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STATUS OF CORRECTION MAGNET SYSTEMS IN THE MAIN RING AT FERMILAB

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Abstract

For reducing the chromaticity and suppressing various resonances, several systems composed of trim quadrupoles, skew quadrupoles, regular and skew sextupoles and octupoles are now used in the main ring. These systems make it possible to achieve the transmission in the main ring of 90% or better for the routine operation with the intensity in excess of 10^{13} protons per pulse. In particular, insertion of one-inch plastic spacers in chromaticity correcting sextupoles has been very effective in compensating for high-order nonlinear fields in the bending magnets.

Introduction

When a stable coasting beam of 7 GeV was established in December 1971, there were only thirty-six iron-core sextupoles in the main ring in addition to customary trim dipoles. Since then, the correction magnet systems have gone through a series of changes, both in their complexities and in the total number of elements. At present, there are 24 trim quadrupoles, 18 skew quadrupoles, 180 sextupoles, 18 skew sextupoles and 78 octupoles. Of 180 sextupoles, 168 for controlling the chromaticity have one-inch plastic spacers in order to compensate for high-order nonlinear fields. The development of the systems has played a major role in the increase of the beam intensity, from 5×10^{9} protons/pulse at 200 GeV in March 1972 to 1.6×10^{13} protons/pulse in January 1975. Equally significant is the increased tolerances for many parameters which are essential for a stable accelerator operation. The survival of the 8-GeV coasting beam is another indication of the improvement. The exponential beam decay time was ~2.5 sec in 1973 compared to the present ~50 sec, a value consistent with the expected gas scattering. This report is to summarize the status of the correction magnet systems and to describe new features that have not been given in previous reports.[1,2] Transverse damping systems in the main ring for suppressing collective beam instabilities have already been reported[3] and the design as well as the performance of the new, fast damping system are given in another report of this conference.[4]

Correction Magnets for Various Resonances

In six superperiods, A to F, of the main ring, there are 774 dipoles (378 type B1 and 396 type B2) with the total length of 4,699 m and 240 quadrupoles (192 normal and 48 short) with the total length of 473 m. The location of each correction magnet is specified by the nearest station number. Each station is nominally at six inches from the downstream end of a quadrupole. There are two stations in a normal cell and five in a long-straight cell. Two-digit station numbers are identical for all superperiods and horizontal (vertical) stations are given odd (even) numbers below 20 and even (odd) numbers above 20. At a horizontal (vertical) station, the betatron oscillation parameter $\beta_{h(v)}$ ranges from 93 m to 100 m and $\beta_{v(h)}$ from 28 m to 31 m. The dispersion parameter η is 2.1 m - 5.9 m at horizontal stations and 1.2 m - 3.4 m at vertical stations. Together with the phase advance from station to station, these parameters play a crucial role in the selection of the optimum location of correction magnets and in the estimation of their required strength. All correction systems have the same periodicity as the ring superperiod in magnet locations. The operating tunes are usually $\nu_h \simeq 19.42$ and $\nu_v \simeq 19.38$ although they can be moved independently. The resonance-free area around 19.4 is wider than the area around the design value of 20.3. Also, it was found out that the influence on the beam of intrinsic third-integer resonances $3\nu_{h(v)} = 60$ and $\nu_{h(v)} + 2\nu_{v(h)} = 60$ are difficult to eliminate completely. Unless the tune is suddenly shifted by a temporary loss of quadrupole current regulation, uncorrected resonances cause a substantial amount of beam loss only at low energies where the beam emittance is large and the effect of the remanent field is severe. Correction magnets are therefore operated in dc mode although skew quadrupoles and octupoles can be programmed if necessary. It is of course essential that sextupoles for correcting the chromaticity be programmable. In the past, some air-core elements were used as a temporary measure but they have all been replaced by iron-core magnets.

A. Trim quadrupoles for $2\nu_{h,v} = 39$.

Twenty-four at stations 36, 39, 42, and 45; azimuthal harmonics = 3, 9, 15, etc.; equivalent stopband width = 0.07 - 0.08 (horizontal) and 0.05 - 0.06 (vertical).

B. Skew quadrupoles for $\nu_h = \nu_v$.

Eighteen at stations 27, 37 and 43 with the same strength. The required strength of skew quadrupoles of course depends on the amount of tune split. Typically, at injection,

$$\left|\Sigma(B'\ell/B\rho)\sqrt{\beta_h\beta_v}\right| = 0.1 - 0.2.$$

*Operated by the Universities Research Association, Inc., under contract with the U.S. Energy Research and Development Administration.

