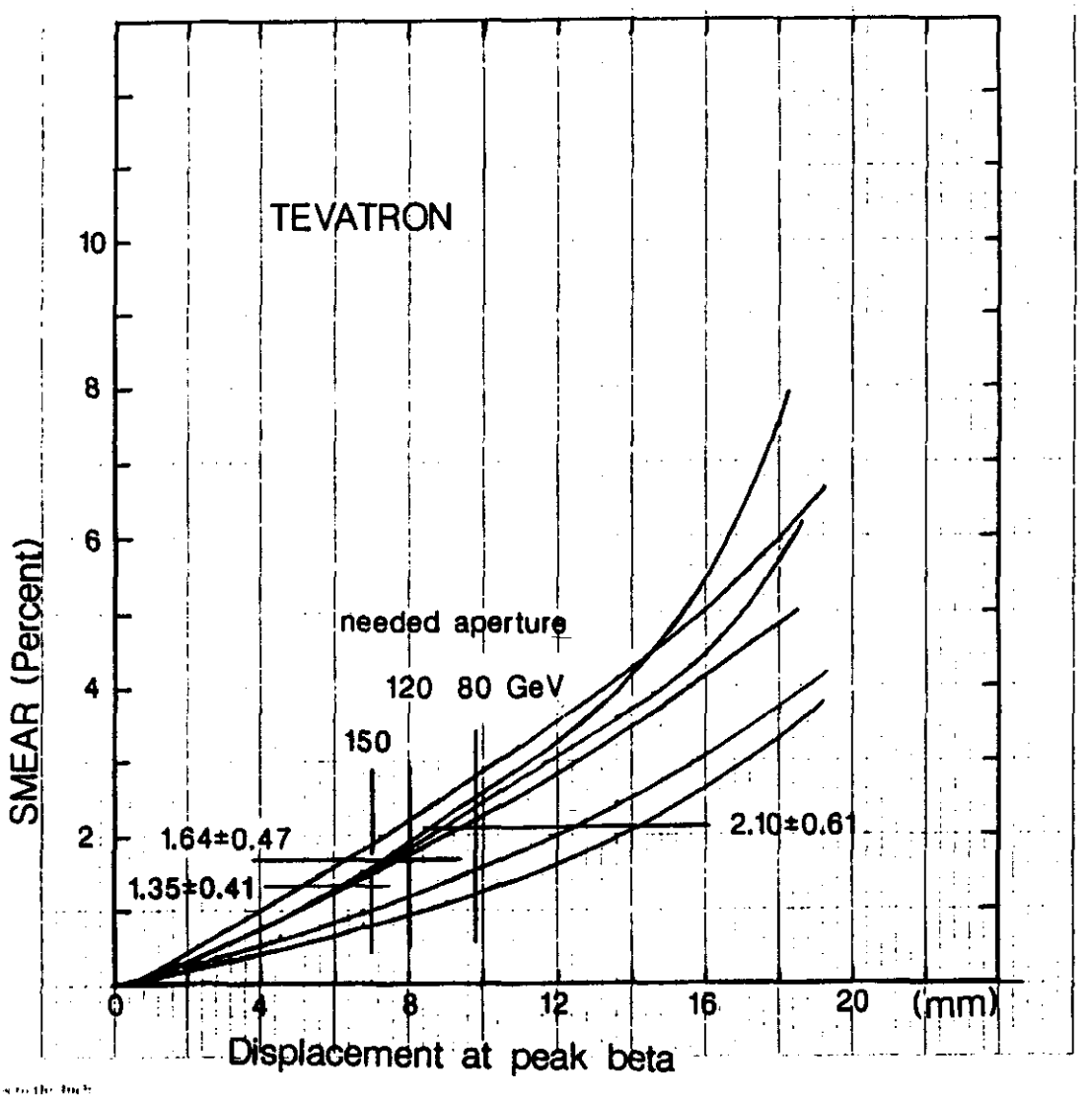

Fig. 4 Smear vs amplitude for the Tevatron using their measured rms multipole errors.

