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CORRECTION OF THE CLOSED ORBIT AND VERTICAL DISPERSION AND THE TUNING AND FIELD CORRECTION SYSTEM IN ISABELLE*

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Summary

Each ring in ISABELLE will have 10 separately powered systematic field correction coils to make required corrections which are the same in corresponding magnets around the ring. These corrections include changing the ν-value, shaping the working line in ν-space, correction of field errors due to iron saturation effects, the conductor arrangements, the construction of the coil ends, diamagnetic effects in the superconductor and to rate-dependent induced currents. The twelve insertion quadrupoles in the insertion surrounding each crossing point will each have a quadrupole trim coil. The closed orbit will be controlled by a system of 84 horizontal dipole coils and 90 vertical dipole coils in each ring, each coil being separately powered. This system of dipole coils will also be used to correct the vertical dispersion at the crossing points. Two families of skew quadrupoles per ring will be provided for correction of the coupling between the horizontal and vertical motions. Altogether there will be 258 separately powered correction coils in each ring.

I. Systematic Field Correction Coils

The systematic field correction coils include quadrupole trim coils located in the quadrupoles, sextupole coils located in the dipoles, octupole coils located in the dipoles, decapole coils located in the dipoles, and duodecapole coils located in the quadrupoles. The quadrupole trim coils are divided into two families which are separately powered in order to be able to separately control ν_x and ν_y. One family is located in the focusing quadrupoles, and the other in the defocusing quadrupoles. In a similar way, each of the above 5 multipole windings are divided into two separately powered families.

In the following, the multipole field of a coil is described by $B_y = B_0 b_n X^n$ and $B_x = B_0 a_n X^n$, where b_n and a_n are the multipole coefficients and B_0 is the main dipole field.

Table I lists each of the correction coils and gives its location, its capacity at 400 GeV, the required accuracy of correction at 30 GeV, the tolerance on the error of correction at 30 GeV (peak value), the maximum field generated by the correction coil, and the required full-scale power supply accuracy to keep the error in the ν-value due to all the power supplies below 0.001 in a beam that extends from $\Delta p/p = 0$ to $\Delta p/p = 0.01$ at 30 GeV.

Quadrupole Trim Coils. The coils of the two-family quadrupole correction system are located in the quadrupoles in the insertion region. The maximum quadrupole field that the coils produce is 0.12 kG/cm, which is 2% of the main quadrupole field and corresponds to $b_1 = 2.4 \times 10^{-3}$/cm at 50 kG. At 400 GeV, these trim coils can move the ν-value along the diagonal ($\nu_x = \nu_y$) by $\nu_x = \nu_y = 0.3$, and perpendicular to the diagonal ($\nu_x = -\nu_y$) by $\nu_x = \nu_y = 0.45$. A large motion along the diagonal can be achieved using the bypass power supply which can make the current flowing through the normal cell quadrupoles slightly different from that in the main dipole. Changing the ν-value from $\nu_x = \nu_y = 22.6$ to $\nu_x = \nu_y = 21.6$ requires a bypass current of about 6.7% of the main dipole current. The bypass does not move the ν-value exactly along the diagonal, but along the line $\nu_y = 1.2\ \nu_x$, so that at $\nu_x = \nu_y = 21.6$ a perpendicular correction corresponding to about $\Delta\nu_y = 0.15$ is required to move the ν-value back to the diagonal.

Sextupole Coils. The sextupole coils are to provide the required chromaticity to correct the sextupole fields produced by iron saturation, superconductor diamagnetic effects, and eddy currents due to $\dot{B}$ during the acceleration stage, and to shape the working line in ν-space. One family of sextupole coils is located in the two dipoles adjacent to the focusing quadrupole in the normal cell, and the other family is located in the remaining 4 dipoles that are on either side of the defocusing quadrupole, and also in all the dipoles in the insertion region. This division helps to lower the size of sextupole correction required.

