Title
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Publication Date
1983-08-01

UC-38
LBL-16019
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Accelerator & Fusion Research Division

Presented at the 12th International Conference on High-Energy Accelerators, Fermi National Accelerator Laboratory, Batavia, IL, August 11-16, 1983

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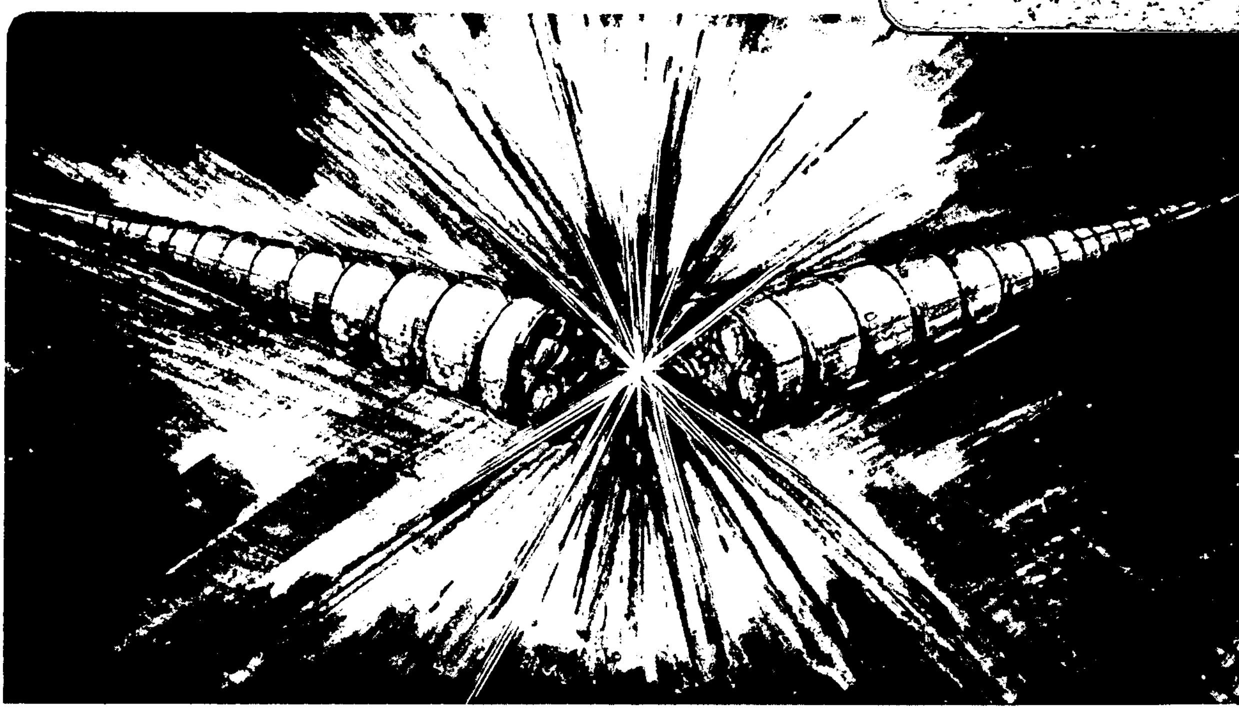

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

LBL-16019

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*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, U. S. Dept. of Energy, under Contract No. DE-AC03-76SF00098.

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Summary

The effects of magnet misalignments in a 20-TeV on 20-TeV $\bar{p}p$ collider are simulated numerically. Both short-range and long-range alignment errors are considered for an example lattice design, and closed-orbit errors are simulated. Finally, closed orbit corrections using a "least-squares" scheme are performed. Automatic surveying methods are attractive for a multi-TeV collider, because of the large accelerator circumference, the large number of magnets, and the small tunnel cross section. The specific example of an automatic surveying scheme based upon an Inertial Navigation System is discussed, and the most important sources of error are described.

