Compensation of time-dependent persistent current effects in superconducting synchrotrons

D. A. Herrup, W. Kinney, M. J. Lamm, and A. Mokhtarani
Fermi National Accelerator Laboratory, Batavia, Illinois 60510
(Received 18 November 1993; revised manuscript received 20 January 1994)

Persistent currents in superconducting accelerator magnets are caused by the magnetization of the superconducting filaments in the field of the magnet itself. The magnetized filaments create additional field distortions which can have an important effect on beam dynamics. During the initial operation of the Tevatron as a colliding beam accelerator, the chromaticities at the injection energy were found to be time dependent, leading to instabilities and particle loss during injection and at the start of acceleration. Laboratory measurements on single Tevatron dipole magnets indicated that these effects were due to time-dependent persistent current phenomena. Using additional laboratory measurements and beam observations, we have developed a set of procedures to compensate the time-dependent chromaticities due to the persistent currents. The application of these procedures has eliminated all problems caused by time-dependent persistent current effects. We will discuss the general problem of persistent current distortions in superconducting accelerators, and, then, the laboratory measurements, the beam observations, and the successful implementation of the correction schemes. While these procedures have worked well, they have limitations which will be discussed, as well as possible future improvements and implications for future projects.

PACS number(s): 41.85.Gy, 41.85.Lc

PERSISTENT CURRENT EFFECTS IN SUPERCONDUCTING MAGNETS

The construction of high energy hadron colliders [1] requires the use of superconducting magnets to reduce power consumption and to provide a superior environment for both collider and fixed target experiments. In these accelerators, magnetic field quality is a major concern. Successful accelerator operations require that beam be stored for hours (hundreds of millions or billions of turns) in collider operation or tens of seconds (millions of turns) in fixed target operation. In the "cosθ" superconducting magnets [2] the magnetic field is determined primarily by the placement of the individual superconducting strands. However, a unique property of superconducting magnets is the presence of persistent currents in the individual superconducting filaments. The multipoles of these fields can play an important part in the beam dynamics.

Persistent currents in type II superconductors can be understood in the context of the Meissner effect and the critical state model of Bean [3]. This model posits that for low fields, a type II superconductor will maintain 0 field in its interior. Surface currents (the persistent currents) at the critical current density will be induced to null any external field [4]. As a result, at low excitation the individual superconducting filaments will be carrying a net transport current and also a set of equal and opposite persistent currents. As the external field increases, the volume of the filament in which the persistent currents flows increases until a "penetrating field" is reached, at which time the filament has been divided in half with a positive persistent current running on one side and an equal and opposite negative current running on the other side. For fields above the penetrating field, the field inside the superconductor rises linearly with the external field. These persistent currents modify the field due to the transport current. This model indicates that the distortions will have the multipole symmetry allowed by the magnet (dipole, sextupole, decapole, etc. components for a dipole magnet, quadrupole, duodecapole, etc. for a quadrupole magnet). This persistent current multipoles will be largest at low excitation (i.e., at injection) where the critical current is largest, and they will also be proportional to the filament radius.

The Tevatron at Fermilab contains 774 superconducting dipole magnets [5] which operate between 0.66 T (corresponding to 150 GeV) at injection and 4.4 T at the peak design field (1 TeV). Due to the high injection field and small (9 μm) superconducting filaments, the only component large enough to affect the beam dynamics is the sextupole component (b_2). The persistent current sextupole component is about seven units of $b_2(10^{-4}$ in.$^{-2})$. It affects only the chromaticities, and is compensated with the ordinary chromaticity sextupoles which are placed adjacent to the focusing and defocusing quadrupoles. In contrast, at the hadron electron ring anlage (HERA) where the injection field is 0.23 T and the filaments are 14–16 μm in the dipoles and 19 μm in the quadrupoles, there are substantial persistent current sextupole (35 units), decapole, and duodecapole fields which must be compensated to maintain a reasonable dynamic aperture [6]. To accomplish this, special "beam pipe" correctors were developed [7]. It must be remembered, however, that the multipole moments reflect the properties of the magnets. The translation from a multipole moment to an effect on beam dynamics requires consideration of the lattice and other parameters of the accelerator. Although the persistent current b_2 in the HERA magnets is a factor of 5 larger than in the Tevat-

1063-651X/94/49(6)/5660(8)/$06.00

ron, the lower dispersion in HERA mitigates the effect relative to the Tevatron. In the Tevatron one unit of b_2 corresponds to 20 units of horizontal chromaticity and 17 units of vertical chromaticity, while in HERA there are roughly eight units of chromaticity for each unit of b_2 [8].

During fixed target operation, the Tevatron is ramped continuously with a single cycle including a 1 sec "front porch" during which the current in the Tevatron bus is held constant at 660 A (150 GeV) for injection to occur, while in collider operation there is a 1–3 h front porch during which the proton (p) and antiproton ($\bar{p}$) transfers are tuned up and the bunches to be used in physics running are injected. Observations during the 1987 collider run indicated that the chromaticities on the injection front porch varied with time [9], often resulting in particle loss due to instabilities and resonance excitation. The observed changes were consistent with a time-dependent sextupole component in the dipoles. In addition, at the start of acceleration, large, sudden particle losses were observed, and the $\bar{p}$ transverse emittances doubled while the p emittances were unchanged. The tune space available in the Tevatron is 0.029, and is determined by the spacing between the seventh (0.571) and the fifth (0.6) order resonances. During the initial collider operations, the beam-beam induced tune spread for the $\bar{p}$'s was greater than 0.01. This, in conjunction with moderately large chromaticity shifts induced by the changing b_2, was hypothesized to result in the $\bar{p}$ tune distribution having components outside of the working area (σ_p/p is 0.5×10^{-3} at injection) and lead to the loss and emittance growth patterns observed.