The maximum sextupole field produced by the sextupole coils is $b_2 = 6 \times 10^{-4}/\mathrm{cm}^2$ at 50 kG. The b_2 required to make the chromaticity $\gamma = p\, d\nu/dp \simeq 2$ is about $b_2 = 2 \times 10^{-4}/\mathrm{cm}^2$ in one family and $b_2 = -2 \times 10^{-4}$/cm in the other family. The b_2 introduced by iron saturation effects at high fields is estimated as about $b_2 \simeq 2.5 \times 10^{-4}$.

Table I

	Multi-pole	Location	Capacity at 400 GeV (cm^{-n})	Accuracy at 30 GeV	Tolerance Δb_n at 30 GeV (cm^{-n})	Field at r=6cms (kG)	Full Scale Power Supply Accuracy	Comments
Systematic	b_1	Cell Quads	2.4 E-3	.9 E-3	2 E-6	.72	6 E-5	2% Correction
Field	b_2	Dipoles	6.0 E-4	.2 E-3	1 E-7	1.3	1 E-5	
Correction	b_3	Dipoles	8.0 E-5	.5 E-3	4 E-8	.84	4 E-5	
System	b_4	Dipoles	5.0 E-6	.8 E-3	4 E-9	.31	6 E-5	
	b_5	Cell Quads	1.0 E-6	2.0 E-3	2 E-9	.40	14 E-5	
Bypass	b_1	---	8.4 E-3	.2 E-3	2 E-6	2.52	2 E-5	7% Correction
	b_1	Q1	7.8 E-3	1.0 E-3	8 E-6	1.4	7 E-5	6½% Correction
Insertion	b_1	Q2	7.8 E-3	1.0 E-3	8 E-6	1.4	7 E-5	
Quad.	b_1	Q4	7.8 E-3	3.0 E-3	24 E-6	1.4	21 E-5	
	b_1	Q5	7.8 E-3	2.0 E-3	16 E-6	1.4	14 E-5	
Trims	b_1	Q6	7.8 E-3	2.0 E-3	16 E-6	1.4	14 E-5	
	b_1	Q7	7.8 E-3	2.0 E-3	16 E-6	1.4	14 E-5	
Central	b_0	QF	400 G	1.3 E-3	.05 G	.4	10 E-5	
Orbit	a_0	QD	400 G	1.3 E-3	.05 G	.4	10 E-5	
Correction	b_0	Q2,Q5	1000 G	.6 E-3	.05 G	.4	10 E-5	
System	a_0	Q1,Q4	1000 G	.6 E-3	.05 G	.4	10 E-5	
Coupling Correction System	a_1	Q1	2.4 E-3	1.3 E-3	3 E-6	.72	10 E-5	

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Octupole Coils. The octupole coils are primarily to shape the working line in ν-space. The two families of octupole coils are located in the dipole in the same manner as the sextupole coils. The maximum capacity of the octupole coils is $b_3 = 8 \times 10^{-5}/\text{cm}^3$ at 400 GeV. The severest requirement on the size of the octupole coil appears to come from a possible brickwall effect[1] at 400 GeV. The $b_3 = 8 \times 10^{-5}/\text{cm}^3$ can produce a ν-spread in the beam at 400 GeV of $\Delta\nu_x = \Delta\nu_y = 2 \times 10^{-3}$ assuming the energy spread in the beam is $\Delta p/p = 1.5 \times 10^{-3}$.

Decapole Coils. The decapole coils are to correct the decapole fields produced by iron saturation, superconducting diamagnetic effects, and eddy currents due to $\dot{B}$ during the acceleration stage, and to shape the working line in ν-space. They are located in the dipoles in the same manner as the sextupoles. The maximum capacity of the decapole is $b_4 = 5 \times 10^{-6}/\text{cm}^4$ at 400 GeV. The saturation effect at 50 kG is about $b_4 = -4 \times 10^{-6}/\text{cm}^4$. Shaping the working line is primarily important at 30 GeV, and the decapole can produce a ν-spread $\Delta\nu_x = \Delta\nu_y = 0.6$ over the beam at 30 GeV, assuming that the beam extends from $\Delta p/p = 0$ to $\Delta p/p = 0.01$ at 30 GeV.