Lattice

The storage ring lattice considered in this study is a $\bar{p}p$ version (i.e., a single-ring version) of a 20-TeV on 20-TeV collider, sometimes referred to as the Superconducting Super Collider (SSC). A two-ring, proton-proton version of this lattice is being described at this conference.[1] Some important parameters of this lattice are given Table 1. The beta functions in both planes range approximately from 2 m to 1700 m in the straight sections, and from 90 m to 275 m in the arcs.

Table 1. Collider Parameters

Max. Energy of Each Beam	20 TeV
Circumference	78.144 km
Number of Superperiods	6
Number of Quads per Straight	28
Number of Quads per Arc	147
Total Number of Quads	1050
Total Number of Bend Magnets	5184
Bend Field at 20 TeV	8.307 T
Vertical Tune	82.39
Horizontal Tune	88.40

Numerical Simulations

The purpose of this calculation is to simulate numerically the consequences of surveying and alignment errors on the closed orbit of the stored beam. The surveying errors are first simulated in some detail in order to produce realistic, correlated alignment errors for quadrupole magnets. It is, of course, the transverse offset errors of quadrupole magnets which produce the bulk of the closed orbit errors. After the closed orbit errors have been calculated, the measurement and the correction of the closed orbit are simulated. The final result consists of the residual closed orbit errors after correction.

The computer program ALIGN used in this calculation was originally developed for performing similar calculations concerning PEP.[2,3] Table 2 summarizes the survey and alignment errors which were used in these simulations. Generally, these assumptions are intended to be optimistic: it may be difficult to keep these errors so small.

Survey Monument Errors (Horizontal Plane)

The overall scheme of survey and alignment assumed here for the SSC closely follows the one which was used successfully for PEP.[4] First, a surface survey locates twelve primary monuments, one placed at each end of every long straight section. The purpose of these monuments is to determine the overall shape of the storage ring, and the surface survey takes place over long distances (on the order of ten kilometers). Only the radial errors of monuments are considered here, since they contribute more to the closed orbit errors than do the azimuthal errors. Figure 1 shows the nature of the errors simulated by ALIGN. For simplicity, we consider a series of four primary monuments (labelled A, B, C, and D) which are to be placed accurately in the pattern shown. If we assume that monuments A and B have been placed satisfactorily, then monument C should be located at a distance L from monument B

Table 2. Survey and Alignment Errors Assumed

Sources of Errors	Number of Elements	$\pm\Delta\theta$ (rad)	Characteristic Distance L (m)	Transverse Error (mm) $\pm a = \pm L\,(\Delta\theta)$
Horizontal Plane				
Primary Monuments	12	$\pm 2 \times 10^{-6}$	~6500	~±13
Secondary Monuments	432	$\sim\pm 5.6 \times 10^{-6}$	160	±0.9
Individual Quads	1050	$\sim\pm 2.5 \times 10^{-6}$	~80	±0.2
Vertical Plane				
Individual Quads	1050	$\sim\pm 2.5 \times 10^{-6}$	~80	±0.2

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and at a specific angle shown by the dotted line. If the radial position of monument C is not located with perfect accuracy, however, the angle will have an error $\pm\Delta\theta$, such that the radial error of monument C is $\pm a = \pm L\ (\Delta\theta)$. Similarly, the locations of monuments B and C are used to locate monument D. Note that these errors accumulate, in the sense that the error in locating monument D depends on the accuracy with which monument C has been placed. Since the twelve primary monuments are located on a circle, closure is used to ensure that in these simulations the first and last primary monuments are located consistently.