At the conclusion of that run, laboratory measurements on a single dipole indicated that there was a significant time-dependent b_2 over a 15 min front porch (the longest measured) [9]. These initial measurements were followed by a more detailed set on a prototype 1-m long dipole without the iron yoke [10]. These measurements showed that there was a nearly logarithmic decrease in b_2 with time on the front porch as the superconducting filaments demagnetized, and that at the start of the ramp, this drift was undone as the filaments were remagnetized. The measured drift was about two units (2×10^{-4} in.$^{-2}$) in b_2 over a 1 h front porch. An uncompensated two unit shift in b_2 will consume the entire Tevatron working space.

The "flux creep" model first proposed by Anderson [11] predicts a logarithmic demagnetization of the persistent currents. Initially this was accepted as the explanation for the observations in dipoles. However, more detailed studies indicated that the rate of demagnetization in full-length magnets was a factor of 10 greater than that observed in short samples of the cable used in the same magnets [12]. In addition, the DESY group discovered a history dependence upon the demagnetization which is completely outside of the flux creep model [13]. More recently, tests on the superconducting super collider (SSC) magnets have shown that the behavior of the demagnetization with temperature is not consistent with any known model [14]. Although the nearly logarithmic behavior has been observed in a wide variety of magnets manufactured with different cables and designs, its origin is not understood.

The time-dependent effects depend upon the excitation history of the magnet. During the recent (1992–1993) collider run, the acceleration rate was halved due to the failure of an rf cavity. At the time, there were no measurements of the time-dependent persistent current effects with the new ramp. Acceleration was accompanied by about a 10% beam loss for p intensities of less than 110×10^9 p/bunch, and up to a 60% loss for higher intensities. A program to remeasure the corrections and apply the new data to accelerator operations was undertaken. Independently of this work, Fermilab had developed a new magnetic field probe for use on model SSC dipoles [15]. This system was modified and used for persistent current measurements of full-length Tevatron dipoles. We shall describe the laboratory measurements, the observations of beam dynamics, and the solutions we have developed to eliminate these problems.

LABORATORY MEASUREMENTS OF TEVATRON DIPOLES

Our intention in making measurements was to obtain data on $b_2(t)$ which would be useful in improving Tevatron operators under the full range of operating conditions. In general, the conditions that vary are the history of the magnet (whether the magnet had been quenched or held in a long flat-top store) and the duration of the front porch. The measurements were performed on spare full-length dipoles using a tangential probe and data acquisition system that was capable of measuring b_2 at a 6 Hz rate for 10 sec bursts, separated by several seconds of data analysis [15]. The immediate prehistory consists of either a full field quench or 1 h at a 4 T flat top, in each case followed by the cycle of six preramps [9], a front porch of variable duration, and the final ramp to flat top. Data were recorded during the last preramp, the front porch, and at the beginning of the final ramp.

These measurements have been made on five magnets. One has been studied in great detail, varying the front porch length from 30 min to 6 h and repeating measurements to check for consistency, and the others have been studied only with "standard" runs consisting of 30 min front porches. Table I is a list of the magnets and histories used.

The b_2 hysteresis for a ramp cycle of magnetic TB353 is shown in Fig. 1. In this run, the magnet preparation consisted of a 4000 A quench. Figure 2 is a plot of the excitation cycle, which is identical to that used in Tevatron operations. It consists of a short porch at 400 A (90 GeV), an injection front porch at 660 A (150 GeV), and the ramp to a flat-top current of 4000 A (900 GeV), followed by a ramp down to 400 A. This particular run included an injection front porch of 60 min duration, and the drift in b_2 during this period is clearly visible. The measurements are taken about 4 ft from the end of the magnet, ensuring this to be a measurement of the body sextupole component. This particular magnet has a geometric body field of roughly 14 units, most of which is canceled by the end fields. We are interested in two

TABLE I. Summary of the measurements of the logarithmic slope of b_2 on the injection front porch.

Magnet	Temperature (K)	History	Length of front porch (min)	Slope (b_2/decade)
TB353	4.6	Quench	30	0.354
TB353	4.6	Quench	60	0.331
TB353	4.6	Quench	60	0.341
TB353	4.6	Quench	30	0.375
TB353	4.6	60 min flat top+quench	60	0.387
TB353	4.6	Quench	30	0.352
TB353	3.6	Quench	30	0.400
TB353	3.6	Quench	60	0.364
TB353	3.6	60 min flat top+quench	60	0.408
TB353	4.6	Quench	120	0.312
TB353	4.6	Quench	360	0.353
TB1220	4.6	Quench	30	0.327
TB1220	4.6	Quench	30	0.332
TB1207	4.6	Quench	30	0.546
TB1207	4.6	Quench	30	0.528
TB1207	4.6	Quench	360	0.441
TB1207	4.6	Quench	120	0.451
TB492	4.6	Quench	30	0.453
TB492	4.6	Quench	30	0.376
TB492	4.6	Quench	360	0.468
TB862	4.6	Quench	30	0.607
TB862	4.6	Quench	30	0.519

features of the data: the drift in b_2 during the injection front porch and how b_2 reconnects to the hysteresis curve at the start of acceleration.