Duodecapole Coils. The duodecapole correction coils are to correct duodecapole fields produced by iron saturation in the quadrupoles, possible coil edge effects in the quadrupoles, and to shape the working line in ν-space at 30 GeV. They are located in the quadrupoles in the same manner as the normal cell quadrupole trim coils. The duodecapole coils may be omitted from the insertion quadrupoles. The maximum capacity of the duodecapole is $b_5 = 1 \times 10^{-6}/\text{cm}^5$ at 400 GeV. The saturation effect at 50 kG is about $b_5 = 0.14 \times 10^{-6}/\text{cm}^5$. This duodecapole can produce a ν-spread of $\Delta\nu_x = \Delta\nu_y = 0.03$ over the beam at 30 GeV, assuming the beam extends from $\Delta p/p = 0$ to $\Delta p/p = 0.01$ at 30 GeV.

Bypass. The dipoles and the quadrupoles are essentially in series. However, a bypass, suggested by K. Robins, is introduced across all the cell quadrupoles, so that the cell quadrupoles can carry a current slightly different from that in the dipoles. The bypass can then be used to correct for the difference in the iron saturation effects in the dipoles and quadrupoles which may be of the order of 3.5% of the main dipole current. The bypass can also be used to vary the ν-value roughly along the diagonal $\nu_x \simeq \nu_y$. This allows one to reduce the size of the quadrupole trims required, as the quadrupole trims need vary the ν-value only perpendicularly to the diagonal about $\nu_x \cong -\nu_y \simeq 0.4$. A bypass of about 7% is required to correct the saturation effects and to be able to change the ν-value about $\Delta\nu_x \simeq \Delta\nu_y \simeq 1$.

II. Closed Orbit and Vertical Dispersion Correction System

The dipole correction coils of the closed orbit correction system are located in the quadrupole. Each defocusing quadrupole has a vertical dipole coil, 90 per ring, and each focusing quadrupole has a horizontal dipole coil, 84 per ring. The beam position monitors or pickup electrodes are also placed near each quadrupole. A vertical position beam monitor is located near each defocusing quadrupole, upstream from the quadrupole, and a horizontal position beam monitor is located near each focusing quadrupole, upstream from the quadrupole, with the one exception of the beam monitors near the Q1 and Q2 quadrupoles. A vertical and a horizontal beam monitor are located near Q1, on the side of Q1 closest to the crossing point. These two beam monitors on either side of the crossing point can determine the beam position at the crossing point. There are no beam monitors near Q2.

The vertical beam position monitors are located at the β-maximum of the vertical motion, and the horizontal beam position monitors at the β-maximum of the horizontal motion. Putting the beam position monitors at their corresponding β-maximum rather than at the β-minimum reduces the residual error in the closed orbit between probes by about a factor of 8.

An effort was made to keep the size of the dipole correction coils down by relying on movement of the quadrupoles to accomplish large corrections. Most of the dipole correction coils have a capacity of 400 G, with the exception of the four vertical dipole coils, and the four horizontal dipole coils near each crossing point which are used for local steering of the beams at the crossing points and which have a capacity of 1000 G. It is assumed that the quadrupoles can be moved with an accuracy of 0.075 mm rms.

At the startup of the accelerator, the errors in the location of the quadrupoles of about 0.25 mm rms, and in the vertical alignment of the dipoles of 0.5×10^{-3} rad rms lead to a possible initial peak orbit displacement of 27 mm horizontally and 23 mm vertically with 90% probability. As a first step in the correction procedure, this large central orbit error will be corrected by moving all the quadrupoles around the ring. This is computed to lead to a remaining possible peak orbit error of 9 mm horizontally and 7.7 mm vertically with 90% probability, which results from the assumed accuracy in moving the quadrupoles of 0.075 mm rms.

