Fermi National Accelerator Laboratory

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Compensation of Time-Dependent Persistent Current Effects in the Tevatron

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Abstract

Time-dependent persistent current effects play an important role in the beam dynamics of superconducting synchrotrons. In the TEVATRON collider, these changes manifest themselves in variations of the sextupole moments of the dipole magnets during the injection front porch and acceleration. I will briefly review the physics of persistent currents and then discuss the effects observed in the TEVATRON and the strategies used to eliminate all apparent problems, enabling the TEVATRON to accelerate the highest intensities that the Main Ring has been able to deliver. The approach taken is that of an accelerator physicist, not a magnet designer.

Introduction

The Fermilab TEVATRON includes of 774 superconducting dipole bending magnets. The injection energy is 150 GeV, corresponding to a magnetic guide field of 0.66 Tesla. At low excitation, persistent current effects create significant distortions of the magnetic field. In the TEVATRON, the sextupole component (b_2) is most affected by these distortions. The dominant effect on the beam dynamics is to cause additional, large contributions to the chromaticities. In 1987, during the first TEVATRON collider run, a substantial time-dependence was observed in the chromaticities on the 150 GeV injection front porch[1]. Motivated by these observations, measurements on TEVATRON, HERA, and SSC dipoles have shown that there are large time-dependent persistent current effects at low excitation[2].

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[1] D. Finley et. al., "Time Dependent Chromaticity Changes in the TEVATRON,", Proceedings of the 12th Particle Accelerator Conference, Washington, D.C., March 16-19, 1987.

[2] See, for example, R.W. Hanft et. al., "Studies of Time Dependence of Fields in TEVATRON Superconducting Dipole Magnets'," Proceedings of the 1988 Applied Superconductivity Conference, San Francisco, CA, August 21-25, 1988, H. Brück

I will first describe a model which successfully accounts for time-independent persistent current effect. I will then discuss the observed time-dependent effects, the efforts to deal with these problems in the three TEVATRON collider runs, and possible future work at Fermilab.

Persistent Current Effects

Static persistent currents can be understood using the "critical state" model[3] of type II superconductors. The model postulates that a type II superconductor will attempt to maintain zero magnetic field in its interior in response to changes in an external magnetic field. This is accomplished by generating surface currents with the critical current density J_c and a shape which cancels the external field within the superconductor.

Figure 1 illustrates the development of persistent currents in a single superconducting filament in an external magnetic field. This model has been used by the DESY group to predict the static multipoles of the HERA dipoles with great precision[4]. In Figure 1a, a filament is immersed in an external field B_e, with $B_e < B_p$, where B_p is the "penetrating" field. To cancel the effect of B_e within the filament, a bipolar $\cos\theta$ current distribution with J_c is induced at the edges of the filament. As B_e is increased the persistent currents fill a larger and larger fraction of the cross section of the filament. At $B_e = B_p$ the filament is fully penetrated and the persistent currents flow in the entire cross section of the filament (Fig. 1b). If the external field is raised beyond B_p, the filament can no longer cancel the external field changes, and the field within the filament increases with increasing external field. If the external field is decreased to below B_p, an additional set of persistent currents attempting to cancel the changes to the internal field will be induced, as in Fig. 1c.

Several things are immediately apparent from this model. Persistent currents will flow in every filament in a magnet that is in a non-zero magnetic field. They will create a magnetic moment proportional to the filament radius, the amount of penetration of the filament and the critical current, which is a function of the temperature and the magnetic field. Thus, they will be largest at low field (ie., injection), where B is small and J_c is large. They will also create all magnetic multipoles allowed by the symmetry of the magnet. For instance, in a dipole one will have dipole, sextupole, decapole, etc., and in a quadrupole, quadrupole and duodecapole, etc. Finally, since the magnets are ramped, the fields can become quite complicated.

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et. al., "Time Dependence of Persistent-Current Field Distortions in the Superconducting HERA Magnets," Proceedings of the 2^{nd} European Particle Accelerator Conference, Nice, June 12-16, 1990, and A. Devred et. al., "Time Decay Measurements of the Sextupole Component of the Magnetic Field in a 4-cm Aperture, 17-m-Long SSC Dipole Magnet Prototype,", Proceedings of the IEEE Particle Accelerator Conference, San Francisco, May 6-9, 1991.

