7. CORRECTION AND ADJUSTMENT MAGNETS

7.1 Correction Magnets in a Superconducting Accelerator

If this were a report on the design of a conventional accelerator, there would be little need to discuss this system under a distinct heading. Mention could be made of the corrections required at injection field, adjustments could be treated as aspects of other systems, and free space in the lattice could be identified for later insertion of additional elements if needed.

The situation is markedly different in the case of the superconducting accelerator. Two factors are especially noteworthy. First, error fields are no longer solely a low-excitation phenomenon. Inevitable deviations in superconductor location from the ideal configuration produce significant field distortions that are independent of excitation. Thus, certain corrections are required at all field levels. Second, the beam pipe is relatively inaccessible, buried throughout most of its length inside an essentially continuous cryostat. Elements can no longer be added or shifted about with ease. Rather, it is appropriate to design and construct the correction and adjustment magnets as integral parts of the main magnet system. To be sure, space remains within the lattice to permit introduction of further devices at a later stage, but it is intended that the more numerous element types be installed at the outset.

7.2 Placement of Correction Elements

The magnets of this system are superconducting coils located within the main quadrupole cryostats. A steering dipole is within each main quadrupole coil; other multipoles are immediately downstream of the quadrupole. The latter include a trim quadrupole and sextupole at every normal-cell quadrupole. In addition, either an octopole or a skew quadrupole appears at many of these locations.

Other elements will be required, particularly in and near the long straight sections. At this writing, the design of the normal-cell quadrupole assembly is receiving emphasis, and this discussion will concentrate on the auxiliary magnets to be installed therein. Even with this limitation, the number of devices is large. There are 180 normal cell quadrupoles; steering dipoles, trim quadrupoles, and sextupoles alone represent 540 elements.

7.3 Functions and Strengths

Under this heading the principal roles anticipated for the various elements will be outlined. Strengths will be expressed as field integrals at 1 in. radius, at levels appropriate for 1 TeV.

7.3.1 Steering dipoles. The primary function of the steering dipoles is correction of the closed orbit at all energies. The rigidity of the superconducting-magnet system and the tight tolerance on orbit centering imposed by extraction argue against a reliance on main-magnet motions for orbit correction. In the case of the present Main Accelerator, the high-energy closed orbit initially exhibited a peak in excess of 1 in. in the horizontal plane. A major reduction was made by moving 25 quadrupoles by displacements of up to 0.25 in. Similar motions of the superconducting quadrupoles are not attractive to contemplate, in view of the stresses engendered on the cryogenic system. For extraction, it is desired that the closed orbit excursions be held within bounds of ±0.1 in. It would be unrealistic to assume that this requirement could be achieved and maintained without high-energy steering.

It is likely that orbit distortions will be large, at least during initial operation. At points in the normal cells where the amplitude function is a maximum, the rms orbit distortion due to dipole field errors and quadrupole misalignments can be written as

$$<x^2>^{\frac{1}{2}} \simeq \tfrac{1}{4}[a^2 + \frac{5}{9} b^2]^{\frac{1}{2}} \text{ in.},$$

where a characterizes the rms dipole field error in units of 0.1%, and b the rms quadrupole misalignment in units of 0.01 in. In the horizontal plane, a arises from the fluctuation in the field-length product from dipole to dipole; in the vertical plane, a receives contributions from both rotational alignment error and any uncertainty or instability in the dipole field direction. As a specific example, consider the vertical plane, where the magnet aperture is more restricted. The choice a = 1.4 would allow for 1-mrad rotational misalignment during installation and 1-mrad uncertainty or instability in the field direction. The choice b = 2 (0.02 in. placement error), though larger than that normally associated with the conventional accelerator, is not excessive in view of the greater difficulty in referencing the quadrupole magnetic center to external fiducials. Then the rms orbit distortion would be 0.5 in. and, if the errors obeyed a Gaussian distribution, there would be a 60% probability of a peak distortion greater than 1 in.

Horizontal steering will be accomplished by a dipole within each horizontally focusing quadrupole and vertical steering by a "skew" dipole within each vertically focusing quadrupole. The dipole strength required to compensate the deflection generated locally, that is, by the quadrupole misalignment and by the eight neighboring main dipoles, is, for uncorrelated dipole errors

$$\left(\int B d\ell\right)_{rms} = 23\,[a^2 + 0.31\,b^2]^{\frac{1}{2}}\ \text{kG-in.},$$

where a and b have the same significance as above. The choices a = 1.4, b = 2 yield 41 kG-in. at the rms. For Gaussian errors, a steering strength of about 130 kG-in. would be implied in order to have 90% probability of successful correction at 100 locations.

