LATTICE AND OPERATION

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Summary

The work of this subgroup concentrated on two main areas. The first concerned the different multipole correction schemes which could be applied to the proposed C.D.R. lattice in order to enlarge its dynamic acceptance. The second is made up of several topics concerning the setting-up and operation of the machine.

Some multipole correction schemes have already been included in the C.D.R. These are indispensable to make the SSC a workable accelerator, and they are based on well proven techniques. They have been reviewed during this workshop and some improvements have been suggested.

Another class of correction schemes has also been considered. Their efficiency is not yet firmly established, and therefore they should not be relied upon at the design stage. However, after some development, they hold the promise of a non-negligible improvement of the machine performance, and therefore no feature in the design should preclude the possibility of their later implementation. Most attention has been given to this class of corrections, and directions for further work on this topic have been suggested.

Discussions on machine operation uncovered no insurmountable problem. The tuning up can be done with sufficiently low beam intensity so that the magnets will not quench. Increasing the longitudinal emittance during acceleration as required might not be easy due to the fact that the beam is intrinsically unstable, but solutions to this problem have been found elsewhere when necessary. Background in the experiments induced by particle losses is a serious concern, and much work remains to be done on this subject.

Multipole Corrections

Chromaticity corrections

In the C.D.R. it is foreseen to correct the chromaticity of the machine with only two circuits of sextupoles. Is this sufficient or would it be wise to foresee the use of a larger number of families?.

With two families it is only possible to correct the first order variation of the tune with momentum. This usually leaves quadratic and third order terms, and it has to be checked that these do not produce too large variations of the tunes over the necessary energy acceptance. More precisely, it is desirable that at $\pm$ 1o/oo energy deviation (injection energy) or $\pm$ .5o/oo (high energy) the tune shift be less than 0.005. The chromaticity to be corrected comes from the focussing in the arcs and in the insertions, and the sextupole errors in the dipoles. The decapole (and higher order terms) in the dipoles add to the chromatic aberrations. The average value of the sextupole and decapole errors in the dipoles (systematic components) will be corrected by specialized windings in the dipoles themselves. The residual random variation of the sextupoles will be minimized by sorting the magnets prior to installation. The effect of the insertions on high order chromatic aberrations has been minimized by choosing the phase advance between two clustered I.R's to be an odd multiple of 90°. Under these conditions, it is found (L. Schachinger) that the high order chromatic aberrations are just tolerable with two families of sextupoles. The recommendation is to stick to two sextupole families, but to apply great care in the correction of the sextupole and decapole effects in the magnets (more on this in the next chapters).

Correction of the systematic sextupole (b_2) and decapole (b_4) errors in the bending magnets

Correction coils will be placed inside the magnets to cancel the average measured value of b_2 and b_4. It is assumed that 90% of the effects can be eliminated in this way. Then the chromaticity correcting sextupoles will be energized so as to cancel the calculated chromatic effect of the focussing quadrupoles in the arcs and in the insertions. Provided that under these conditions a test beam of low intensity and small emittance can be injected and stored, accurate measurements of tunes versus momentum can be made. The chromatic aberrations thus revealed can be minimized by empirically changing the excitation of both the b_2 and b_4 loops, and the chromaticity sextupole circuits.

This procedure would eliminate the average effect of the b_2 and b_4 terms only if these were the dominant contributing factors to the measured chromatic aberrations. If this were not the case, a flattened chromaticity curve would not ensure that errors in the magnets have been on average eliminated. Their influence on the dynamic aperture could still be noticeable.

It is therefore recommended to evaluate the chromatic aberrations produced by residual b_2 and b_4 terms of a few percent of the uncorrected ones, and to compare these with aberrations coming from other sources.

Minimization of the effects of random multipoles in the magnets

Random multipole errors cause a strong reduction of the dynamic aperture. In particular the random sextupole term b_2 plays a dominant role in restricting the linear aperture. In order to get sufficient aperture it is proposed in the C.D.R. to reduce its effect by sorting the magnets on b_2. Alternatively, one could use the already existing sextupole correction windings in the magnets, but this time individually powered, to cancel b_2 down to the level of the precision at which this term can be magnetically measured on each dipole unit. A less extreme solution (R. Talman) would be to foresee a limited number n of circuits for powering the sextupole correction windings and to hook up each magnet to one of these, according to its measured b_2. This is equivalent to an elaborate magnet sorting scheme, but leaves the possibility of reducing another multipole error (for instance a_2) by sorting. With n = 8 circuits it is estimated that the r.m.s. variation of a given multipole will be reduced by a factor of five. This gives a considerable improvement in the linear aperture of the SSC, with the smear at the needed aperture of 5 mm going down from 8.8 % (uncompensated) to 3.2 % (compensated).