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

[4] H. Brück et. al., "Field distortions from persistent currents in the superconducting HERA magnets", Z. Phys. C - Particles and Fields 44, 385-392 (1989).

Fig. 2[5] is a plot of the measured sextupole component in a HERA dipole as a function of current (the arrows indicate the direction of the ramp) and the predictions of a calculation based on the model I have described. In both HERA and the TEVATRON, the persistent current sextupole affects only the chromaticity, and this can be cancelled with the ordinary chromaticity sextupoles. In the TEVATRON there are no other significant persistent current effects, while in HERA, there are also significant decapole and dodecapole fields which are compensated locally with beam pipe correction coils. The settings were determined using the model, and the beam lifetimes were satisfactory.

This model does not include time dependence. However, observations in the TEVATRON in 1987 showed that there was a substantial time-dependent component in the persistent current fields, causing b_2 shifts of up to 2 units (50 units of chromaticity) during the injection front porch [6]. This drift appears to be linear when the independent variable is chosen to be log t [7]. In Fig. 3 I plot the observed sextupole moments in a TEVATRON and an HERA[8] dipole as a function of time on the injection front porch. The "flux creep" model of Type II superconductors[9] predicts a logarithmic time decay of persistent currents. Although it superficially explains the observed changes in magnetization, further observations on short samples of superconductor as well as on HERA and SSC dipoles indicate that the demagnetization rate observed in complete magnets is much larger than measured in short samples[10]. Also, there are history and temperature dependences which are outside of the flux creep model[11]. Recently, a model of this phenomenom has been developed[12]. It assumes a redistribution of the persistent currents among the strands in a magnet. Although qualitatively this model appears to explain the effect, quantitative modelling has not yet been done.

Acceleration is accompanied by a change in the bend field in the dipoles. This change remagnetizes the superconducting filaments, and a new critical state will be formed with a slightly larger external field. As a result, a persistent current distribution very similar to that at the start of the ramp is formed. The drift of b_2 on the front porch is undone, and the 1-2 units of drift in b_2 is removed in the first seconds of acceleration. If uncompensated, this can lead to large changes in the chromaticities and possible instabilities or beam loss due to resonance excitation.

Fig. 4 is a plot of the measured b_2 as a funciton of excitation current of a TEVATRON dipole during a complete ramp cycle. The 60 minute injection front porch is indicated on the plot. The data do not appear continuously because the measurement system was designed to take 60 readings in 6 seconds, spend several seconds analyzing the data[13], and repeat

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[5] P. Schmüsser, private communication. Note that the European convention is to use b_1 for the dipole component, b_2 for the quadrupole, b_3 for the sextupole, etc.

[6] Finley et. al.

[7] R. W. Hanft et. al.

[8] P. Schmüsser, private communication.

[9] P.W. Anderson, Phys. Rev. Letters 9, 309 (1962).

[10] See the Proceedings of the Topical Workshop on Magnetic Effects of Persistent Currents in Superconductors, March 5-7, 1990, Fermi National Accelerator Laboratory and P. Schmüsser, "Field Quality Issues in Superconducting Magnets," Proceedings of the IEEE Particle Accelerator Conference, San Francisco, CA., May 6-9, 1991.

[11] A. Devred et. al.

[12] R. Stiening, "A Possible Mechanism for Enhanced Persistent Current Sextupole Decay in SSC Dipoles," SSCL-359, January, 1991.

[13] M. Lamm et. al., "A Facility to Test Short Superconducting Accelerator Magnets at Fermilab,", FERMILAB-Conf-92/292.

the measurements, etc. The arrows indicate the direction of the ramp. It is necessary to approach the injection current from below in order to prevent large jumps in b_2 as the persistent current contribution jumps from the upper branch to the lower branch of the curve as acceleration starts. By programming an undershoot, the system is made less sensitive to power supply control problems. The geometric b_2 of this magnet is about 18 units, and the persistent current contribution is approximately -6 units at the lowest current of the ramp, and -5 units at the injection current. One sees roughly 2 unit drift of b_2 during the front porch.