Table 1. RMS Multipole Values

	SSC Uncompensated	SSC Compensated	Tevatron
a_2	0.6	0.15	0.192
a_3	0.7	0.7	0.096
a_4	0.2	0.2	0.0128
a_5	0.2	0.2	0.006
a_6	0.03	0.03	0.0
a_7	0.2	0.2	0.0
a_8	0.05	0.05	0.0
b_2	2.0	0.5	0.4
b_3	0.3	0.3	0.0512
b_4	0.7	0.7	0.033
b_5	0.1	0.1	0.0031
b_6	0.2	0.2	0.002
b_7	0.2	0.2	0.0
b_8	0.1	0.1	0.0

All values are in parts per 10^4 at 1 cm.

iii) Fig. 3 is like Fig. 2 except the phase advance per cell is 90°. The uncompensated smear at 5 mm is 5.8±1.3% which is appreciably better than the 60° case, as is the result after compensation, 2.4±0.9%. The improvement factor is not quite as great as in the 60° case. Presumably this is because the chromaticity control sextupoles, which are not changed in the compensation process, are relatively more important in the 90° case.

iv) Similar results for the Tevatron are shown in Fig. 4. At the nominal injection energy of 150 GeV the needed aperture is 7 mm and the smear is 1.35±0.41%. Also shown are values for other injection energies, derived using the scaling described previously These are relevant in interpreting experimental results such as those of R. Johnson et al.[12] who investigated Tevatron behavior at energies as low as 80 GeV, well below the nominal injection energy.

Conclusions

It is my contention that dipole field quality has not yet been adequately incorporated into the design and cost optimization of the SSC. Insufficient attention has been paid to quadratic field variation which, on the one hand, dominates the performance, and on the other hand, can be cheaply controlled by sextupole trim windings. Because such coils are of dominant importance for the first time in the SSC, their importance has not been obvious and since there has not been much experience with them, it is all the more important that their design be pursued urgently. Especially important is verification that they can reliably give the assumed field improvement.

An aggressive way to exploit the field improvement due to these coils would be to save money by reducing the bore size. This would be appropriate if we had confidence that there was sufficient safety margin in the relation between needed-aperture and linear-aperture which has so far been assumed. This would be true if, for example, it could be stated that the SSC was as conservative as the Tevatron. From the graphs in this paper it can be seen that such a claim would, at present, be unjustified. A modest approach would be to exploit the improved field quality only to justify such a claim. An intermediate strategy would be to leave the bore size unchanged and to allow the cell length to increase in order to save money. That is the course of action I will assume in making the following miscellaneous and speculative comments. They are subsidiary to the main conclusions, which have already been stated.

From Figs. 2 and 3 it can be seen that the smear with a 90° lattice is appreciably better than with a 60° lattice. But a more important advantage in increasing the phase advance is to reduce the importance of higher multipoles. Their most important effects are systematic, showing up mainly as chromatic effects, due to the systematic displacement $\eta\delta$ of a particle off momentum by δ at a point where the dispersion is η. Because η is halved when the phase advance is increased from 60° to 90° the convergence of the multipole series, made up of ascending powers of $\eta\delta$, improves greatly as the phase advance is increased. This would further validate the attitude that "the ball on which to keep your eye" is the random quadratic field variation. The modest increase in cost associated with such an increase in phase advance could be recovered from the previously mentioned cost saving of longer cells.

Once it has been accepted that b_2 and a_2 are dominant, it should not be difficult to agree that a plan for guaranteeing their accurate measurement, such as described earlier, should be an essential ingredient of the magnet acceptance procedures. It seems (to me) unlikely that the precision being demanded can be reliably guaranteed from measurements on warm magnets but that remains to be investigated. If cold measurements are needed on every magnet they should clearly be made at the excitation corresponding to injection, though it would be a serious problem if there were any important dependence of random errors on excitation (i.e., random persistent current fields). It also seems sensible, to the extent allowed by costs and to the extent it helps the aperture, to exploit the knowledge of each magnet by compensating it individually.

It has been left uncertain whether or not a_2 trim coils are required and that depends entirely on its achieved rms error. If it is less than, say, ±0.4 then a_2 can be ignored. If it is greater than, say, ±1.0 units then trim coils are needed. The intermediate range can probably be handled by sorting. In any case the measurement precision required for a_2 is the same as for b_2. If full length a_2 coils are not present the redundant measurement method, so highly recommended above, would be unavailable for a_2, but a somewhat less satisfactory redundancy using the full length b_2 coils and measuring the rotation of the multipole axis might be adequate.

All conclusions which have been stated clearly need further study.

References

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