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ISABELLE CLOSED ORBIT CORRECTION SYSTEM*

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SUMMARY

The proposed closed orbit correction system for the ISABELLE storage accelerators is described. Results given include the initial orbit displacement error expected, the degree of correction that is expected by moving quadrupoles and by exciting dipole correction coils, the limitations on orbit correction due to the number and location of the probes (pick-up electrodes) and the accuracy requirements on the power supplies that stem primarily from the need to keep the two narrow beams in proper collision with each other.

I. INTRODUCTION

The closed orbit correction system in ISABELLE may be thought as having two separate functions. One function is global correction of the closed orbit around the two rings of the accelerator. The second function is local beam steering at each of the beam intersection points, in order to regulate the collision of the two beams. Local beam steering requires four dipole correction coils around each intersection point or 24 such correction coils in an accelerator having six intersection points. It appears economical to use the local beam steering correction coils for global correction of the orbit. The number of correction coils provided for global correction is 48 coils per ring, and thus half of these correction coils have dual roles, being used for both global correction of the closed orbit and for local beam steering. An attempt has been made to reduce the number of correction coils, and the 48 coils per ring is considerably less than the four correction coils per betatron wavelength or 84 coils per ring which is often assumed to be required.

The degree of closed orbit correction achievable depends on the number of probes (pick-up electrodes), the number of correctors, and the accuracy of the correction coil power supplies. The orbit will also be corrected by moving the quadrupoles, as this reduces the number of dipole correction coils required, and also reduces the magnetic field that the correction coils need to provide.

The number of probes is roughly four per betatron wavelength or 90 vertical probes and 96 horizontal probes. The number of vertical correctors or dipole correction coils is eight per sextant or 48 around the ring and there are the same number of horizontal correctors. These correction coils are located in the quadrupoles and are azimuthally distributed roughly uniformly in betatron phase. Of the eight dipole coils per sextant, four are also used for local steering of the beam at the intersection point, and these four were distributed in betatron phase to allow them to be effective for global correction of the orbit.

The arrangement of the probes, dipole correction coils and quadrupoles around the ring is shown in Fig. 1.

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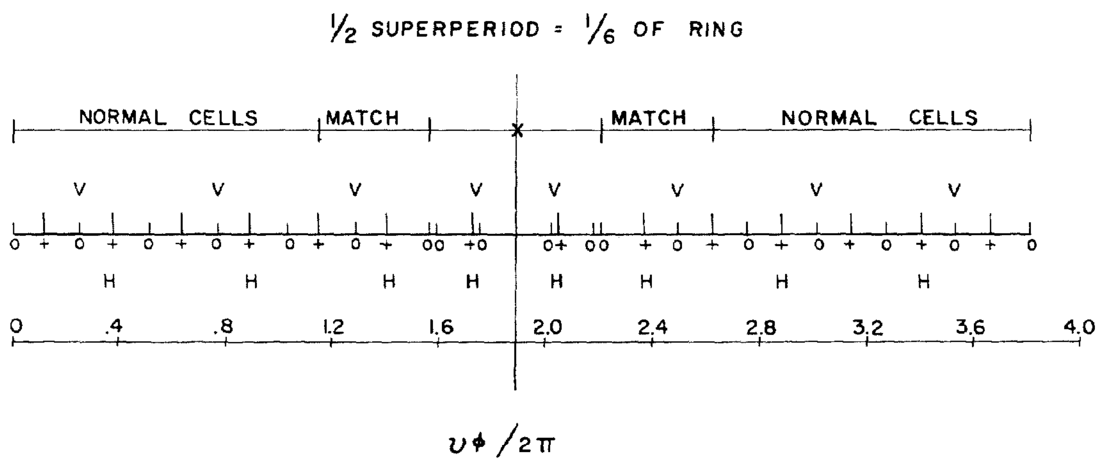

Fig. 1. Arrangement of probes, dipole correction coils, and quadrupoles around the ring. Symbols are defined as follows: 0, vertical probe; +, horizontal probe; V, vertical dipole coil; H, horizontal dipole coil; |, horizontal quadrupole; ı, vertical quadrupole.

The accuracy of the power supplies for the dipole correction coils needs to be sufficient to maintain proper collision of the two narrow beams which are crossing at a small angle. This requires a power supply accuracy at high field excitation of 10^{-4} for the correction coils in the two quadrupoles on either side of the intersection point and of 10^{-3} for the remaining correction coils.

The proposed correction system is believed to be able to correct the closed orbit as follows: Vertically, the peak corrected orbit displacement will be about 2 mm in the center of the divergent normal quadrupoles. The local beam steering system will maintain the vertical position or the crossing point within 0.1 mm at 30 GeV and within 0.02 mm at 200 GeV. Horizontally, the displacement will be about 1 mm in the center of the convergent normal quadrupoles. The local beam steering system will maintain the horizontal position at the crossing points within 0.2 mm at 30 GeV and within 0.04 mm at 200 GeV.