In the second step of the correction procedure, the remaining closed orbit error is corrected using the dipole correction coils. This is computed to leave a possible remaining peak orbit error of 0.2 mm horizontally, and 0.4 mm vertically. In the computation of the result, the dipole correction coils were assumed to have a peak error of 0.1 G corresponding to a full scale power supply accuracy of 1×10^{-4}. Errors due to inaccuracies in the beam position monitors were not included. The maximum required dipole correction found in the computer simulation was 100 G. If a particular required dipole correction is found to be more than 200 G, then this correction would be done by moving the corresponding quadrupole, so that at least 200 G of the 400 G capacity of the dipole correction coils would be available for further corrections.

Vertical dispersion, the dependence of the vertical closed orbit on the particle momentum, is also corrected using the closed correction system. This is done by displacing the orbit vertically in the dipoles where the sextupole chromaticity correctors are located, and in the quadrupoles. Displacing the orbit vertically generates skew quadrupole fields in dipoles where the sextupole coils are located, and generates horizontal dipole fields in the quadrupoles. The skew quadrupole fields and horizontal dipole fields generated contribute to the vertical dispersion and thus can be used to correct the vertical dispersion.

After the orbit is corrected as described above, the vertical dispersion is computed to have a possible peak value of $Y_p = 60$ mm with 90% probability. This vertical dispersion is corrected[2] by moving the orbit vertically using the dipole correction coils in such a way as to make the vertical dispersion zero at the six crossing points. This is computed to require a possible peak vertical displacement of the orbit by 2 mm. The maximum required dipole correction found in the computer simulation was 200 G to correct the orbit and the vertical dispersion.

Local Beam Steering. In order to have precise control of the position of the beam at the crossing point, a local displacement of the central orbit is produced using four of the dipole correction coils. To produce a vertical displacement of the central orbit, the dipole correction coils in magnets Q1, Q4, Q10 and Q40 are used, and to produce horizontal displacement of the central orbit, the dipole correction coils in magnets Q2, Q5, Q20, and Q50 are used. These dipole correction coils have a capacity of 1000 G and can produce a 6 mm displacement of the beam both horizontally and vertically at 400 GeV.

III. Coupling Resonance Correction

In order to correct the coupling between the horizontal and vertical oscillations, two families of separately excited skew quadrupole correction coils are provided.[3] One family is in the Q1 and Q2 quadrupoles in the insertion upstream from the crossing point, and the other family is in the Q1 and Q2 quadrupoles downstream from the crossing point. The skew quadrupole coils can be in either Q1 or Q2 or both. The expected width of the coupling resonances $\nu_x - \nu_y = 0$, due primarily to random skew quadrupole error, is 0.015 rms, which corresponds to 75% coupling between horizontal and vertical motion for particles whose ν-values are 0.01 from the $\nu_x = \nu_y$ resonance line. The maximum capacity of the skew quadrupole correction coil is $a_1 = 2.4 \times 10^{-3}$/cm or 120 G/cm at 400 GeV assuming the coil is located only in Q1 quadrupoles. The required full scale power supply accuracy is 10^{-4} in order to keep the coupling to less than 1% at 30 GeV.

IV. Insertion Quadrupole Trims

Each of the twelve quadrupoles in the insertion region surrounding each crossing point has a quadrupole trim coil. These quadrupole trims are to correct for differences in the iron saturation effect in the insertion quadrupoles and the main dipoles, and for the slight difference in the required effective lengths for the Q1, Q2, Q10 and Q20 quadrupoles, the Q5, Q6, Q7, Q50, Q60 and Q70 quadrupoles, and the Q4 and Q40 quadrupoles. The expected iron saturation effect to be corrected is 3.5% in the field gradient.

By choosing the quadrupole lengths correctly, the total effective correction required for the two effects, the length variation and iron saturation effects, is about 2.5%.

Another effect that also may need corrections is the random variation in β_y and β_x at the crossing point, which causes the beam-beam interaction to loose its 6-fold symmetry, and makes the beam-beam nonlinear resonances more dense. The peak random variation in β_x and β_y is about 12%. Correction of this effect may require an additional 4% capacity for the quadrupole trim coils or a total of 6.5%. All the quadrupole trims are separately powered.

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