A steering dipole strength of 170 kG-in. has been selected. This figure is considered compatible with the concerns of the preceding paragraphs, with feasibility of construction, and with the desire to reserve some capability for orbit manipulation beyond centering.

7.3.2 Trim quadrupoles. Since the main dipoles and quadrupoles are connected in series, trim quadrupoles must assume the burden of tune correction and adjustment. For half-integer extraction, appropriate quadrupole harmonic terms are needed. In addition, if quadrupole error terms in the main magnets become sufficiently large, compensation of perturbations in the amplitude or dispersion functions could be appropriate.

The dominant single influence on trim-quadrupole strength arises from colliding-beam possibilities. Typical interaction-region designs introduce an added phase advance of close to π in both planes of oscillation; the trim quadrupoles must, in effect, lower both tunes by approximately 0.5 to restore the operating point. The trim-quadrupole strength at 1000 GeV may be inferred from

$$\Delta\nu_H = 0.0214\,(B'\ell)_F - 0.0062\,(B'\ell)_D$$

$$\Delta\nu_V = -0.0062\,(B'\ell)_F + 0.0214\,(B'\ell)_D,$$

where the subscripts indicate the focusing character in the horizontal plane of the adjacent quadrupole. A reduction of both tunes by 0.5 implies a contribution to trim quadrupole strength of 33 kG-in.

Considerably smaller strengths are associated with tune correction. Quadrupole moments in the main dipoles have been a source of concern. A systematic quadrupole term, b_1, in the dipoles would produce tune shifts $\pm 1.1\times 10^3\, b_1$ in the two planes of motion. The magnet-selection criteria require that b_1 for each dipole lie within the range $\pm 2.5\times 10^{-4}$/in. If the systematic component were half that value, 5 kG-in. would be required of each trim quadrupole. Recent magnet measurement data suggest that the average value of b_1 will be considerably less.

For half-integer extraction, a typical value of the total strength on the 39th harmonic is 170 kG-in., to be distributed among a suitable distribution of trim quadrupoles. Contributions to this harmonic from quadrupole fields in the dipoles must be compensated. The measurements alluded to in the preceding paragraph indicate a standard deviation for b_1 comparable to the bounds of the magnet-selection criterion. If so, the driving term on either the sine-like or cosine-like phase of the 39th harmonic due to b_1 in the dipoles would be 23 kG-in. at the rms.

At present, there is no cause for alarm concerning disturbances in the amplitude or dispersion functions. For example, if the bound for b_1 established by the magnet-selection criteria is again taken as the standard deviation of the distribution and the distribution is assumed to be Gaussian--an extreme case--then there would be a 20% chance of a peak in the amplitude function 20% in excess of its design value.

The trim-quadrupole strength has been specified at 60 kG-in., safely above the requirement imposed by a single interaction region after allowance for tune correction. Only a few such quadrupoles will be needed for extraction-harmonic generation.

7.3.3 Sextupoles. The principal role envisaged for the sextupoles is control of the chromaticity, although if the third-integer resonance is used as an extraction mode, harmonic generation would be required as well. Only the former application will be considered here.

Thus far, the dipoles have exhibited a substantial systematic sextupole term at high field. Of course, significant sextupole fields due to persistent currents are present at low excitation, but, at present, the average b_2 at high fields is the dominant factor to be considered in chromaticity correction.

The contributions to the chromaticity from systematic sextupole terms in the dipoles and from chromatic aberration in the quadrupoles can be written

$$\xi_H = 2.64\times 10^5 \langle b_2\rangle - 22$$
$$\xi_V = -2.45\times 10^5 \langle b_2\rangle - 22, \qquad b_2 \text{ in (in.)}^{-2}$$

where the natural chromaticity of -22 is that associated with the basic lattice exclusive of any enhancement from colliding-beam interaction regions. The magnet-selection criteria impose a bound of 6.0×10^{-4} in.$^{-2}$ on the magnitude of b_2; if the average value of b_2 is taken to be one-half of the bound, the chromaticity in one plane or the other would be about 100. Compensation of the effect of the average b_2 requires sextupole strengths of 9 and 15 kG-in. at horizontally focusing and defocusing quadrupoles respectively.

A colliding-beam interaction region can be expected to significantly increase the natural chromaticity (though by less than a factor of two). Provision of an adjustment range of twice the natural chromaticity of the basic lattice adds 9 and 17 kG-in. to the sextupole strengths at focusing and defocusing quadrupoles.