Twelve quadrupoles at stations 25 and 43 are rolled by 8 mrad each in order to suppress the coupling at high energies.[1,2]

C. Regular sextupoles for $3\nu_h$, $\nu_h + 2\nu_v = 58$.

Twelve at stations 28 and 35; even azimuthal harmonics. At injection,

$$|\Sigma \beta_h^{3/2} (B''\ell/B\rho)\exp(i58\phi_h)| = (115\text{-}225)/\sqrt{m},$$

$$|\Sigma \sqrt{\beta_h}\beta_v (B''\ell/B\rho)\exp(i58\phi)| = (25\text{-}50)/\sqrt{m}$$

where $\phi = (\phi_h+2\phi_v)/3$ and $\phi_{h,v}$ are betatron phases normalized to 2π.

D. Skew sextupoles for $3\nu_v$, $2\nu_h + \nu_v = 58$.

Eighteen at stations 14, 17 and 22; even harmonics. This system was very important when it was not possible to change ν_h and ν_v independently. With the modification of the chromaticity correcting sextupoles, which will be discussed in the next section, the tune is controlled much better during the injection and the required strength of skew sextupoles has been substantially reduced. At injection,

$$|\Sigma \beta_v^{3/2} (B''\ell/B\rho)\exp(i58\phi_v)| = 17/\sqrt{m},$$

$$|\Sigma \sqrt{\beta_v}\,\beta_h (B''\ell/B\rho)\exp(i58\phi)| = 15/\sqrt{m}$$

where $\phi = (2\phi_h+\phi_v)/3$.

E. Octupoles

Thirty at horizontal stations 17, 22, 28, 36 and 42; forty-eight at vertical stations 21, 23, 25, 27, 33, 35, 37 and 39. Strengths of these two groups are adjusted separately and they are programmable. The function of this system is to eliminate or introduce a tune spread in the beam rather than to correct for any fourth-integer resonance. Octupoles at vertical stations are sometimes excited to the maximum strength in order to help suppress the coherent vertical instability. The amount of tune spread that can be created is then 0.015 - 0.025 depending on the vertical size of the beam. Octupoles were once used to reduce the distortion of the tune as a function of the radial position.

It should be noted here that the dipole remanent field is often very sensitive to the mode of the main bend field ramping.[5] For example, the remanent sextupole field strength B" in B1 dipoles is 0.72 kG/m^2 after the normal 300-GeV ramping but it is reduced to 0.55 kG/m^2 after a 400-GeV ramp. If the 400-GeV ramp is tripped at flattop, the current decays more slowly than the normal invert and B" is further reduced to 0.49 kG/m^2. On the other hand, in B2 dipoles, B" changes very slightly, 0.69 to 0.63 kG/m^2, when the ramp is changed from 300 GeV to 400 GeV. It is therefore reasonable to expect a change in the strength of azimuthal harmonic components of the remanent field as well. Optimum settings of some of the correction magnets will be somewhat different for 300-GeV and 400-GeV operations. So far, there have been only two periods of 400-GeV run but the change has already been clearly noticeable. Settings are also liable to change in a long period due to dipole and quadrupole replacements in the ring.

Sextupoles for Correcting Chromaticity

By far the most important correction magnets in the main ring are 168 sextupoles for controlling the chromaticity, i.e., the dependence of the tune on momentum. These sextupoles are located at fourteen horizontal and fourteen vertical stations in each superperiod. Horizontal and vertical groups are adjusted separately and they are programmed to accommodate the increasing momentum of the beam and the rising effect of the eddy-current sextupole field during the parabola of the ramp. Sextupole currents are set by the relation

$$I_{sext.} = a+b\cdot I_b+c\cdot\partial B/\partial t$$

where a, b and c are constant factors fed from the control console, I_b is the main bend current and $\partial B/\partial t$ is obtained from a direct measurement of the bend field in a magnet.

The system was originally designed to reduce both horizontal and vertical chromaticities to ~0, up to 50 GeV, over the range of ±0.25% in $\Delta p/p$. Since the momentum spread of the injected beam is typically 0.1 - 0.2%, the system worked satisfactorily under normal operating conditions. It soon became clear, however, that a further increase in the acceptable momentum range is desirable for stable and reliable operation. The regulation of the injection field may not always be as it should be and the momentum of thirteen booster pulses may not be identical when they are injected into the main ring. At low energies, the distortion of the linear dependence of the tune on momentum is mostly caused by decapole and higher multipoles of the remanent field in bending magnets. A series of measurements have been made on the bending magnets that have experienced the same history of ramping as the magnets in the ring.[6] These measurements have shown that the gradient of the remanent field as a function of radius is almost pure sextupole in the central region but it increases more slowly than a sextupole field does in the outer regions. Results for the B1 dipole after the normal 300-GeV ramp are shown in Fig. 1. Similar results have been obtained for the B2 dipole. In order to compensate for this high-order nonlinear field, one-inch plastic spacers have been inserted in all correction sextupoles with excellent results. Combined fields of four B1 magnets and one correction sextupole with the spacer is shown in Fig. 2. The compensation is near perfect to almost ±2". With the insertion of spacer, the sextupole field in the central region of correction magnets decreases by ~40% and there is a corresponding increase in the required excitation. There is, however, no significant deterioration in the sextupole characteristics of the field in the central region.