II. LOCAL BEAM STEERING

Accurate control of the vertical and horizontal position of the beam at the beam crossing points is obtained by using four 1 kG dipole coils, two on either side of the crossing point, to obtain a local bump in the closed orbit. The vertical bump coils are in Q1, the vertically focusing quadrupole adjacent to the crossing point, and in QDM, the vertically focusing quadrupole in the matching section. The horizontal bump coils are in Q2, the horizontally focusing quadrupole near Q1, and in QFM, the horizontally focusing quadrupole in the matching section.

Each of the four coils produces the bump $\Delta\theta_k = \Delta B_k L_k / B\rho$, where ΔB_k is the dipole coil field, and L_k is its length. To produce a local bump which does not affect the central orbit outside the region contained by the four coils, the bumps $\Delta\theta_k$ must satisfy the two equations

$$\begin{gathered}\sum_{k=1}^{4} \beta_k^{\frac{1}{2}}\, \Delta\theta_k \sin\nu\, (\varphi_k - \varphi_1) = 0, \\ \sum_{k=1}^{4} \beta_k^{\frac{1}{2}}\, \Delta\theta_k \sin\nu\, (\varphi_k - \varphi_4) = 0,\end{gathered} \tag{2.1}$$

where B_k and φ_k are the beta function and phase at the particular bump, and it has been assumed that the field bumps may be treated as point field bumps. Since we have four parameters and only two equations, we can obtain any desired position and slope of the orbit at the crossing point.

Computer studies indicate that 1 kG dipole coils can produce an orbit displacement of about 7.5 mm at the crossing points. A more exact set of equations that applies to field bumps of finite extent is

$$\begin{gathered}\sum_{k=1}^{4} \beta_k^{\frac{1}{2}}\, \Delta\theta_k \sin (\varphi_k - \varphi_1)\, f\,(k,\, 1) = 0, \\ \sum_{k=1}^{4} \beta_k^{\frac{1}{2}}\, \Delta\theta_k \sin (\varphi_k - \varphi_4)\, f\,(k,\, 4) = 0, \\ f(k,\, n) = \frac{1}{L_k} \int ds\, (\beta/\beta_k)^{\frac{1}{2}} \frac{\sin\nu(\varphi - \varphi_n)}{\sin\nu(\varphi_k - \varphi_n)}\,.\end{gathered} \tag{2.2}$$

The colliding proton beams in ISABELLE have small transverse dimensions. The beam size in the vertical direction is about 2 mm at 30 GeV and about 1 mm at 200 GeV. In order to make the two beams collide and to keep them colliding, the vertical position control of the beam needs to be accurate within a small fraction of the beam size. The accuracy of the power supplies used to excite the dipole correction coils needs to be good enough to give this control of the vertical position of the beam.

Two effects were found to be important in determining the required accuracy for the power supplies for the dipole correction coils.

1) The current in the dipole correction coils may change with time. If a power supply has an accuracy of 10^{-3}, then it is assumed in this paper that this means that the current in the coils may change with time by 10^{-3} of the maximum current the power supply is designed to deliver. It is possible that this drift in the current may be correctable by some feedback mechanism using observations on the beam. However, no such correction has been assumed here. It is assumed in this paper that inaccuracies in the power supplies should be small enough so that this current drift will move the beam vertically by less than 1/10 the vertical size of the beam.

2) Interaction between the different local bump steering systems. Each beam crossing point has four dipole correction coils, two on either side, which make up the local beam steering system for this particular crossing point. These four dipole correction coils are used to generate a local orbit bump to adjust the position of the beam at the crossing point without affecting the closed orbit at any other location around the accelerator ring. Because of inaccuracies in the power supplies, the local orbit bump generated by a local beam steering system may not be truly local and affect the beam position at other crossing points. This interaction between the six local beam steering systems at the six crossing points is undesirable and may possibly lead to an unstable situation if this interaction is strong enough. It is assumed in this paper, that inaccuracies in the power supplies should be small enough so that the local beam steering system at one crossing point will move the beam at any other crossing point by less than 1/10 the vertical size of the beam.

Considerations based on the above two effects lead to the accuracy requirements that the power supplies for the correction dipole coils in the Q1 and Q2 quadrupoles have an accuracy of 10^{-4} and power supplies for the dipole coils in the normal quadrupoles QD and QF have an accuracy of 10^{-3}. This power supply accuracy provides vertical control of the beam at the crossing point which is better than 0.1 mm at 30 GeV.