A strength of 50 kG-in. has been adopted for the sextupole located at each normal-cell quadrupole. This value is some 50% higher than the sum of the needs at defocusing quadrupoles as outlined above.

7.3.4 Octopoles. There are two major functions for the octopoles; both are associated with the only process requiring large betatron oscillation amplitude, resonant extraction. In the half-integer case, octopoles provide the nonlinearity that divides the phase plane into stable and unstable regions. Whatever extraction resonance is used, octopoles permit control of the dependence of tune on oscillation amplitude.

The version of half-integer extraction currently preferred employs a 39th octopole harmonic in association with a 39th quadrupole harmonic. The strength of neither harmonic is unique, though specification of one defines the other for fixed values of other extraction parameters. Nevertheless, a total octopole strength of 450 kG-in. on the 39th harmonic for elements placed near focusing quadrupoles is at the upper end of the adjustment range.

Adjustment of the amplitude dependence of tune is useful in its own right. But octopole terms in the main magnets also produce such a tune dependence and correction may be necessary. Of particular concern would be a systematic b_3 in the main dipoles, a possibility that cannot be excluded by measurements to date. The measurements do suggest that it is most unlikely that the average value of b_3 will be as large as one-half the selection criteria bound of 2.0×10^{-4} in.$^{-3}$. As an illustration, if the average value of b_3 were that large, then the tune shifts associated with a 1-in. horizontal-oscillation amplitude and negligible vertical amplitude would be 0.055 and 0.090 in the horizontal and vertical, respectively. Correction by zero-harmonic octopoles implies totals of 260 and 620 kG-in. at focusing and defocusing quadrupoles.

The individual octopole strength has been specified as 30 kG-in. The extraction requirement is satisfied for both sine-like and cosine-like harmonics by octopoles at eight successive focusing quadrupoles at corresponding locations in four adjacent sectors; octopoles are omitted in sectors D and E to minimize amplitude growth between the primary septum and the extraction channel. To correct the zero-harmonic terms in the extreme case of the preceding paragraph, an additional 36 octopoles would be necessary, 12 at focusing quadrupoles and 24 at defocusing quadrupoles. Therefore, the octopoles are at most 68 in number.

7.3.5 Skew quadrupoles. At an early stage of the operation of the Main Accelerator at high energy in 1972, it was observed that a large horizontal oscillation would couple over into the vertical in a single turn. Magnet measurements thus far indicate that an analogous situation will occur here; in fact, a recent analysis of the data on 22 magnets with serial numbers above 100 suggests that the coupling effect may be larger by a factor of two or more than in the Main Accelerator case. In such a circumstance, tune splitting is not effective in ameliorating the effect; rather, skew quadrupoles must be provided.

Skew quadrupoles will be incorporated into the multipole package at locations where octopoles are not necessary. Patterned after the standard trim quadrupole, but rotated by 45°, the skew-quadrupole strength will be essentially the same--60 kG-in. each. At present, it is intended that from 18 to 24 of these elements be installed. The skew-quadrupole coefficient in the main dipoles will be closely monitored in order to review the number and distribution of the skew quadrupoles as construction proceeds.

7.4 Excitation

In this section, comments will be made regarding the tolerances on the currents delivered to the correction and adjustment magnets, and on their arrangement in circuits. Current leads for each magnet are to be brought out of the cryostats. The interconnections among elements can therefore be modified with some freedom. All elements are designed to achieve their nominal maximum strengths at a current of 50 A.

7.4.1 Current tolerances. Because of their role in orbit correction, the steering dipoles inherently require independent bipolar power supplies. Stability and ripple suppression at 0.1% of full scale is needed in order to satisfy the demands of injection and extraction.

The trim quadrupoles and octopoles participate in the half-integer resonant extraction process. The current tolerances that would be associated with a relatively unmodulated slow spill of several seconds duration are unrealistic, but by powering these elements with a limited number of supplies designed at or near the state of the art, the sources of modulation can be held to a minimum in variety and strength, and the usual spill-feedback techniques will have a greater chance of success. Hence, the quadrupoles and octopoles will be wired in functional groups, each powered by a supply providing current stability in the range 0.01% to 0.005% of full scale.

The remarks of the preceding paragraph apply to any sextupoles used to generate third-integer extraction harmonics. The sextupoles also enter any extraction process through the chromaticity correction that they perform, although the tolerances become less severe. It is attractive to adopt the same approach to excitation of the sextupoles as that to be used for the trim quadrupoles and octopoles. But a caveat is in order; it may be necessary to resort to individual sextupole excitation if local compensation of the dipole coefficient b_2 becomes advisable.