The storage ring magnets in the arcs cannot be located relative to the primary monuments, so a network of 432 secondary monuments is placed in the tunnel and is surveyed relative to the primary monuments. The secondary monuments are placed sufficiently closely so that a clear line of sight is available between neighboring secondary monuments. The curvature of the storage ring produces a sagitta of 23 cm in a portion of the ring located between two adjacent secondary monuments. The surveying errors of secondary monuments accumulate in the same manner as for primary monuments (shown in Figure 1). However, the closure constraint is different in that the first and last secondary monuments in an arc are located relative to the appropriate primary monuments. No secondary monuments are located in the straight sections, so that the alignment errors in the straights are underestimated. However, this is probably a reasonable model, since it is likely that special efforts will be made in magnet alignment and orbit corrections in the straights, where there are large values of the beta functions.

The long-range magnet misalignments in the horizontal plane are attributable to the errors in locating survey monuments. However, in the vertical plane we assume that there are no significant long-range surveying errors, because a liquid level system[5] such as that used at PEP can provide highly accurate elevation references at every survey monument.

Magnet Alignment Errors

The individual storage ring elements are located horizontally relative to a line-of-sight established between the nearest survey monuments. Vertically, they are located relative to elevation reference points provided by the liquid level system. Again, the most important alignment errors (in terms of producing orbit errors) are the transverse alignment errors of quadrupole magnets. An offset quadrupole magnet deflects the particle beam, because it produces a spurious dipole field at the design orbit.

Closed Orbit Errors

The quadrupole magnet offsets simulated by ALIGN, along with the betatron functions and the betatron phase advances of the ideal lattice, are used to calculate the closed orbit errors in the SSC.

Simulations of Orbit Correction

The measurement of closed orbit errors is simulated in ALIGN by specifying the locations of 336 beam position monitors. The beam position is measured at each monitor with a random measurement error (one standard deviation = 0.5 mm). Then, the information from the position monitors is utilized by a "least-squares" orbit-correction subroutine MIKADO[6] to calculate the strengths of correction dipole magnets. In these calculations, 336 correction dipoles were assumed, and the computer program selected the most effective 25 or 50 correctors from the ones available. There are six monitors and six correctors in each straight section, and the rest are distributed throughout the arcs.

Ensembles of Rings

Since the numerical simulations described here are subject to statistical errors arising from the selection of random numbers, the results reported here all refer to averages over ensembles of 5 possible storage rings generated by the computer program.

Table 3. Results of Simulations

Run Number	Sources of Errors Included	Number of Correctors Used		Closed Orbit Errors (mm) Ring (RMS)	Straights (max)	Arc (max)	Arc (max) / a
Horizontal Plane							
1	Primary Monuments	25	Uncorr.	50.19	453.34	23.69	1.8
			Corrected	28.28	256.67	19.45	
2	Secondary Monuments	25	Uncorr.	125.78	867.06	75.02	83.4
			Corrected	64.67	689.75	99.80	
3	Individual Quads	25	Uncorr.	10.04	48.46	24.31	121.6
			Corrected	1.16	7.52	3.83	
4	All the Above	25	Uncorr.	133.47	974.55	85.97	
			Corrected	64.38	703.47	80.13	
5	All the Above	50	Uncorr.	133.47	974.55	85.97	
			Corrected	42.28	376.04	128.35	
Vertical Plane							
6	Individual Quads	25	Uncorr.	13.53	62.30	27.41	137.1
			Corrected	1.27	7.46	4.07	

Results of Simulations

Table 3 summarizes the results of these simulations. The rows in the table give the results of the different simulation runs. Runs 1 through 5 concern the horizontal plane, and Run 6 is a vertical plane calculation. The column labelled "Number of Correctors Used" gives the number of dipole steering mangets selected from the 336 available. The next three columns give the closed orbit errors before and after orbit correction. The first of these gives the RMS orbit errors all around the ring, and the next two give the maximum orbit errors observed in the straights and the arcs. The last column provides multiplication factors relating the maximum uncorrected orbit error in the arcs to the size of the alignment errors which produced the orbit. These factors are useful for evaluating different assumptions about alignment accuracies, since the uncorrected orbit errors are proportional to the alignment errors. The denominator "a" is the transverse error defined in Figure 1 and listed in Table 2.