For correction sextupoles located at vertical stations, a gap somewhat larger than one inch is better but this is not very important since the dispersion parameter is generally small at vertical stations. Increased range of momentum can be seen in Figs. 3 and 4 showing, respectively, the tune as a function of momentum before and after the insertion of the spacer.

For 300-GeV runs, the correction sextupoles are adjusted to produce

$$\Delta\nu_h = (176+36)(\Delta p/p),$$

$$\Delta\nu_v = (-54-118)(\Delta p/p)$$

where the first terms are contributions from sextupoles at horizontal stations and the second terms from those at vertical stations. The vertical chromaticity is somewhat overcompensated to create a tune spread of ~0.03. The new fast damper[4] will probably remove the need for this tune spread. Variation of the sextupole excitation as a function of the cycle time is shown in Figs. 5 and 6. Injection of thirteen booster pulses takes place during the first 0.8 sec followed by the 0.2 sec parabola. The rate of acceleration after that is 100 GeV/sec.

References

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3. R. Stiening and E.J.N. Wilson, Proceeding of the IXth International Conference on High-Energy Accelerators, Stanford Linear Accelerator Center, May 2-7, 1974, p. 329.

4. E. Higgins, Q. Kerns, H. Miller, B. Prichard, R. Stiening, and G. Tool, to be published in this issue.

5. B.A. Prichard, Jr., Fermilab Technical Memo TM-543, January 1975.

6. B.A. Prichard, Jr., loc. cit. A detailed discussion of the spacer can be found in this technical memo.

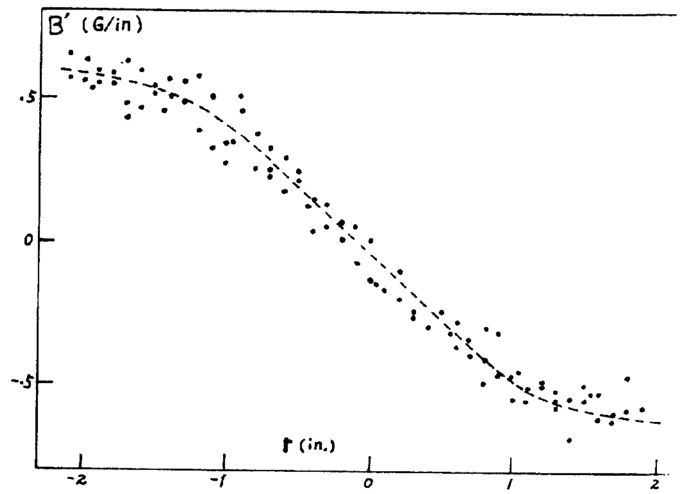

Fig. 1 Gradient of the remanent field in B1 magnet after the normal 300-GeV ramp. The central slope gives B"=0.72 kG/m^2.

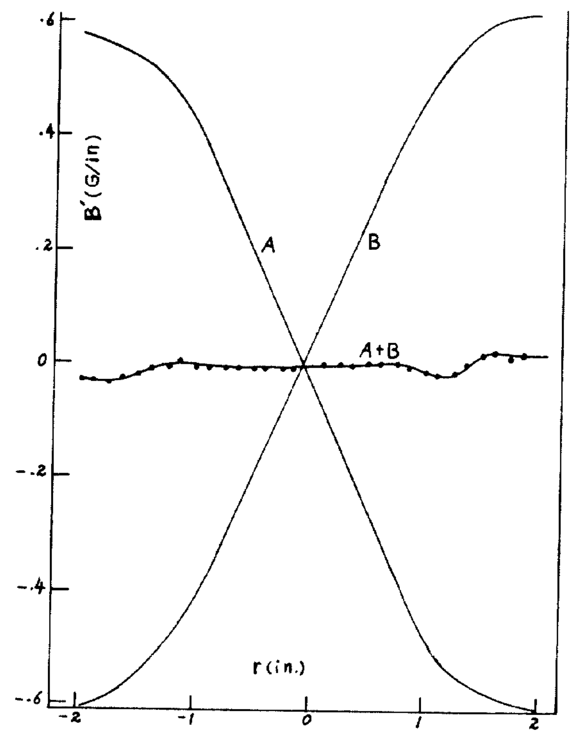

Fig. 2 (A) Gradient of the total remanent field of four B1 magnets. (B) Gradient of one correction sextupole field with one-inch plastic (G-10) spacer.