The 1987 TEVATRON Collider Run

The 1987 TEVATRON collider run provided the first real experience in operating a superconducting synchrotron as a colliding beam facility. The TEVATRON had operated as a fixed target accelerator for several years, but in that mode of operation the accelerator is ramped continuously and there is not a chance for significant time-dependent persistent current effects to develop. In collider operation, there is an injection front porch at 150 GeV of 1-3 hours during which the transfers into the TEVATRON are tuned up, and there is an extended flattop at 900 GeV during which high energy physics running occurs.

D. Finley et. al.[14] observed that during the 1-3 hour front porch the chromaticities changed by up to 70 units. Furthermore, they noted that at the start of acceleration the tune spectra, which are continuously monitored with a set of Schottky detectors which detect coherent betatron oscillations, broadened to the point at which it was impossible to observe any coherent signal. The p transverse emittance increased by about 30% during the ramp, and the $\overline{p}$ emittances doubled.

In order to understand these effects, experiments at the injection energy were undertaken. In one experiment, the history of the TEVATRON before injection was varied. Two sets of measurements of the chromaticities were made, one in which the TEVATRON was set to the injection energy after ramping continuously to flattop for 2.5 hours, and one in which a TEVATRON magnet had quenched, necessitating turning off all the power supplies, followed by a single ramp to flattop and then back down to the injection energy. In both cases, the full TEVATRON ramp was used. The drift in the chromaticities was found to be different from one experiment to the other. It was also discovered that by ramping the TEVATRON to flattop and back to injection six times before each shot set-up, the variations in the chromaticity drifts were minimized. Subsequently, this cycle of ramps was performed before every store.

A by-product of these experiments, shown in Fig. 5[15], was a careful set of chromaticity measurements on the front porch after the six ramps. These were used operationally to set

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[14] Finley et. al.

[15] Fermilab TEVATRON log book ED10, p. 62.

the chromaticities as a function of time into the front porch. Use of this technique produced acceptable lifetimes.

Finley et. al.[16] made a set of measurements on TEVATRON-style dipoles (dipoles without the iron yoke) to look for a time-dependent b_2. In each case, the magnet was prepared with the cycle of 6 ramps and the measurements taken out to 900 seconds on the front porch. They show a clear change in b_2 of about 0.8 units over this period.

No attempt was made to measure b_2 at the start of acceleration. An algorithm was used which calculated the drift to the end of the front porch, and once acceleration started, held b_2 constant until the value of b_2 from the normal hysteresis curve equaled the end of front porch value, and from that point on, b_2 followed the hysteresis curve (Fig. 6). This algorithm did not reduce emittance growth during the ramp.

The 1988-1989 TEVATRON Collider Run

During the interval between the 1987 collider run and the 1988-1989 Collider run, a collaboration formed between Technical Support physicists and Accelerator Division physicists to attempt to understand the persistent current effects by making a thorough set of magnetic measurements. The measurements were designed to study the drift in b_2 during the injection porch and at the start of acceleration under TEVATRON operating conditions. The magnet used was a 1 meter long prototype dipole without the iron yoke. It was cooled in a vertical dewar. Magnetic moments were measured using a Morgan coil that rotated at 4 Hz. and provided measurements at a 2 Hz. rate. The magnets were excited with the TEVATRON waveform in use at the time[17].

All data were taken starting with a 4000 amp quench of the magnet followed by the cycle of 6 ramps, a front porch, and a final ramp to flattop. The test data from this magnet indicated that the drift in b_2 on the front porch is approximately logarithmic in time. In the first few seconds of acceleration, the drift in b_2 was undone and b_2 rapidly decreased to join the normal hysteresis curve, rather than being constant until the hysteresis value reached the value at the end of the flattop. These data are summarized in Fig. 7a (the logarithmic drift on the front porch) and Fig. 7b, which shows the response of b_2 at the start of the ramp. From Fig. 7b, one sees that the drift increases with increasing front porch, and the longer the front porch, the longer it takes for b_2 to rejoin the hysteresis curve.