Runs 3 and 6 show that the misalignment of individual quadrupole magnets produces maximum closed orbit errors of around 25 mm in the arcs. It is quite encouraging that these errors can be corrected to about 4 mm, in both planes. The orbit errors are about twice as large in the straight sections, but special steering can be provided in the straights to solve this problem.

Runs 1 and 2, however, indicate that monument surveying errors can lead to horizontal orbit errors of about 80 mm in the arcs. These errors are not readily corrected. The orbit correction program was able to make only modest improvements. In fact, in Run 2 the orbit was improved in the straights only at the expense of worsening them in the arcs.

All types of horizontal magnet alignment errors are included in Runs 4 and 5. Run 5 shows that the use of more correctors generally improves the orbit correction, but only at the cost of larger orbit errors in the arcs.

It is clear that the closed orbit errors encountered in this simulation are unacceptable in terms of what can be accommodated by magnet aperture allowances. This statement applies especially to the rather uncorrectable orbit errors due to monument surveying errors. Of course, the specific numerical predictions of this calculation depend on the details of the physical model and the correction scheme. Nevertheless, the primary conclusion of this paper is that a closed orbit correction scheme which is widely and successfully used today appears inadequate for the SSC. It is likely that providing closed orbit allowances in the magnet apertures and inventing better schemes for closed orbit corrections will both be required in order to arrive at a consistent design for the SSC.

If the SSC were perfectly aligned, or if the misalignments were perfectly compensated, then there would be no closed orbit errors. Therefore, it is plausible that some solution exists. An important task will be to demonstrate, presumably with simulations, that some scheme will actually work. Only then will we know that small-aperture magnets will be usable in spite of alignment errors, magnetic field errors, and beam measurment errors.

Possible future extensions of these simulations include looking at beam emittances and x-y coupling, adding the effects of magnetic field errors, and combining these orbit calculations with beam-beam simulations.

Automatic Survey and Alignment

Because of the large number of individual storage ring elements, the bulk of the survey and alignment task for a large accelerator consists of surveying and aligning individual elements relative to nearby monuments and to liquid-level reference elevations. This task can be divided into the five following sub-tasks.

1. Set up surveying instruments.
2. Adjust instruments to take readings.
3. Record data.
4. Analyze data.
5. Re-align magnets and other elements.

Traditionally, all five sub-tasks have been performed manually. More recently, some sub-tasks have been automated through the development of new instruments, such as at PEP (sub-tasks 3 and 4) and at the SPS (sub-tasks 2 and 4). It is clear that for a huge project such as the SSC, it would be a substantial advantage to automate all five sub-tasks. Subtasks 2, 3, and 4 can be automated readily. Subtask 5, the re-alignment of elements, might be accomplished by means of some type of robot. Sub-task 1, the setting up of surveying instruments, may be the most difficult to automate.

Two approaches to automating the setting up of surveying instruments come to mind. One way is to install permanently around the ring a series of surveying instruments, each of which is to survey a small portion of the storage ring. Although this approach has advantages, the cost of a large number of precision surveying instruments may well be prohibitive. A second approach is to consider one mobile surveying system which surveys elements as it moves around the ring. If this mobile system can keep track of its own position as it moves between survey monuments, the surveying task might be greatly simplified. The type of instrument which is required for an isolated vehicle to keep track of its own position is an Inertial Navigation System.

Inertial Navigation System

An Inertial Navigation System (INS) was considered but not selected for the surveying of PEP beam elements.[7,8] Similar considerations apply to the use of an INS for a multi-TeV collider.

The basic idea is to mount an INS and an "optical tracker" on a vehicle. As the vehicle passes through the tunnel, the optical tracker measures the locations of LED targets mounted on each accelerator magnet. The INS itself consists of an Inertial Measurement Unit (a set of accelerometers mounted on a gyro-stabilized platform), a clock, and a computer; and the task of the INS is to keep track of the location of the vehicle as it moves along.