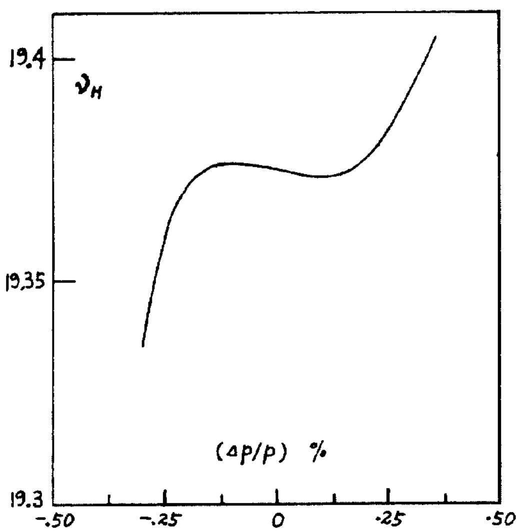

Fig. 3 Horizontal tune as a function of momentum deviation with normal correction sextupoles.

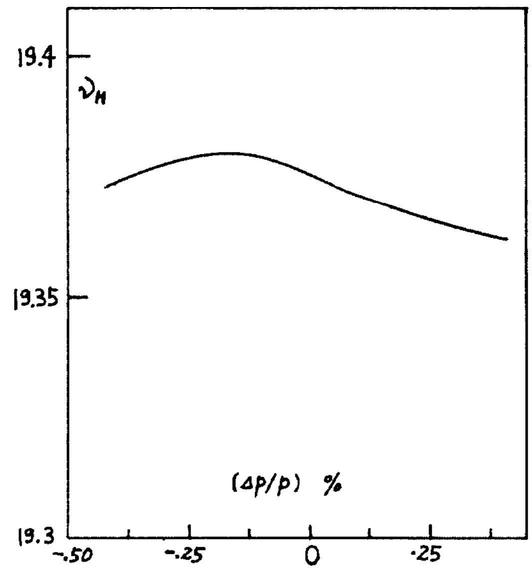

Fig. 4 Same as Fig. 3 when one-inch plastic spacers are inserted in the sextupoles.

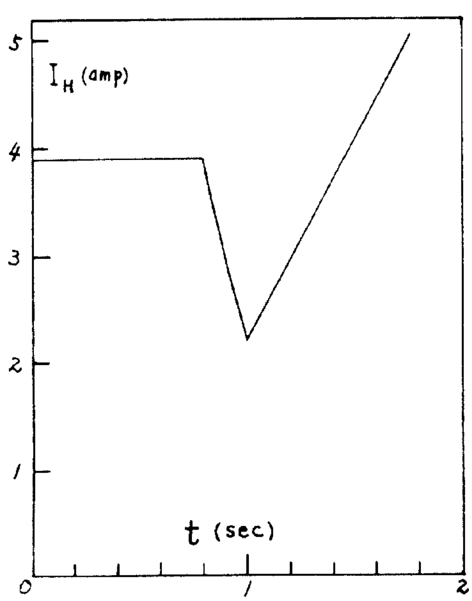

Fig. 5 Excitation of the correction sextupoles at horizontal stations. For positive values of I_H, B" is positive. Injection takes place during the first 0.8 sec followed by a 0.2 sec parabolic rise of the main bend field. The rate of acceleration after 1 sec is 100 GeV/sec. The maximum excitation of the sextupoles is ~7 amp.

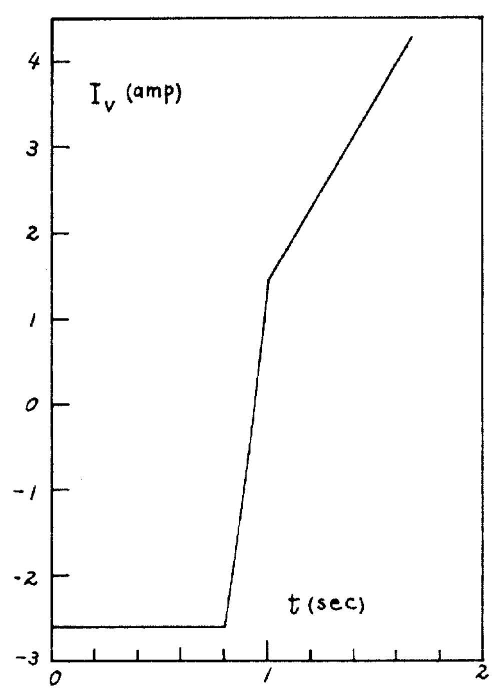

Fig. 6 Excitation of the correction sextupoles at vertical stations. For positive values of I_V, B" is negative.