The results of these measurements were used in the programs which generate the sextupole ramps. For the injection front porch, the data measured in 1987 (Fig. 5) were fit to a logarithmic function

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[16] Finley et. al.

[17] R.W. Hanft et. al. and D.A. Herrup et. al., "Time-Varying Sextupole Corrections During the Tevatron Ramp," Proceedings of the 1989 IEEE Particle Accelerator Conference, Chicago, IL, March 20-23, 1989, p.518.

$$b_2(t) = -2.3643 + 0.263*\ln(t)$$

where the two constants were determined from the fit. Every few minutes on the front porch, the sextupole waveforms were recalculated using the current time at 150 GeV and the new values sent to the power supply controllers. The results of this scheme are shown in Fig. 8, in which the measured chromaticities as a function of time at 150 GeV are shown[18]. These chromaticities represent the difference between the logarithmic function for b_2 and the actual value in the ring. If the logarithmic correction accurately described the drift in the dipoles, the chromaticities would be constant. As can be seen from the figures, there are deviations of 4-5 units over the 2 hours of front porch during which these data were taken. For shot set-up times of less than about 3 hours, the algorithm prevented instabilities (kept the chromaticity positive) and also kept the chromaticity low enough so that a large tune spread would not cause particle loss. For front porches of longer than 3 hours, it was necessary to make a single adjustment to the chromaticities to make the lifetimes acceptably long.

The data measured from the test magnet were used directly to calculate the corrections at the start of acceleration. Data were taken for 30 minute, 60 minute, and 360 minute front porches. A two-dimensional interpolation, in length of front porch and energy, was used to calculate the sextupole currents as a function of energy. At each energy in the ramp, the difference was calculated between the hysteretic value of b_2 and the interpolated value based on measurements during the ramp after the front porch. This Δb_2 was then used to correct the sextupole current at that energy. The calculation was done immediately before the ramp, to ensure that the front porch time was correct. The time for the ramp from the injection front porch to 156 GeV (where b_2 has joined the hysteresis curve) is 2-3 seconds, depending upon the length of the front porch.

This algorithm was adequate for operations. Due to the beam-beam interaction, the p intensity was limited to 85E9/bunch. During acceleration there were only small (<5%) losses from the p bunches and none from the $\overline{p}$ bunches. The source of this loss was never understood. Both the p and $\overline{p}$ transverse emittance were preserved during acceleration and the spectrum analyzers did not show any signs of instabilities.

The 1992-1993 TEVATRON Collider Run

Several significant changes occurred between the 1988-1989 run and the 1992-1993 run. Electrostatic separators were installed in the TEVATRON with the intention of reducing the head-on beam-beam tuneshift by a factor of 6, thus allowing increased p intensities. This forces the TEVATRON to run closer to intensity-dependent instability thresholds. In addition, at the beginning of the run an RF cavity failed, which required slowing down the

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[18] D. Johnson, private communication.

TEVATRON ramp. The time-dependent persistent currents are known to vary with the ramp shape, and at the time the change was made there were no measurements of $b_2(t)$ with the new waveform.

Possibly as a result of the changes to the ramp, the persistent current behavior in this run was much different than previously. For the injection front porch, the logarithmic function from the 1988-1989 run was used. Fig. 9 is a plot of the measured chromaticities as a function of time on the front porch. The chromaticities are constant to within 2 units (compared with the 4-5 units in Fig. 8) over the three hour period, and beam lifetimes greater than 10 hours have been achieved. This correction is adequate, and there has not been any need to modify the 150 GeV algorithm. It is possible that the differences between the 1988-1989 and 1992-1993 data are due to the different waveforms.

Acceleration was initially done using a simple modification of the 1988-1989 algorithm. A fixed waveform was used, with the time at which the persistent current correction was removed (ie., $\Delta b_2 = 0$) as the only parameter. The waveform was taken from the 1988-1989 magnet measurement data. At the start of acceleration (when b_2 starts to change) there were sudden losses of about 10% in p bunched beam intensity. The spectrum analyzers showed clear evidence of an instability. In fact, if the intensity was increased beyond 120E9 p's/bunch, much larger losses and emittance growth occurred. To prevent this from happening, the Main Ring single bunch intensity was limited to less than 120E9 p's/bunch. At these p intensities, the beam-beam tuneshift is about 0.01, well under the 0.024 allowed in the TEVATRON.