Errors in the horizontal position of the beam will not keep the beam from colliding, but will move the collision region longitudinally, that is along the direction in which the beams move. Because of the small crossing angle of the beams, about 10 mrads, a small horizontal displacement of the beam results in a much larger longitudinal shift in the position of the collision region, larger by about a factor of 100. The accuracy requirement given above of 10^{-4} in the power supplies for the dipole correction coils in Q1 and Q2, and 10^{-3} for those in the normal QD and QF, provides longitudinal control of the position of the collision region which is better than 4.5 cm. The collision region has a longitudinal extent of about 70 cm.

III. GLOBAL ORBIT CORRECTION

Before any correction of the closed orbit is made, the largest sources of field errors that distort the closed orbit are random errors in the location of the quadrupoles, assumed to be 0.25 mm rms, and random errors in the vertical alignment of the dipoles, assumed to 5×10^{-4} mrad rms. Vertically, this produces an rms orbit displacement of about 6 mm due to the quadrupole error and about 3 mm due to dipole error, and a total rms displacement Δy_{rms} = 7.0 mm as measured in the center of the defocusing quadrupole, QD, in the normal cells. The corresponding total rms displacement horizontally is Δx_{rms} = 7 mm as measured in the center of the focusing quadrupoles, QF, in the normal cells. The peak displacement of the orbit will be, with a 90% probability, ± 30 mm horizontally and ± 30 mm vertically. The beam has a better than 90% chance of going around the accelerator before any corrections are made.

The first correction of the orbit may be made by moving the quadrupoles. The important limit on how much correction can be achieved in this way is the accuracy with which the quadrupoles can be moved which is assumed to be 0.075 mm rms. This correction reduces the rms displacement down to about Δy_{rms} = 3 mm and Δx_{rms} = 2.3 mm, and the peak displacement of the orbit, with 90% probability, to ± 10 mm vertically and ± 10 mm horizontally.

After correction of the orbit by moving the quadrupoles, the orbit may be corrected by exciting the 48 dipole correction coils around each ring. This further reduces the rms displacements to about Δy_{rms} = 0.6 mm, Δx_{rms} = 0.25 mm, the peak displacement of the orbit, with 90% probability, to ± 2 mm vertically and ± 1 mm horizontally, and the peak displacement at the crossing points, with 90% probability, to ± 0.8 mm vertically, and ± 0.06 mm horizontally. The maximum dipole coil correction required, with 90% probability, is about 280 G.

It appears possible to correct the orbit using the 48 dipole correction coils directly, without going through the step of correcting by moving quadrupoles, and without exceeding the correction capacity of the 1000 G dipole correction coils. Using the correction coils directly reduces the rms displacement down to about Δy_{rms} = 1 mm, Δx_{rms} = 0.7 mm, the peak displacement of the orbit, with 90% probability, to ± 2.8 mm horizontally and ± 3.7 mm vertically, and the peak displacement at the crossing points, with 90% probability, to ± 0.14 mm horizontally and ± 1.5 mm vertically. The maximum dipole coil correction required, with 90% probability, is about 500 G.

A limit on how well one can correct the closed orbit stems clearly from the number of probes and their location, since the probes provide the information for correcting the orbit. One way of estimating this limit is to say that if one has 100 probes around the ring, then one has enough information to correct out the first 50 harmonics present in the closed orbit. The reduction factor, R, that one obtains by cancelling out the N harmonics which are closest to the n = ν harmonic can be estimated from[1,2]

$$R = \sum_{|n-\nu|>N/2} \frac{1}{n^2-\nu^2} \Big/ \sum_{n=0}^{\infty} \frac{1}{n^2-\nu^2} ,$$

which for $\nu \simeq 21$ and N = 50 gives a reduction factor of R = 1/10.

Usually, the result achieved is different from this theoretical reduction factor depending on the sources of field errors and the location and accuracy of the correctors. For example, if the misalignment of the quadrupoles were the only source of errors, and one used the moving of the quadrupoles as correctors, then in this case one would achieve a reduction factor of R = 0. The system proposed above appears to achieve a reduction factor of about R = 1/12.

The location of the probes also plays a role in limiting the ability to correct the closed orbit. A measure of this limitation can be obtained by using as correctors all the quadrupoles which are adjacent to either the vertical probes or horizontal probes according to which displacement is being considered. Since there is now just as many correctors as probes, one can choose the corrections to make the displacement zero at the probes and then see how much orbit displacement remains elsewhere in the ring. It was found that when the probes were placed near the β_{max} quadrupoles, the remaining orbit displacement was considerably smaller than when the probes were placed near the β_{min} quadrupoles. The remaining orbit displacement was 0.4 mm and 3 mm for the two cases. For this reason the probe was placed near the β_{max} quadrupoles.

The closed orbit computations reported above were done with the aid of the CLOSORB program. I wish to thank K. Jellett for his help in writing this program and in doing the computations. I also wish to thank E.D. Courant, S. Giordano, H. Hahn, J. Herrera, J.W. Humphrey, M. Month and A. van Steenbergen for helpful discussions.

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