Data taken during the front porch of the cycle from Fig. 1 are shown in Fig. 3 [16], along with a logarithmic fit. We have parameterized these data in terms of the logarithmic slope. We have studied the reproducibility of these measurements by repeating the experiment seven times. The results are plotted in Fig. 4(a). The average slope is 0.345±0.020/decade. The data are also summarized in Table I.

We have studied magnetic TB353 under a variety of conditions which are summarized in Appendix A. In order to get some idea of the reproducibility of these measurements from magnet to magnet, we performed a simpler set of measurements on additional magnets. The magnets were chosen to encompass the range of construction techniques and cable used in the entire Tevatron project. The results are shown in Fig. 4(b). While the spread in slopes for a given magnet is roughly ±20%, there is

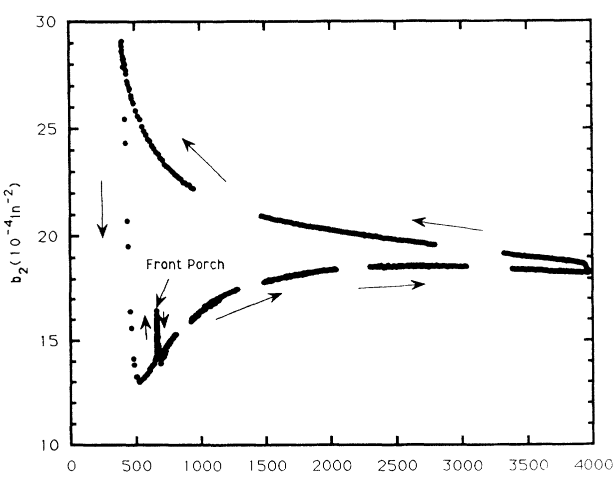


FIG. 1. b_2 hysteresis for a complete Tevatron ramp cycle including a 60 min front porch. The arrows indicate the front porch and the direction of the ramp.

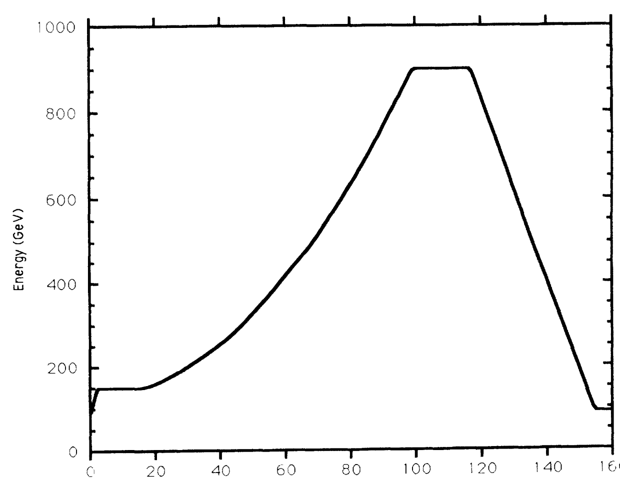


FIG. 2. Ramp wave form for the Tevatron dipoles. 1 GeV corresponds to 4.4 A.

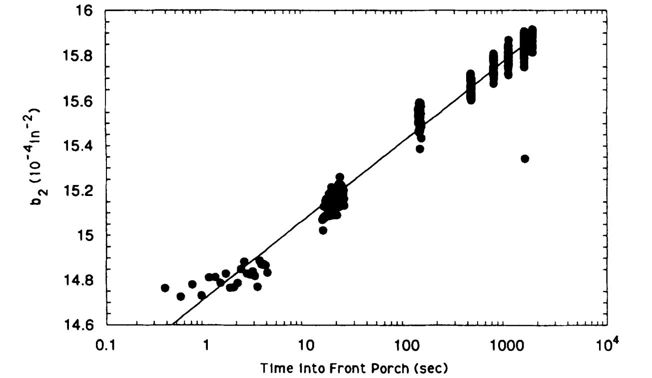


FIG. 3. $b_2(t)$ during a 30 min front porch. The line is a logarithmic fit to the data with slope of 0.354 units/decade.