In an attempt to remove this limitation, another program of measurements was undertaken with the Technical Support physicists. Once again, the intent was to emulate TEVATRON operating conditions as closely as possible and measure the time-dependence of b_2 in operational TEVATRON dipoles. In conjunction with the SSCL, a tangential probe rotating at 6 Hz. and providing measurements of the magnetic moments at 6 Hz. had been developed[19]. This probe easily adapted for use in a full-length TEVATRON dipole. The waveform used to drive the dipole was the new TEVATRON ramp, although for comparison, one set of measurements was made using the old waveform. The measurement cycle consisted of a quench at 4000 amps followed by the 6 ramps. At this point the ramp was stopped at the 150 GeV injection front porch for anywhere from 1/2 to 6 hours. During this time b_2 was measured every 5 minutes. At the end of the front porch, another ramp cycle was executed. During this last cycle, b_2 data were collected as rapidly as possible.

We have collected a large body of data on time-dependent persistent current effects. We have varied the initial conditions (whether the measurements started with a quench or with an hour at the 900 GeV flattop), the length of the front porch (from 30 to 360 minutes), and the temperature of the magnet (from 4.6°K to 3.6°K, in preparation for the lower temperature operation of the TEVATRON). While we have not yet fully analyzed all of these data, the data from one dipole and a 60 minute front porch have been used to correct the TEVATRON sextupole waveforms operationally.

In Fig. 10 I plot the measured sextupole component as a function of time while on the sixty minute front porch. I have also plotted the logarithmic function currently in use, which

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[19] M. Lamm et. al.

holds the chromaticities constant to less than 2 units over a 3 hour period (Fig. 10). The two functions are normalized to have the same value at t=0.1. Although both appear to be linear in log(t), there is a large discrepancy between the two slopes. Since the logarithmic function used to program the sextupole currents at injection is based on TEVATRON measurements, we conclude that the behavior of b_2 in the TEVATRON cannot necessarily be modelled by a single dipole. This discrepancy is not understood.

Fig. 11a is a plot of b_2 vs. time at the start of acceleration measured on a TEVATRON dipole using the 1992-1993 waveform (Figure 11b is the same for the 1988-1989 waveform). These data are also taken with a 60 minute front porch. This shape is quite different from that observed using the 1988-1989 ramp. From this graph, one immediately notices several things: the quality of the data are much better for the 1992-1993 data, due to the improved probe and the slower ramp, which allows us to acquire more measurements in a given energy range, and the shapes of the curves are different.

These new corrections were installed in the sextupole waveform generators. When the corrections were installed we had data for only a 60 minute front porch. It was assumed that the shape of the $b_2(t)$ curve was invariant out to 5.5 seconds, where $\Delta b_2 = 0.0$, and that only the starting point (ie., the drift at injection) varied with the length of the front porch. The Δb_2 curve was simply translated vertically by the logarithmic drift on the front porch.

The improvement with this algorithm was immediately evident. In Fig. 12a I show the intensities during the ramp with the original algorithm, showing the 10% loss, and in 12b, the intensities with the new algorithm. The beam loss has been eliminated and transmission from 150 GeV to flattop is almost 100%. There is no measurable emittance growth at the start of the ramp. This behaviour has been typical of the ramp since the new algorithm was installed. Whereas previously, to eliminate instabilities, the Main Ring intensity had been limited, after the algorithm was installed the intensity limitation was removed, and the TEVATRON has been able to accelerate without loss the highest intensity bunches (up to 150E9 p's/bunch) that the Main Ring has yet been able to deliver.

