MODELING THE SSC

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An interactive, graphical simulation has been developed which is being used to design operational procedures and correction algorithms for the SSC. All algorithms use only measurable quantities to calculate corrector strengths, and thus are suitable for correcting a real accelerator. This strategy has been successfully applied to establishment of first turn, global orbit correction, global decoupling, and systematic multipole correction. In all cases, several different sources of error were included in the simulations, in order to take into account the effects of collusion between errors.

Introduction

The SSC will be a large, complex accelerator. Each ring will contain approximately 3800 dipoles in 288 cells. There will be nearly 700 beam position monitors and orbit correction dipoles per ring. Half an hour will be needed to fully load both rings, making errors in this procedure extremely costly. Recovery time from a quench will be a minimum of 30 minutes. Large systematic multipole errors from persistent currents in the dipoles must be corrected quite accurately using beam measurements. Time decay of systematic multipoles, as observed in the Tevatron, may be large and must be corrected dynamically. Dynamic correction of the tune and chromaticity up the ramp will be necessary. Especially during commissioning, corrections must be made in the presence of other errors, not yet corrected, which will complicate the correction process. In light of these complications, it will be necessary to make many corrections automatically, and it is imperative that we understand how corrections will interact and develop algorithms now which can handle the complex SSC environment.

To this end we are developing simulations of SSC operations. The initial focus has been on commissioning, with simulation of tune correction, orbit correction, global decoupling and non-linear chromaticity correction. Efforts are made to make these simulations as realistic as possible. All simulations use only quantities which will be available in the real accelerator, with realistic measurement errors. Many sources of errors, both systematic and random, are included in the simulations, so that collusion between errors is properly taken into account.

The simulations use interactive, highly graphical interfaces, which economically present the designer with diverse information which is useful during design for debugging potential correction algorithms and during operation for diagnosing failures of both the algorithms and the measurement and correction devices in the machine. We have endeavored to make these interfaces uniform across the various correction algorithms. Eventually we envision various levels of automation, from fully automated correction to low-level manual control, with the level controlled by the user, so that when an automatic algorithm fails, the user can step down through levels of manual operation to see what went wrong and correct it. Initially most algorithms have been implemented with a level of automation suitable to our confidence that the underlying algorithm will be successful, and more automation added as our confidence in and experience with the algorithm increases. We see a similar process taking place during commissioning and operations, where the procedures developed through experience with the operation of the machine will be an essential part of all correction algorithms.

Orbit Correction

Establishing a first turn will be one of the earliest tasks in commissioning the SSC. We have simulated both first-turn and global orbit correction, using the same correction algorithm [1]. The algorithm used employs local, three-corrector bumps. Advantages of such a scheme are: it works on an arbitrary region of the accelerator, and thus it can be used for local, first-turn, and global orbit correction; effects of the algorithm are confined to the region of interest; and the algorithm is stable in regions with no beam position monitors. This implementation allows the goal orbit to be any arbitrary trajectory, and permits monitors and correctors to be weighted. The latter is very useful for instance when monitors are unreliable, and for prohibiting the program from setting correctors to currents larger than they will in reality be able to deliver.

The graphical interface to orbit correction is shown in Figure 1. On the right is a bird's-eye view of the SSC, with the highlighted area indicating which portion of the machine's beam position monitor readings are displayed on the left. The region of interest can be changed by zooming or panning on either the bird's-eye view or the BPM display. The buttons below the displays allow the user to correct the highlighted region and reinject beam, to find the closed orbit of the machine, to save the current state of the simulation, and various other tasks.

This algorithm was successful in producing corrected orbits for particles injected on-axis, on-momentum around the SSC lattice, in simulations of machines created using several random seeds. Errors introduced include: random dipole steering errors and quadrupole misalignments; dipole misalignments; random multipole errors; errors which produce linear coupling such as quadrupole rotations and random skew quadrupole errors in the dipoles; and systematic multipoles which have been fully corrected. Simulations with systematic multipole errors which have been 90% corrected have been performed also, to date without random multipole errors. The beam position monitors were misaligned with respect to their quadrupoles, and had finite resolution. For the 90° injection lattice, after a first turn orbit was found, global correction yielded *r.m.s.* orbits in accord with theoretical estimates. The results of this simulation were used to set corrector strength specifications and to provide corrected