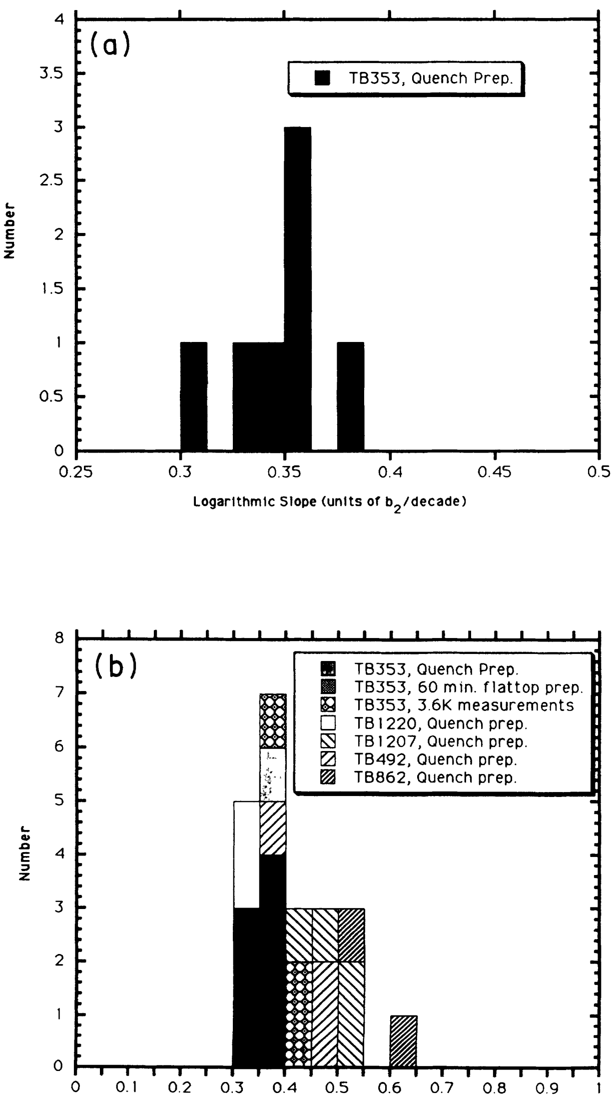


FIG. 4. (a) Logarithmic slopes for seven runs with a quench preparation for magnet TB353. (b) Summary of logarithmic slopes for all runs.

about a 40% spread from magnet to magnet. We do not know what controls this spread. The possibility that it is controlled by the microscopic properties of the superconducting cable is ruled out upon examination of the data for magnets TB1220 and TB1207. In general, when Tevatron coils were assembled into magnets, no concern was paid to ensure that the different coils in a magnet were made from the same cable. However, all magnets numbered 1200 and higher were made from the same batch of cable which had substantially better short sample performance than previous cable, and the data for these magnets are consistent with that of the other magnets [17]. We note that the HERA group has also observed a similar spread in the time dependence for magnets manufactured identically [18]. They have also noticed significant systematic differences between sets of magnets manufactured with different techniques and using slightly different cables. They do not yet understand the cause.

The logarithmic drift in the persistent current moments is due to the escape of flux lines from the individual superconducting filaments. At the start of the ramp, the changing "external" field (caused by the transport current) remagnetizes the filaments, resulting in persistent current moments almost equal to those at the beginning of the front porch, with the only difference being due to the small decrease in the critical current due to the larger external field. Calculations on Tevatron cable indicate that the filaments should be fully magnetized after a current change of about 15 A. This occurs at about 4 sec into the ramp (Fig. 2). If these changes are uncompensated, the chromaticities will vary rapidly within this 4 sec interval. From the data for TB353, we see that in a 30 min front porch b_2 drifts by roughly 1.2 units, corresponding to 20–25 units of chromaticity. Swings of that magnitude, if uncompensated, will lead to instabilities as one chromaticity nears 0 or resonance excitation as the other chromaticity becomes very large. In order to compensate these swings, it is necessary to know the detailed shape of $b_2(t)$ as the persistent current drift is removed and the normal hysteresis values are restored and program the chromaticity sextupoles accordingly.

To measure the return of $b_2(t)$ to the hysteresis curve, the data acquisition system was instructed to start recording measurements several seconds before the start of the ramp and stop recording 10 sec later. This interval encompasses the period during which b_2 changes rapidly.

For these measurements, magnet TB1207 has been used. Figure 5(a) is a plot of these data for a run with a 30 min front porch. The zero for the time axis is the start of the ramp. However, the interesting data are really the difference between the hysteresis curve [$b_2(t)$ measured during the last preramp] and the measured curve with a given front porch. The normal cycle (used in the preramps) includes a 150 GeV front porch of roughly 10.5 sec. There is about a 0.8 unit drift in b_2 during this period, which is removed in the first 2 sec of the subsequent ramp. We approximate the hysteresis cure by extrapolating the linear fit to $b_2(t)$ from 2.5–5 sec back to the start of the ramp. The difference is plotted in Fig. 5(b). The data for magnet TB1207 are summarized in

Fig. 5(c), in which we plot only the first 5 sec (our model assumes that the persistent current correction is removed in 4 sec). We include runs with a 10.5 sec front porch (taken from the last preramp), two runs with a 30 min front porch, and runs with 120 and 360 min front porches. The data (except for the 11 sec front porch data, which are not operationally useful) are consistent with complete removal of the persistent current drift (i.e., b_2 has rejoined the hysteresis curve) in about 4 sec. Furthermore, the shape of the reconnection curve is very nearly linear, with the slope being determined by the drift during the front porch. We note that the change in magnetic field in the first 4 sec of acceleration is about 150 G. This is consistent with the field change needed to fully penetrate the 9 μm filaments in the Tevatron superconductor.