Future Plans

The persistent current corrections in use now are adequate for the current TEVATRON operating conditions. Using the logarithmic function measured in 1987 for the injection front porch, lifetimes longer than 10 hours have been observed at 150 GeV, and the dominant source of particle loss does not appear to be chromaticity-related. The corrections at the start of ramp also appear to be adequate to intensities of 150E9 p's/bunch. At that intensity there is no indication of instability or other types of particle losses. We do not know the limits, if there are any, for this algorithm.

Although we seem to have been successful in eliminating problems caused by persistent current effects, there are still several unanswered questions. The algorithm we have been using for the drift on the 150 GeV front porch was determined from real beam measurements on the TEVATRON. When we measure that drift carefully on a single magnet, however, we measure a substantially different drift. The data used to correct b_2 during the ramp (in both 1988-1989 and 1992-1993) has been determined from measurements on a single magnet and seems to represent the ring as a whole. Over the next several months we intend to measure b_2 drift on a sample of up to 10 magnets. While we do not expect these measurements to yield performance improvements, we hope that they will help us understand the parameters that determine the b_2 drift (cable composition, construction techniques, etc).

We have already taken a large data sample with the first magnet we tested using the 1992-1993 ramp. As has been mentioned, these data will be analyzed and it is to be hoped will guide us in further refining the algorithm for acceleration and tell us how b_2 rejoins the hysteresis curve for different front porch times.

The corrections we are using now are adequate up to single bunch intensities of 150E9 p's/bunch. The Main Injector upgrade calls for intensities of 330E9 p's/bunch. We do not know what sort of instability problems to expect at these intensities and if the current algorithm will work satisfactorily. It seems unlikely that we will be able to obtain better data at a higher frequency using the probes currently available. If we are to improve on our current open loop control, we will have to develop some sort of a realtime feedback system. The inputs to such a system could be either realtime measurements of b_2 in a reference dipole or chromaticity measurements.[20]

The persistent current problems at HERA are significantly larger than those in the TEVATRON. After learning of these effects, the HERA group decided to implement an active feedback system for b_2 control. They have instrumented two "reference magnets", one from each of the magnet production lines. They measure b_2 in real time, and have used these measurements to close the loop to the chromaticity sextupoles at their injection energy of 40 GeV. In tests of this system, it has succeeded in maintaining constant chromaticities to better than 1 unit over a 30 minute period. Although this system has not been extensively used, these results give confidence that a feedback solution will work at injection[21]. The HERA group is planning to evaluate this system in more detail during the upcoming run. They also have the ability to close the loop at the start of acceleration. This has not yet been attempted, and it will be very interesting to see the results as this system is brought into operation. If HERA can demonstrate that feedback on a magnet yields a significant improvement in performance, we will seriously consider designing and installing such a system in the TEVATRON.

Acknowledgements

Many people at Fermilab, DESY, and the SSCL have contributed to our study of persis-

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[20] O. Meincke, private communication, and D. Herrup et. al., A Feedback Microprocessor for Hadron Colliders, to appear in Nuclear and Instruments in Physics Research, Section A.

[21] O. Meincke, private communication.

tent current effects in the TEVATRON. The original collaboration with the Technical Support Section included Ray Hanft, Mike Lamm, Bruce Brown, Moyses Kuchnir, and Alvin Tollestrup. This group expanded to include Bill Kinney and Akbar Mokhtarani, Frank Turkot, and Peter Mazur. Their enthusiasm for this program has led directly to our successes in the TEVATRON. In the Accelerator Division, David Finley, Dave Johnson, Mike. Harrison (now at Brookhaven), and Mike Syphers (now at the SSCL) have all been involved in this work. Vinod Bharadwaj first encouraged me to re-open the study of persistent currents. Steve Herb, Ferdi Willeke, Peter Schmüsser, Christoph Stolzenburg, H. Brück, and Olaf Meincke extended their hospitality during a visit to DESY in which I learned about the work being done there. Arnaud Devred and Rae Stiening of the SSCL have also spent much time explaining their ideas to me.