Correction of residual effects:

As soon as a beam of low intensity is circulating in the machine, precision measurements are possible which can be used to further reduce the effect of residual errors.

1) Global effects

The easiest measurements concern those parameters, like tune, coupling, resonance excitation, which reflect integrals over one or many turns. These we call global effects. Coupling is easy to measure and to correct, using a small number of lumped skew quadrupoles. According to experience in existing proton machines, it is sufficient to correct it until the horizontal and vertical tunes can be brought as close to each other as 0.001, and this is usually easy to achieve.

Non linear effects show up as resonance excitation, or "stop-bands". The usual technique used up to now to correct these terms consists in changing the tunes of the beam to bring it close to 1 particular resonance (and far from the others) and to monitor the particle losses induced by this resonance. The losses are minimized by empirically tuning the amplitude and phase of a dedicated hardware or software driven correction circuit. The process is repeated on the other lines and possibly iterated. This technique has been widely used on the CERN PS, PS Booster and SPS. It has the disadvantage that the correction is applied with a tune different from the operational one, hence with different betatron functions. Although the losses on the resonance are largely reduced by such a process, it has been found in the CERN machines that it is usually impossible to get a perfect correction. Another strategy has been used in the Brookhaven AGS (J. Herrera). The 12 sextupole circuits were empirically tuned to optimize transmission without departing from the operation best tune. It is a long and tedious process but which gave good results.

Unfortunately, these methods to correct residual non linearities might prove badly suited to a superconducting machine, since they are based on the monitoring of losses. Other means have to be investigated. For instance, it has been remarked (R. Talman) that in tracking programs nonlinearities manifest themselves as spurious spectral lines when the particle amplitudes are Fourier analysed to find the tune. If these lines could be measured on actual machines with a sufficient accuracy, they could provide a means of correcting the nonlinearities. It is recommended to investigate this possibility in existing machines.

2) Local effects

Perfect global corrections just ensure that certain nonlinear terms cancel over one turn or more. Locally important perturbations may still remain. For instance, after a global correction of coupling the planes of betatron oscillation of the particles may be tilted locally. The accumulation of such errors may be serious in large storage rings with tunes in the range 50 to 100. Devising local correction schemes is theoretically possible (A. Dragt). If the exact distribution of multipoles is known over a sector, a correction map can be calculated which eliminates the smear to a high accuracy. To implement this technique in a real machine poses difficult problems. The first has to do with the diagnostics, which have to be much more elaborate and precise than what is available now. It is proposed (S. Peggs) to measure the beam transfer function over a sector by combining the position information from two adjacent monitors with a knowledge of the optics between them in order to calculate the position of the beam centroid at one of the monitors in four dimensional phase space. This can be done by exciting the beam coherently and then recording its position turn by turn, or by measuring the position of the orbit at the beginning and end of a sector for different perturbations applied to 4 correctors placed outside of this sector. It is recommended to develop these techniques in existing machines and also to test their validity with computer simulation. Another difficulty with local corrections has to do with the availability of efficient correctors. For global corrections, it is not difficult to find places around the ring for orthogonal, or at least non-equivalent correctors. To correct over a sector, one has to devise the lattice from the start in order to provide enough non-equivalent slots to put the correctors. For instance it has been shown (A. Dragt) that the 60° lattice proposed for the SSC in the C.D.R. is not suitable for a local sextupole correction scheme. Solutions could be either to change the phase advance, or to displace the spool windings in alternate cells to make room for non-equivalent places. Giving access to the distributed sextupole correction windings in the dipoles would, of course, provide a very flexible correction pattern.

Machine Operation

Any judgement that can be made on the operation of the SSC relies on the experience accumulated at the only hadron collider existing at present, the $S\bar{p}pS$, and at the up to now unique large superconducting accelerator, the Tevatron. The very success of these two machines is essential to the credibility of the SSC enterprise. In particular, the fact that a number of totally new operational difficulties could be overcome in both cases give us confidence that good design and operator skills can do wonders also for the SSC. However, for this to happen it is of extreme importance that the reliability of all machine parts be very good, and that the best possible instrumentation be provided.