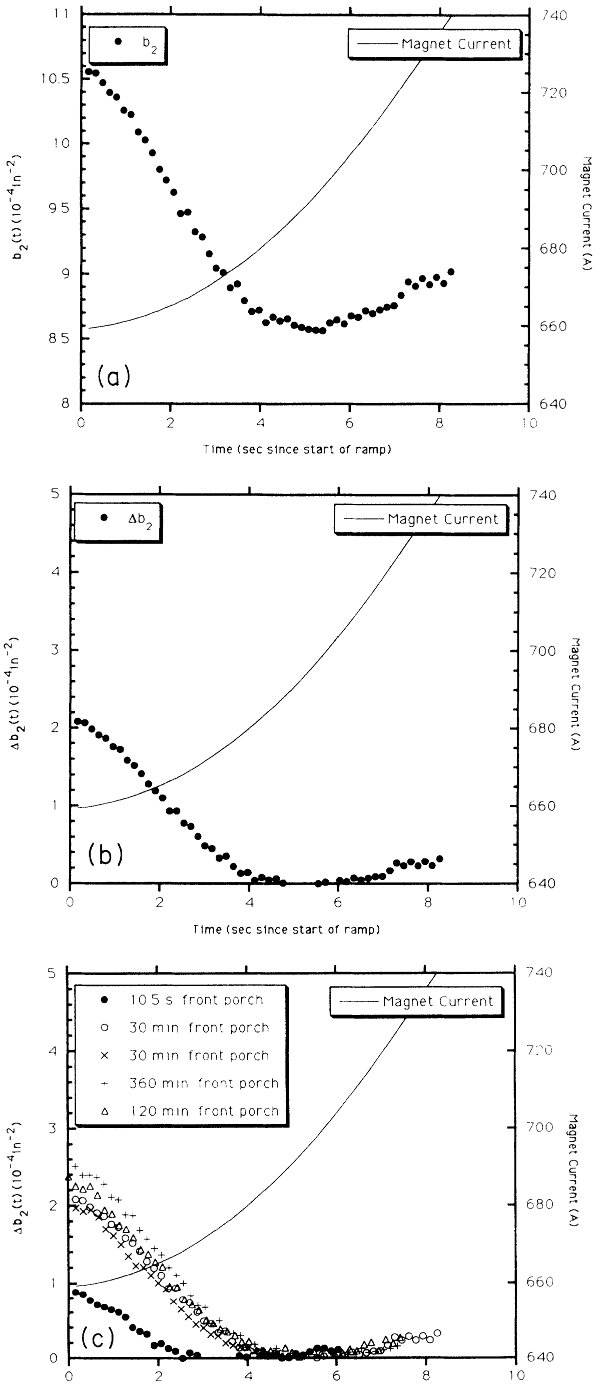


FIG. 5. (a) $b_2(t)$ at the start of the ram for magnet TB1207 with a 30 min front porch. (b) Difference between the b_2 hysteresis curve and the measured b_2 for the data in (a). In this plot and in (c), fluctuations in Δb_2 below 0 (due to measurement error) are not plotted. (c) Summary of the difference between the b_2 hysteresis curve and the measured b_2 for all front porches for magnet TB1207.

This describes the set of measurements made on Tevatron dipoles. In principle, these measurements can be transformed into programs for the sextupole circuits to cancel the time-dependent chromaticities. However, we have only tested five magnets, and we do observe variations from magnet to magnet, making it very difficult to use these data to correct the ring as a whole. These measurements have taught us that the cycle of six preramps eliminates history dependence of the drift, that the drift is logarithmic in time, and the drift seems to be removed linearly with time at the start of acceleration. We can use these observations as a starting point for the Tevatron corrections, but the final corrections will have to be determined using beam measurements.

OBSERVATIONS IN THE TEVATRON

We have indicated in the first section how time-dependent persistent current effects influence the beam dynamics in the Tevatron. Over the past five years of Tevatron collider operation, much effort has been devoted to studying and correcting the effects. In addition, we have successfully modeled some of the corrections based on the results of the laboratory measurements described in the preceding section.

The two regimes to be corrected (the slow drift on the injection front porch and the rapid return to the hysteresis curve at the start of acceleration) presented different operational problems. The slow drift on the front porch can be measured quite accurately simply by making chromaticity measurements. At the start of the ramp, the chromaticity changes by many units over seconds, and we have no method of making real time chromaticity measurements during this period. The betraton tunes are monitored in the main control room with a set of signal analyzers connected to Schottky detectors which detect the coherent oscillations of the beams. At the start of the ramp, there appear to be large coupling and chromaticity changes and as a result, the peaks which are normally seen on the signal analyzers become very broad and indistinct, making it difficult to measure the tunes.

The early measurements of the chromaticity as a function of time on the injection front porch taken in 1987 could be well fit using a logarithmic function [19]. The sextupole currents were programmed to include a time-dependent component with this slope to attempt to maintain constant chromaticities.

During the 1992–1993 collider run the acceleration rate was halved. We remeasured the chromaticities on the injection front porch by varying the frequency of the radio frequency (rf) system, measuring the tune change, and calculating the slope at the origin (the 1987 data were taken by observing the coherent betraton spectrum measured on a set of Schottky detectors and determining the sextupole settings for 0 chromaticity, as indicated by the onset of an instability). The new data also indicate a logarithmic variation of b_2 with time, but with a slope of 0.285 unit/decade, rather than 0.263 measured in 1987. We do not know whether this is due to the different measurement technique, which results in a more accurate measurement, or in a real change in the behavior of the magnet due to the different ramp rate. We do note that with the slower ramp rate, the chromaticities are held constant to less than two units over a 3 h front porch (Fig. 6), whereas with the previous algorithm they varied by about eight units over 3 h [19]. This slope is significantly different from the average slope measured in the laboratory. The difference is about 0.11 unit/decade. Great care was taken to ensure that the preparation for the magnets in the laboratory was identical to that in the Tevatron. We do not understand the source of the discrepancy.

At the start of acceleration, the drift in b_2 on the front porch must be removed and a smooth connection made to the hysteresis curve. Initially in the 1992–1993 run, the algorithm used (Appendix B) was not accurate and limited the p intensities that could be injected into the Tevatron to about 110×10^9 p/bunch. Any bunches with higher intensities were not injected.