7.4.2 Circuits. As noted in the preceding subsection, all steering dipoles are individually powered. Other elements are connected in functional groups.

For the momentum spread associated with single-turn injection at 150 GeV, two sextupole circuits are sufficient for chromaticity adjustment; that is, all sextupoles at horizontally focusing quadrupoles are wired together in the same polarity as are all sextupoles at vertically focusing quadrupoles.

Four trim-quadrupole circuits are required. The two for tune correction and adjustment are assembled in the same fashion as the sextupole circuits, with the exception that eight trim quadrupoles are omitted from the "horizontally focusing" circuit. Four of the latter, at stations B17, B26, C17, and C26 form one of the 39th harmonics for extraction; the other four, at stations B32, B42, C32, and C42 form the other 39th harmonic.

The octopoles will be arranged in four circuits. Octopoles at stations 17, 19, 26, and 28 in sectors F, A, B, and C produce one 39th harmonic; octopoles at stations 22, 24, 32, and 34 in the same sectors produce the other. Specification of the two zero-harmonic circuits can be deferred for the present, awaiting further information on the average value of the coefficient b_3.

7.5 Power Supplies

Two distinct types of power supply will be required - a large number of relatively low-voltage supplies with accuracy at the 0.1% level for the steering dipoles and a much smaller number of high precision supplies for the other elements. There are 180 steering dipoles in the standard cells of the lattice, and at least 4 dipoles will be installed at each long straight section. There will therefore be a need for over 200 supplies of the first variety. That total could increase substantially if individual excitation of sextupoles becomes necessary.

The current requirement is ±50A. The supplies will be designed with load compensation and a conventional roll-off characteristic of 20 db/decade.

7.5.1. Steering dipole supplies. The current stability and ripple limit for these supplies is ± 0.1% of full scale. To complete the specifications, the bandwidth and voltage must be determined. It is reasonable to have a bandwidth which allows the power supply output to follow a constant ramp input within ±0.1% of full scale. The error between programmed input and supply output for a constant ramp is

$$\epsilon \doteq \frac{AB}{2\pi f_0}$$

where

ϵ = lag error (amps)
A = power supply DC gain (amps/volt)
B = input voltage ramp rate (volts/s)
f_0 = power supply bandwith or corner frequency (Hz)

For an error of 0.1% (0.05 A) and a ramp from 0 to 50 A in 10 s, a power-supply bandwidth of 20 Hz is adequate. With this 20-Hz bandwidth, the equation above then yields a maximum output ramp rate for 0.1% accuracy of 6.3 A/s.

The supplies will be installed in the existing Main-Ring service buildings. The longest lead from the supply to dipole and back will be 1000 feet. At 50A and 50 °C, the voltage drop in that length of #2 wire is 8.8 V. The load inductance will be approximately 0.2 H; at the maximum ramp rate, for 0.1% accuracy, the drop across the magnet would be 1.3 V. A maximum power supply output of 15 V satisfies these requirements and provides a higher slewing capability for current changes under conditions where the accuracy specification can be relaxed.

A block diagram of such a supply is shown in Fig. 7-1. The control system provides a bipolar analog reference waveform from a generator with 12-bit resolution and 8 bits for commands to operate and check each