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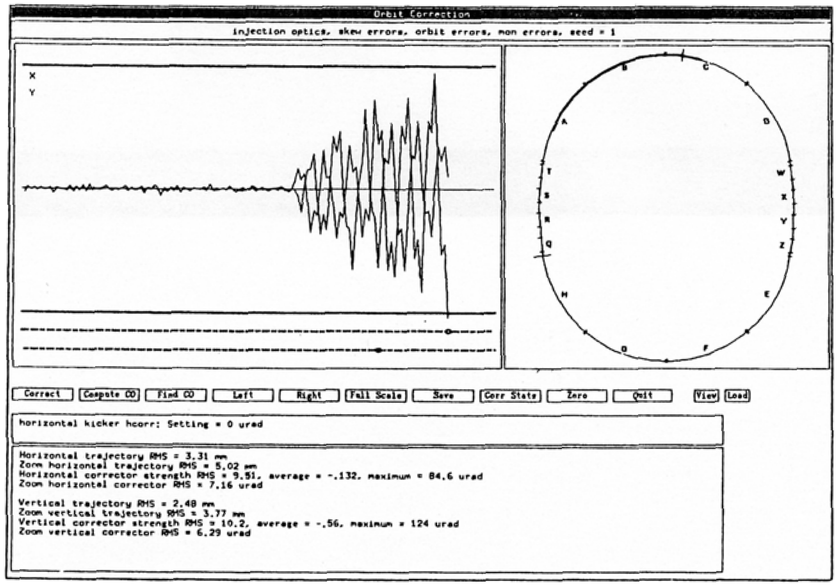

Figure 1. Dependence of the number of accurate iterations on the approximation amplitude, for various pendulum swing amplitudes.

machines for the study of other corrections. Further studies will include injection errors, broken monitors and correctors, and the design of economical interaction region corrector configurations.

Decoupling

The simulation of global decoupling was done using two families of skew quadrupole correctors, with one member of each family in each straight section. The correction procedure is a familiar one, used in the Tevatron, CESR, and the SPS [2]. The two tunes are brought closer and closer together by setting the strengths of the two skew quad families to minimize the tune separation. This procedure is iterated until the tunes are close enough to satisfy the user. This simulation is written in terms of an integrated control system, in which measuring the tunes, plotting them as a function of quad strength, and subsequently changing the magnet settings, can all be done from within the context of a single interface. A typical display is shown in Figure 2. The plot of tunes *vs.* quad strength is generated automatically, with the horizontal scale adjustable by the user. Zooming and panning functions are available. The new quadrupole strength is set with the mouse, by selecting the point on the plot where the tunes are closest together. The difference between the two tunes is displayed as the mouse moves horizontally across the plot.

Coupling errors were introduced into the 90° SSC injection lattice by rotating and misaligning all quadrupoles (including the interaction region quadrupoles) and adding random quadrupole and skew quadrupole errors to the dipoles, which were also misaligned, rotated, and had normal and skew random sextupole errors added. After the orbit was corrected using the scheme described in the previous section, the decoupling procedure was applied to four machines, generated using four different random seeds. After one iteration on the corrector settings, the resulting coupling coefficients met the SSC specifications, i.e. they were all less than 0.005.

Further work in this area will include studies of the collision lattice and inclusion of systematic skew quadrupole errors in the dipoles. The placement of the correctors in this study is not ideal for collision optics, so an alternative placement will be studied. Local decoupling schemes may be necessary, and should be investigated.

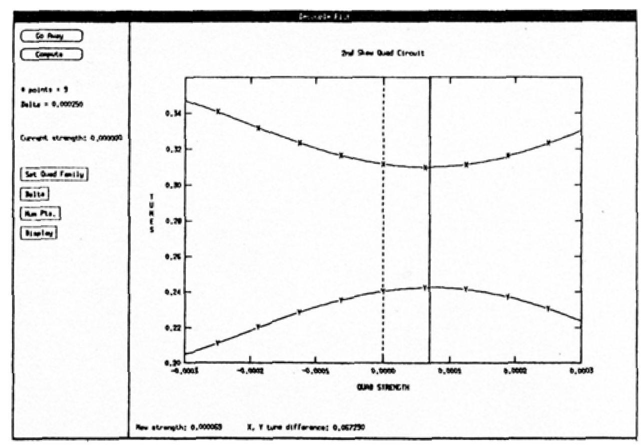

Fig. 2. Decoupling display during correction. The dotted line indicated the current skew quadrupole setting, while the solid line is the user-controlled cursor used to select the new setting.