Due to the speed, continuous nature, and the apparent coupling changes we have not been able to measure the chromaticity at the start of the ramp. The only available data for corrections were the laboratory data taken with TB353 [Figs. 5(b) and 5(c)]. In Appendix B we describe the way in which the corrections were implemented. After the present algorithm was implemented, the limitation disappeared, and we have regularly accelerated bunches with greater than 160×10^9 p/bunch, and the intensity limitation was removed.

Figure 7 illustrates the effects of this change. The only difference between the data in the two plots is that the present algorithm was installed for the data in Fig. 7(b). The front porch for this store was 75 min. The p intensity was greater than 140×10^9 p/bunch, and there is no sudden loss of p or $\bar{p}$ intensity at the start of the ramp (the slow $\bar{p}$ loss was due to an uncompensated tune shift).

CONCLUSIONS

Using a variety of correction techniques based on beam measurements and laboratory dipole measurements, we have developed operational techniques for the compensation of time-dependent persistent current effects. Currently, they remove performance limitations created

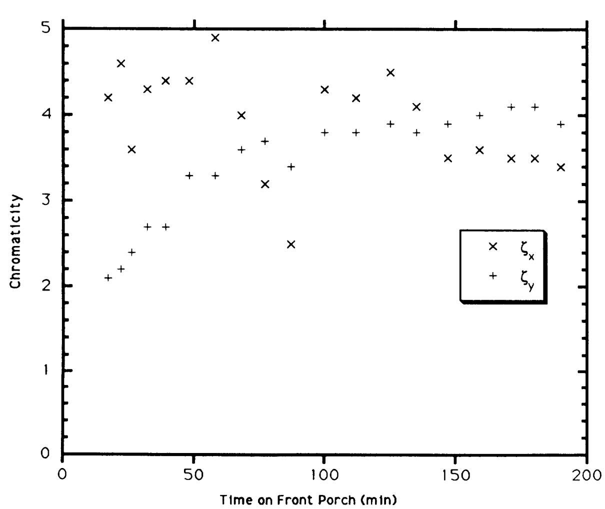


FIG. 6. 1993 data showing the behavior of the chromaticities as a function of time on the injection front porch.

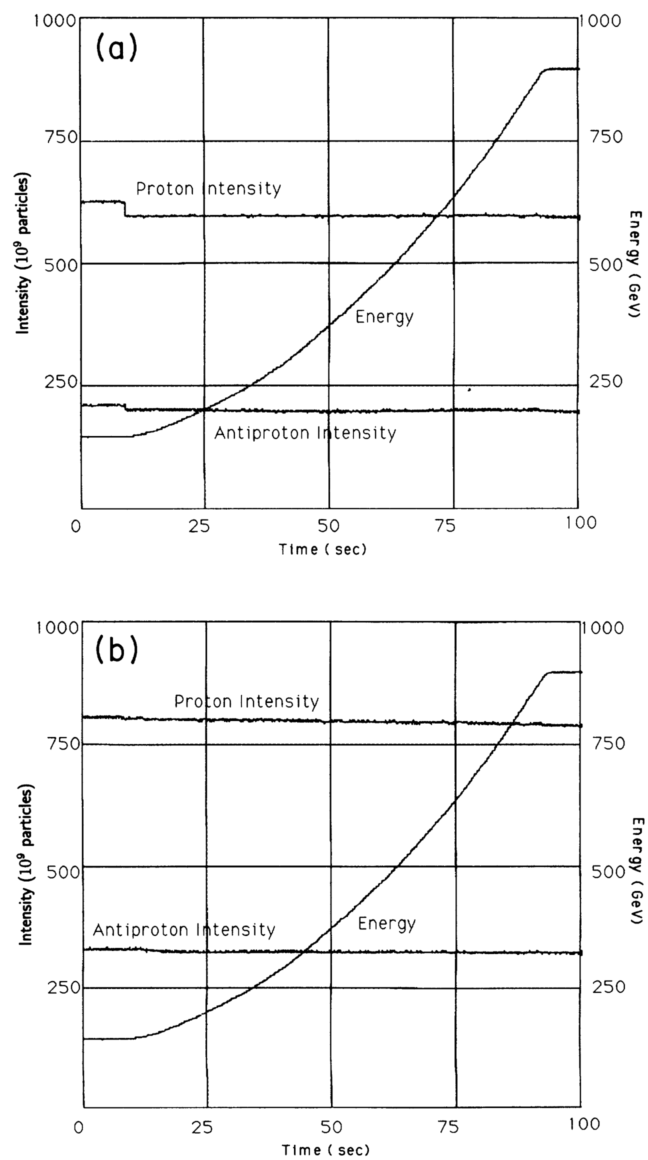


FIG. 7. (a) Particle transmission to flat top before the persistent current corrections were installed. (b) Particle transmission to flat top after the persistent current corrections were installed.

by uncompensated persistent currents.

Tevatron superconducting magnets appear to operate reproducibly over the range of operating conditions. The drift in b_2 during the front porch and the recovery at the start of the ramp are independent of magnet history as long as the cycle of six ramps is performed. The slopes measured in laboratory tests are very different from those measured in the Tevatron, so different that there would be serious stability problems in the Tevatron if they were used operationally. It must be stressed that the laboratory measurements of the recovery from the front porch work very well operationally.