Setting up

In very large machines like LEP or the SSC, it is likely that the beam will not circulate for 1 turn at the first injection. This is because tolerances on magnet errors and quadrupole placement to ensure that the uncorrected closed orbit be contained inside the vacuum chamber are too tight to be met in practice. Therefore the beam has to be steered step by step before a global algorithm can be applied. This procedure is delicate in a superconducting machine since particle losses are unavoidable and they must not lead to the quenching of magnets. It has been successfully applied in the Tevatron by using a low intensity beam of around 2.10^{10} protons distributed in 20 bunches. With this intensity the precision of the beam position monitors (B.P.M.) was of the order of 0.3 mm, and this was sufficient for the correcting process to close after one turn. At each step the beam losses were spread over several magnets, and no quenching was usually noticed.

In the SSC the injection energy is almost 7 times higher and the allowed beam intensity will be consequently reduced. However, at 1 TeV the magnetic field in the SSC magnets is a smaller fraction of the maximum field than in the Tevatron magnets at the injection energy of 150 GeV. Taking these two effects into account it is believed that a beam of up to $5\ 10^{9}$ protons can be used to set up the SSC. At this intensity it should be possible to have a B.P.M.

precision of the order of 0.3 mm since the vacuum chamber diameter is much smaller than in the Tevatron, and this will be adequate (R. Meller).

Longitudinal emittance matching

For different reasons (intra beam scattering lifetime, stability of higher modes) the longitudinal emittance has to be considerably increased during acceleration both in the SSC and its high energy booster. This procedure is widely used in existing machines with high density beams. However, it has been found both in CERN machines and in the Brookhaven AGS (E.G. Raka) that it is not always straightforward to implement it.

A fundamentally stable beam, in which the frequency spread is sufficient to Landau damp all the collective modes, is easy to blow up: it is just necessary to "shake" it gently, and rely on the strong coupling of the collective modes to the incoherent spectrum of the single particles to spread the energy more or less evenly inside the beam. This does not apply to the SSC, where the two lowest order longitudinal modes are not Landau-damped, their stability relying on feedback systems. In this case "shaking" the beam usually has very unpredictable consequences. In the CERN PS, where an increase in longitudinal emittance is necessary to pass transition without losses, the beam has to be stabilized momentarily while shaking is applied. This is done by distorting the normal accelerating voltage with a high frequency harmonic cavity, thus creating sufficient frequency spread.

Physics conditions during coast : Background from particle losses

In the SSC it is hoped that the main source of particle losses will be the proton-proton collisions in the experimental areas. The resulting flux of particles is calculable and consequences for the experiments and for the machine are being evaluated. But other effects may play an important role. During a long storage, the beam emittances slowly increase due to scattering on the rest gas and intra-beam scattering. In the $S\bar{p}pS$, it is intra-beam scattering which is mainly responsible for diffusion and the creation of large amplitude tails in the beam distribution. As a consequence, the loss rate is increased in single beam mode because these large amplitude particles reach the bucket separatrix (longitudinal phase plane) or the dynamic aperture (transverse planes). But the effect is more dramatic in beam-beam mode. The high order betatron resonances generated by the very nonlinear beam-beam fields create a "fast" diffusion of particles in the far tails (between 3 and 5 standard deviations σ) of the beam. As a consequence the practical dynamic aperture in beam-beam mode is not much larger than 3σ of the opposing beam. This fact enhances the effect of any slow diffusion mechanism affecting the beam.

For the SSC the beam-beam effect is smaller than in the $S\bar{p}pS$. However, fast diffusion in the tails is observed in this machine, even for very low values of the beam-beam parameters, comparable to the SSC case. It is therefore probable that there will not be a qualitative difference in this respect between the SSC and the $S\bar{p}pS$. The only favourable feature in the SSC is that synchrotron radiation damping should counteract any slow diffusion effect, like beam-gas or intra-beam scattering.

In the $S\bar{p}pS$ during a good store the proton lifetime is of the order of 50 hours as a consequence of the above mentioned phenomena. The beam intensity being around 5.10^{11}p, this means that about 2 10^{6} p are lost every second. In order to prevent these particles from reaching the physics detectors, collimators are installed on the other side of the ring, and effectively catch most of the large amplitude particles since only a few hundreds reach the detectors every second. Unfortunately, this small proportion is sometimes sufficient to create background problems. With 10^{14} protons circulating in the SSC, the acuteness of the problem will be increased by more than two orders of magnitude, and therefore serious attention should be devoted to it.

At the design stage, it is recommended to minimize any source of noise and modulation of the parameters (especially of the tune) which, however small, are known from $S\bar{p}pS$ experience to enhance the beam-beam induced diffusion rate. Also extremely effective collimation systems have to be devised.