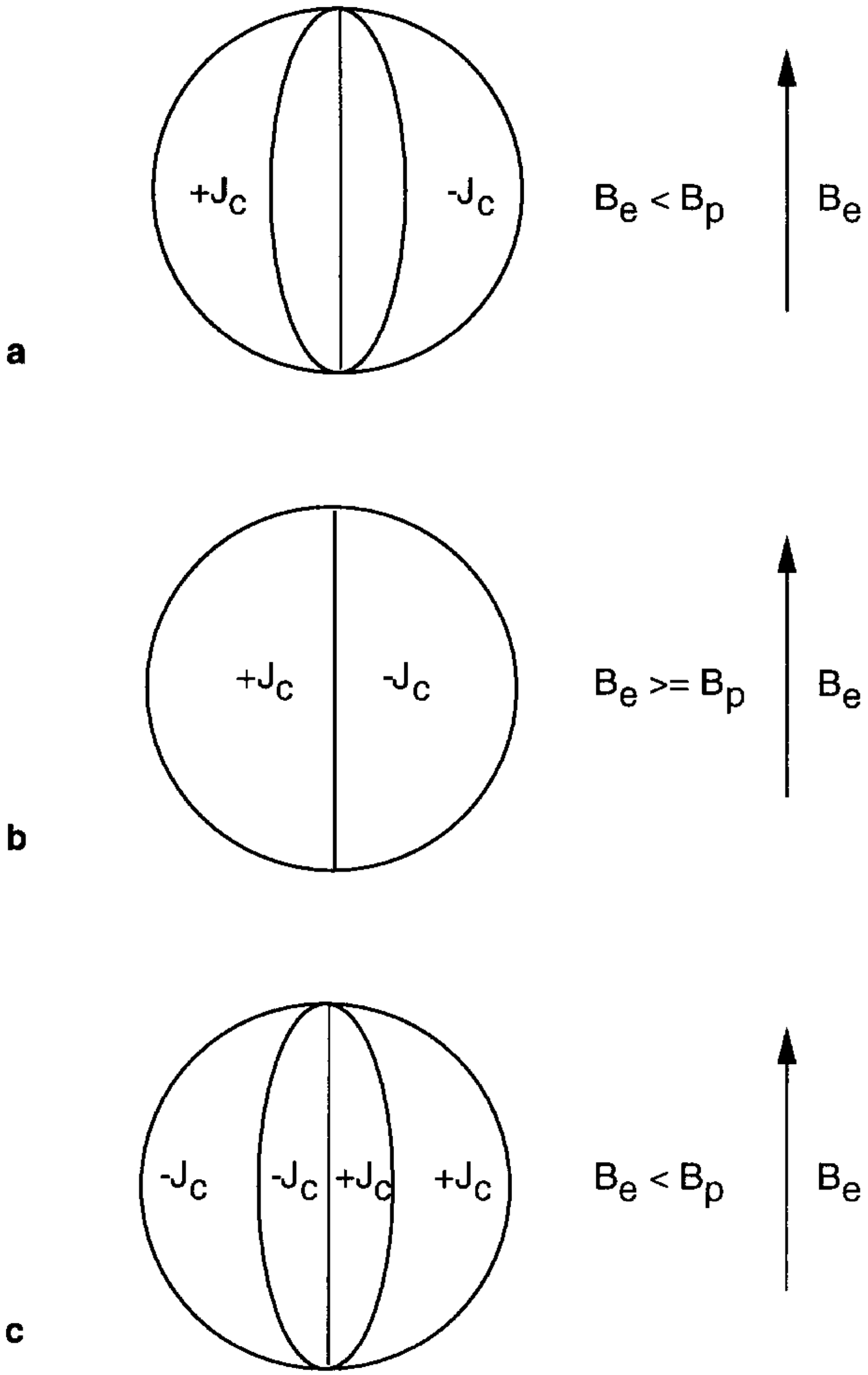

Figure 1. Diagram of persistent currents induced in a superconducting filament in an external magnetic field $\mathbf{B}_e$ as $\mathbf{B}_e$ is increased from 0 to a value greater than $\mathbf{B}_p$, the field at which the filament is fully penetrated. **a** $\mathbf{B}_e < \mathbf{B}_p$. **b** $\mathbf{B}_e > \mathbf{B}_p$, ie., the filament is fully penetrated. **c** $\mathbf{B}_e$ is then decreased to a value below $\mathbf{B}_p$.