The techniques we are currently using are "open loop" in the sense that the corrections have been determined by measurements in the Tevatron (the chromaticity at injection) and by laboratory measurements of a single Tevatron dipole. Their effectiveness relies upon having an accelerator in which the basic parameters are stable. We have already seen one limitation to this system—when the ramp rate was halved the corrections changed drastically and it was necessary to measure the response of a magnet with the new wave form. A more robust system is a real time feedback system. The HERA group has installed such a system which uses as inputs the real time measurements of b_2 from two magnets which are in series with the bend bus of the accelerator. The system calculates $b_2(t)$ and sends corrections to the sextupoles. They have demonstrated that with this scheme it is possible to control the chromaticity on the front porch to 1–2 units [20]. The weakness of this method is that it assumes that the ensemble of magnets in the accelerator acts identically to one or two specially selected magnets. Another approach to eliminate this dependency is to measure the chromaticities directly in real time, and send the corrections to the sextupole circuits. A feedback microprocessor which is capable of applying the corrections on both the front porch and at the start of the ramp exists [21]. This system cannot be used for this purpose since a method of making reliable chromaticity measurements in real time has not been developed.

Several large superconducting synchrotrons (RHIC at Brookhaven, LHC at CERN, and until recently, the SSCL in Dallas) are in their design phases. The SSC in particular has paid great concern to the problem of time-dependent persistent currents. The lessons they have learned have been extremely instructive. We believe that the most important changes were not changes to the magnet design, but rather were a series of changes designed to minimize the sensitivity of the accelerator to persistent currents errors. By increasing the injection energy to 2 TeV (from 1 TeV) they have decreased the critical current and thus decreased the persistent current multipoles by at least a factor of 2. By increasing the phase advance to 90°/cell, the maximum β and η have been decreased, leading to a smaller contribution to the chromaticity from the persistent current multipoles. Finally, increasing the dipole aperture to 5 cm (from 4 cm) moves the source of the multipole errors farther from the beam and decreases their strength. As a result of these changes, the SSC group expected their persistent current errors to be roughly the same scale as those in the Tevatron [22]. They have also engaged in a detailed study of the time-dependent fields in the prototype magnets with the aim of developing strategies to minimize the time dependence [14]. A significant discovery is that by installing a "preinjection front porch" about 10 A lower than the injection front porch, they were able to halve the time drift of b_2. They had intended to implement such a ramp in their operational wave form. They have also spent much effort attempting to develop a model of the time-dependent behavior from first principles [23]. If successful, this model might provide insight into magnet design techniques which would reduce the persistent current decay.

ACKNOWLEDGMENTS

We would like to thank the management of both the Accelerator Division and the Technical Support Section at Fermilab for their support in this research. Pat Colestock and Gerry Jackson in particular encouraged this work. We also thank Ray Hanft, Peter Mazur, Hank Glass, Charlie Hess, and the rest of the Lab 2 and MTF staff for their assistance. Moyses Kuchnir, Rae Stiening, Arnaud Devred, and Alvin Tollestrup have spent much time explaining the physics of persistent currents to us. D.H. would like to thank the HERA group for its hospitality. This work has been supported by the U.S. Department of Energy under contract No. DE-AC02-76CH03000.

APPENDIX A

In this appendix we will summarize the measurements of the drift in b_2 at the injection current. In the text we have described the measurements on TB353 starting from a quench history. We have also investigated whether the initial quench influences the drift by replacing it with a 60 min, 4000 A flat top. The drift was consistent with those in the cycles starting with a flat-top quench. In normal Tevatron operations, the initial conditions before a high energy physics store are either a long flat top (the previous store) or, if the ramp has been turned off, a 15 min, 4000 A flat top. The laboratory data indicate that there should be no difference between these initial conditions.

Tevatron upgrade plans call for the installation of equipment to decrease the temperature from 4.6 to 3.6 K. The persistent current models predict that while the sizes of the persistent current moments will increase (due to the higher critical current), the time dependence will remain the same [14]. We have also tested this with three runs at 3.6 K. Two runs were done with a flat-top quench and one with a 60 min flat top. These data are consistent with the other measurements, and are also included in Table I.

APPENDIX B

The algorithm in use initially during the 1992–1993 collider run used the logarithmic function describing the drift on the front porch, but with time running backwards to 0 in 1 sec. In effect, this removed almost all of the drift in the last fraction of a second before the timer counted down to 0. This correction clearly does not correspond to the curves in Fig. 5(b). The losses shown in Fig. 8(a) occur during this period, and the spectrum analyzers showed very sharp traces with extremely high power, indicating a coherent instability. This was the source of the limitation to $110\times10^9 p$/bunch.

The present algorithm used the data from TB353. For the first 5 sec of the ramp, the difference between the b_2 hysteresis curve and the measured $b_2(t)$ was calculated, and this Δb_2 used to calculate an additional correction to the sextupole circuits. Since the sextupole current required to maintain a constant chromaticity depends linearly on b_2, the additional correction has the same shape as the magnet measurements. For porches longer than 30 min we set the initial value of the drift at the start of the ramp to the value determined from the logarithmic drift, and removed the correction linearly over a 4 sec interval. This parameterization agrees with the curves in Fig. 5(b) to within 0.1 unit of b_2. An error of this size in inconsequential.

[1] For example, the Tevatron at Fermilab, HERA (hadron electron ring anlage) at DESY, the LHC (large hadron collider) at CERN, RHIC (relativistic heavy ion collider) at Brookhaven, and the proposed SSC (superconducting super collider).

[2] R. Palmer and A. V. Tollestrup, Annu. Rev. Nucl. Part. Sci. **34**, 247 (1984).