Non-linear Chromaticity Correction

The SSC will suffer from very strong systematic multipoles due to persistent currents, and these must be corrected for successful operation of the machine. It should be possible to dead-reckon a large fraction of the correction (perhaps 90%) based on warm measurements of the magnets and measurements of the superconductor. However, even a residual error of 10% will cause very large momentum-dependent tune shifts as shown in Figure 3. In the figure, the tune shift is plotted out to the needed momentum aperture of $\pm 0.1\%$, and the vertical scale goes from 0.05 to 0.55. The design requirement on the tune shift is that the tunes stay within the dotted boxes. The operational procedure in this case involves changing the machine RF to move the beam off-momentum and measuring the tune for at least five different momentum values. Initially the change in momentum must be very small ($\leq \pm 0.0025\%$) in order to keep the tune shift small and the beam in the machine. After correction for this small momentum offset, the momentum offset is increased in seven steps until correction of the tune shift (to ≤ 0.005) is achieved at the largest required momentum offset of $\pm 0.1\%$ [3].

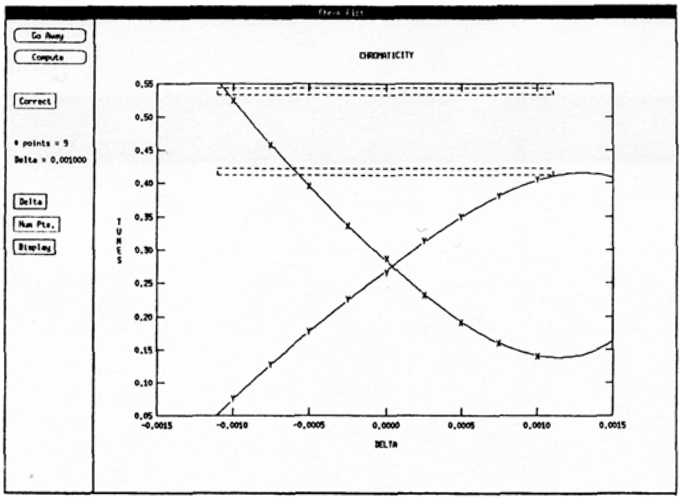

Fig. 3. Chromaticity correction display before correction, for a 4 cm magnet aperture and 1 TeV injection energy. The tunes are required to stay inside the dotted boxes.

The correction procedure uses sensitivity functions for the correctors which are determined from simulations of the ideal machine. To compute these functions, systematic sextupole, octupole, and decapole correctors are set to known strengths (each order independently) in the ideal, linear lattice, and the tune shift with momentum is measured and fit to a polynomial which is first order in momentum offset for the sextupole correctors, second order for the octupole correctors, and third-order for the decapole correctors. These polynomials are then considered to be part of the model of the machine, in much the same way as the beta functions are, and are inputs to a simulation which uses a more realistic model, including orbit errors, tune measurement errors, and, in future, random multipole errors.

For all systematic error correction schemes studied, this procedure was successful in correcting the momentum dependent tune shift to within the required tolerance.

Future Work

We now have the necessary tools to make a full simulation of the initial steps in commissioning the SSC, including systematic multipole errors which are only 90% corrected, random multipole errors in the dipoles, and misalignments and rotations of dipoles and quadrupoles. This process begins with achieving the first turn orbit, followed by global orbit correction. These operations complete, the machine is then decoupled and the chromaticity is corrected. The correct sequence of operations, and the number of iterations necessary will be determined by the simulation.

The algorithms described above are the beginning of an effort to simulate many SSC operations in an environment as close as feasible to the real machine. Two paths remain to be followed. The first is the development of more and more realistic simulations, with the addition of equipment failures, worst-case multipole errors, injection errors, time-dependent drifts in systematic errors, errors which are neither entirely systematic nor entirely random (such as those caused by variation in superconductor from different manufacturers or temperature variations around the ring), and the like. The second path is the development of more operational procedures such as beta function measurement and correction, tune and chromaticity correction up the SSC ramp, and correction of the orbit and coupling during the transition to collision optics. Of course these paths are not completely independent since the addition of more and more errors will necessitate the development of new algorithms to correct them.

In this work we emphasize the eventual use of these correction algorithms in the controls system of the SSC. Currently, the program architecture is being redesigned and reimplemented to be hardware and software independent so that it will be relatively straightforward to keep pace with current technology advances between now and the time when the controls system of the SSC is implemented. The current modeling core is Teapot [4], but we are converting the simulations to use a standard data format so that other modeling programs can be substituted [5]. We also plan to investigate the use of the SSC database as the final source of information about the accelerator, and to use it to store various machine models [6].

Conclusions

Realistic simulations of several operational procedures which will be necessary for commissioning the SSC have been successfully performed. These procedures range from those which are familiar and routine on existing accelerators such as orbit correction and decoupling to those which are more unusual and specific to the SSC such as non-linear chromaticity correction; all will be crucial to the successful operation of the SSC. These simulations are highly graphical, and since their only inputs are quantities which can be measured in the accelerator, they are especially well suitable for eventual use in the control room of the real machine.

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