If we assume that the INS can re-establish its position at each survey monument, then the task of the INS is to keep track of position during the time it takes for the vehicle to move from one monument to the next. A vehicle speed of 1 m/s, for example, implies that 150 seconds would be required to traverse this distance.

An INS can suffer from a large number of errors including initial orientation error, accelerometer scale error, accelerometer bias error, accelerometer drift, high-frequency accelerometer noise, and gyroscope drift. All of these errors can be important, but accelerometer bias is particularly serious. Let us make the optimistic assumption that accelerometer bias can be kept to less than $\pm 9 \times 10^{-6}$ m/s^2. Then the time for the position uncertainty to grow to ± 1 mm is

$$t = \sqrt{\frac{2(.001)}{9 \times 10^{-6}}} = 15 \text{ seconds} .$$

In 150 seconds, the uncertainty would grow to ± 100 mm, so clearly the accelerometer bias can be a fatal source of error.

The only method to reduce the position uncertainty is to provide the INS with additional information on acceleration or velocity, since position information is available only at the survey monuments. Possibly the most promising approach is to provide additional velocity "updates" by stopping the vehicle periodically to measure "zero velocity", or by measuring the position of a fixed target several times. In any case, the apparent inability of an INS to keep track of position all by itself means that it is necessary to study errors, calibrations, and updates in great detail in order to demonstrate the feasibility of using an Inertial Navigation System for surveying storage ring elements.

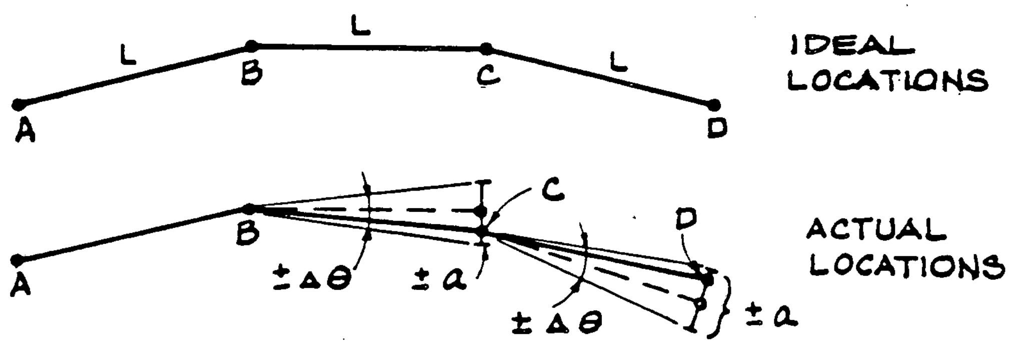
Acknowledgements

We wish to thank Al Garren for his preparation of a $\bar{p}p$ version of his lattice for these simulations.

References

1. A.A. Garren, "20 TeV Collider Lattices with Low-β Insertions," This Conference.
2. R. Sah, "Closed Orbit Distortions due to Survey and Alignment Errors in PEP I," PEP Note 135 (1976).
3. E. Close and A. Garren, "Orbit Properties in PEP with Magnet Misalignments," PEP Technical Memo 157 (1978).
4. T. Lauritzen and R.C. Sah, "The PEP Laser Surveying System," IEEE Trans. on Nucl. Sci., NS-26, No. 3, 4140 (1979).
5. T. Laurizten and R.C. Sah, "The PEP Liquid Level System," IEEE Trans. on Nuc. Sci., NS-28, No. 3, 2876 (1981).
6. B. Autin and Y. Marti, CERN/ISR-MA/73-17 (1973).
7. "PEP Nuclear Accelerator Alignment Concepts," TRW Report 6452.10-75-101, December 29, 1975.
8. R. Sah, "Automatic Surveying Techniques," PEP Note 210 (1976).

Figure 1. Survey Monument Errors



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