[3] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962).

[4] Martin N. Wilson, *Superconducting Magnets* (Clarendon, Oxford, 1983).

[5] Helen T. Edwards, Annu. Rev. Nucl. Part. Sci. **35**, 605 (1985).

[6] F. Willeke and F. Zimmerman, in *Conference Record of the 1991 IEEE Particle Accelerator Conference,* edited by L. Lizama and J. Chew (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1991), p. 2483.

[7] C. Daum *et al.*, IEEE Trans. Magn. **24**, 1377 (1988); R. Brinkmann and F. Willeke, DESY Report No. HERA 88-08, 1988 (unpublished).

[8] S. Herb (private communication).

[9] D. Finley *et al.*, in *Proceedings of the 1987 IEEE Particle Accelerator Conference,* edited by E. Lindstrom and L. Taylor (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1987), p. 151.

[10] See, for example, R. W. Hanft *et al.*, IEEE Trans. Mag. **25**, 1647 (1989); D. A. Herrup *et al.*, *ibid.* **25**, 1643 (1989); D. E. Johnson *et al.* in *Proceedings of the 1989 Particle Accelerator Conference,* edited by F. Bennett and J. Kopta (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1989), p. 521; D. A. Herrup *et al.*, in *ibid.*, p. 518.

[11] P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962).

[12] See the Proceedings of the Topical Workshop on Magnetic Fields in Superconductors, March 5–7, 1990, Fermi National Accelerator Laboratory.

[13] H. Brück *et al.*, in *Proceedings of the 2nd European Particle Accelerator Conference,* edited by P. Marin and P. Mandrillon (Editions Frontières, Gif-sur-Yvette Cedex, France, 1990), p. 329.

[14] A. Devred *et al.*, in *Conference Record of the IEEE Particle Acclerator Conference,* edited by L. Lizama and J. Chew (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1991), p. 2480.

[15] M. Lamm *et al.*, Fermilab Report No. FERMILAB-Conf-92/292, 1992 (unpublished).

[16] Although it is customary to consider hysteresis as a function of current, the controls hardware in the Tevatron can only work as a function of time. All plots and corrections are calculated in time from either the start of the front porch or the start of ramp.

[17] R. Jensen (private communication). The reasons for the improved performance are not understood.

[18] P. Schmüser, in *Conference Record of the 1991 IEEE Particle Accelerator Conference,* edited by L. Lizama and J. Chew (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1991), p. 37.

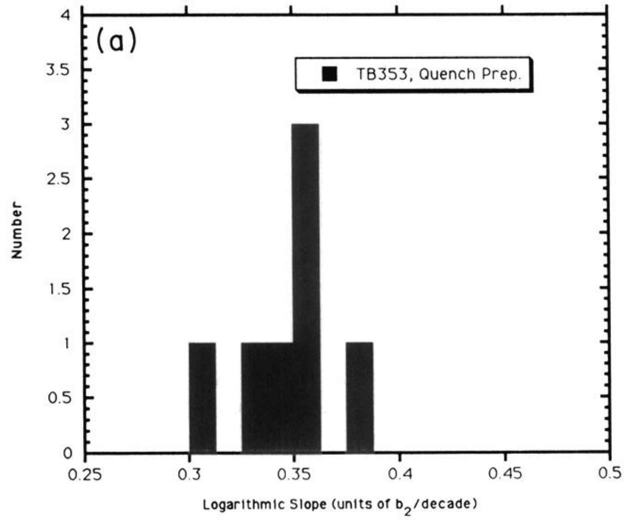
[19] D. E. Johnson *et al.*, in *Proceedings of the 1989 Particle Accelerator Conference,* edited by F. Bennett and J. Kopta (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1989), p. 521.

[20] O. Meincke (private communication).

[21] D. Herrup *et al.*, Nucl. Instrum. Methods Phys. Res. A **329**, 470 (1993).

[22] M. Syphers, in *Record of the 1991 IEEE Particle Acclerator Conference,* edited by L. Lizama and J. Chew (Institute of Electrical and Electronics Engineers, Piscataway, NJ, 1991), p. 117.

[23] R. Steining, SSCL Report No. SSCL-359, 1991 (unpublished).



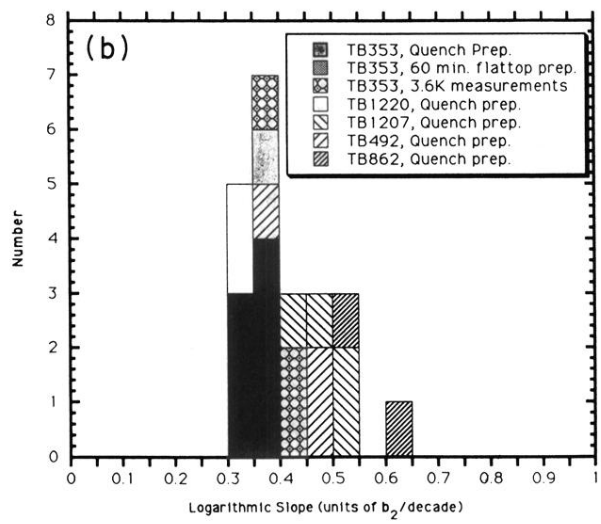


FIG. 4. (a) Logarithmic slopes for seven runs with a quench preparation for magnet TB353. (b) Summary of logarithmic slopes for all runs.