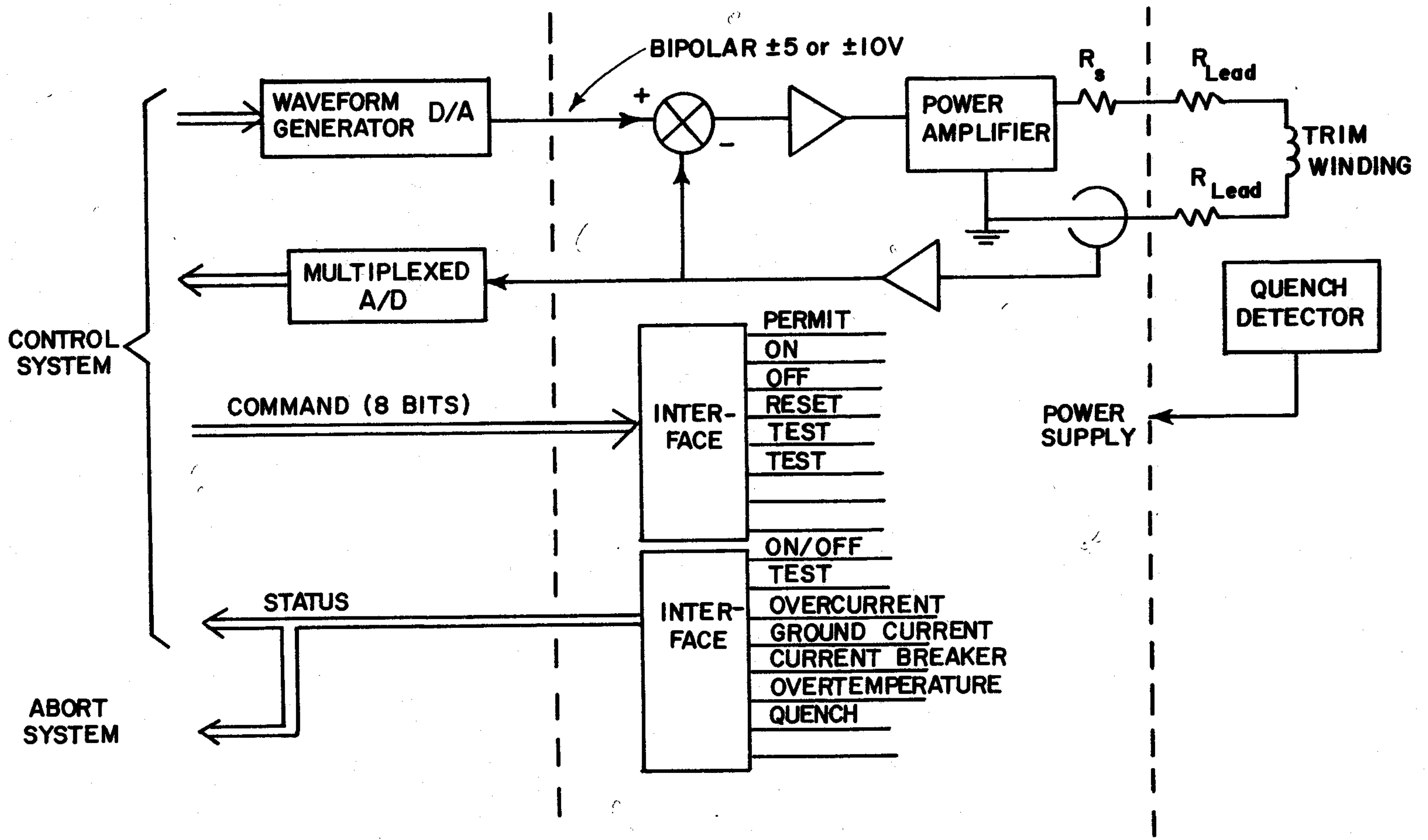

Fig. 7-1. Correction-magnet power supply.

power supply. The current reading is returned to the control system via a multiplexed A/D along with 8 status and fault bits. Isolation is provided between the control system and the power supply for command, status, and faults by means of optical couplers. Isolation of the analog signals is not felt necessary at this time.

The power-supply requirements can be met with either a thyristor-controlled dual converter or a transistorized power amplifier. Either approach would use series output resistors or other techniques to compensate for lead resistance variations, to keep load L/R constant for maximum performance. A preliminary analysis indicates that the costs of the two approaches are about the same.

Quench protection will be provided for each dipole circuit. Several methods are under consideration, but a final design must await system tests that have not been made as yet.

7.5.2. High precision supplies. These supplies are to have a stability and ripple limit in the range 0.005% to 0.01% of full-scale current. To achieve the low ripple current, a transistorized output regulator will be necessary, in which case a bandwidth of 100 to 200 Hz should be obtainable at no extra cost. With this bandwidth, lag error is reduced in comparison to the dipole supplies by a factor commensurate with the increased accuracy.

Although final programmed waveshapes have not yet been established, it is clear that certain of these supplies will have a relatively high output voltage. For the tune adjusting circuits, the requirement can be as high as 250 V. To reduce transistor-bank dissipation, these supplies will use a preregulator to provide variable voltage to the output transistor regulator. The programmable supplies will be operated to keep a nearly constant voltage across the output transistor banks and thus reduce the transistor-bank requirements. By careful design, the transistor-bank regulator for the various high-precision supplies could be the same. The main difference then would be in the choice of the preregulator.

The supplies would be configured much like the steering-dipole supply shown in Fig. 7-1 with a few exceptions. The reference voltage would be provided by a precision 16-bit D/A, and the current sensor would be a high quality current transductor; stability of each at 1 ppm/°C is needed. Suitable components are now available commercially. The waveform generator would be located within the supply to minimize noise pickup. Quench detection and protection will also be provided.