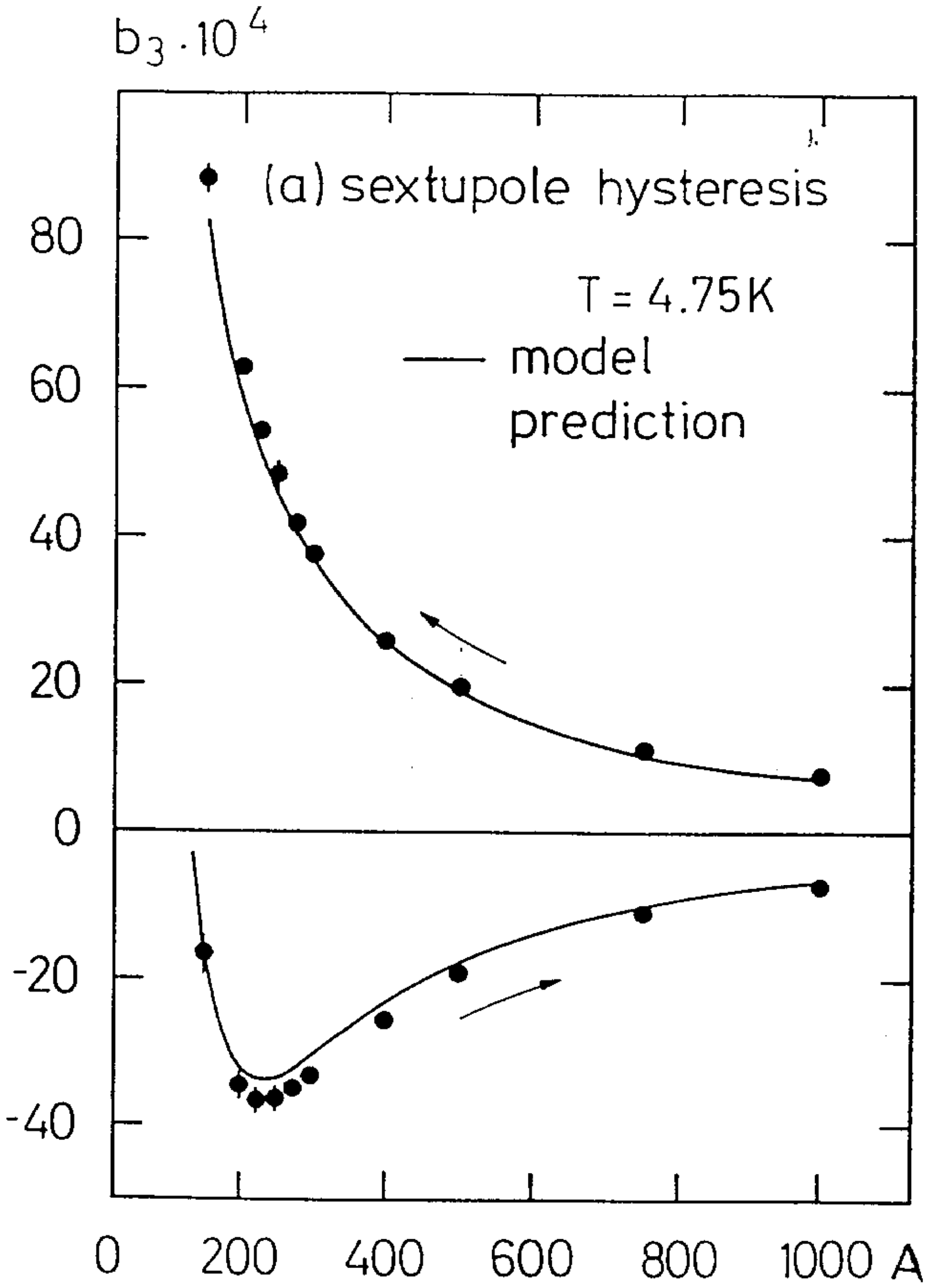

Figure 2. Sextupole hysteresis curve and model predictions for the HERA dipoles. The arrows indicate the direction of the ramp.

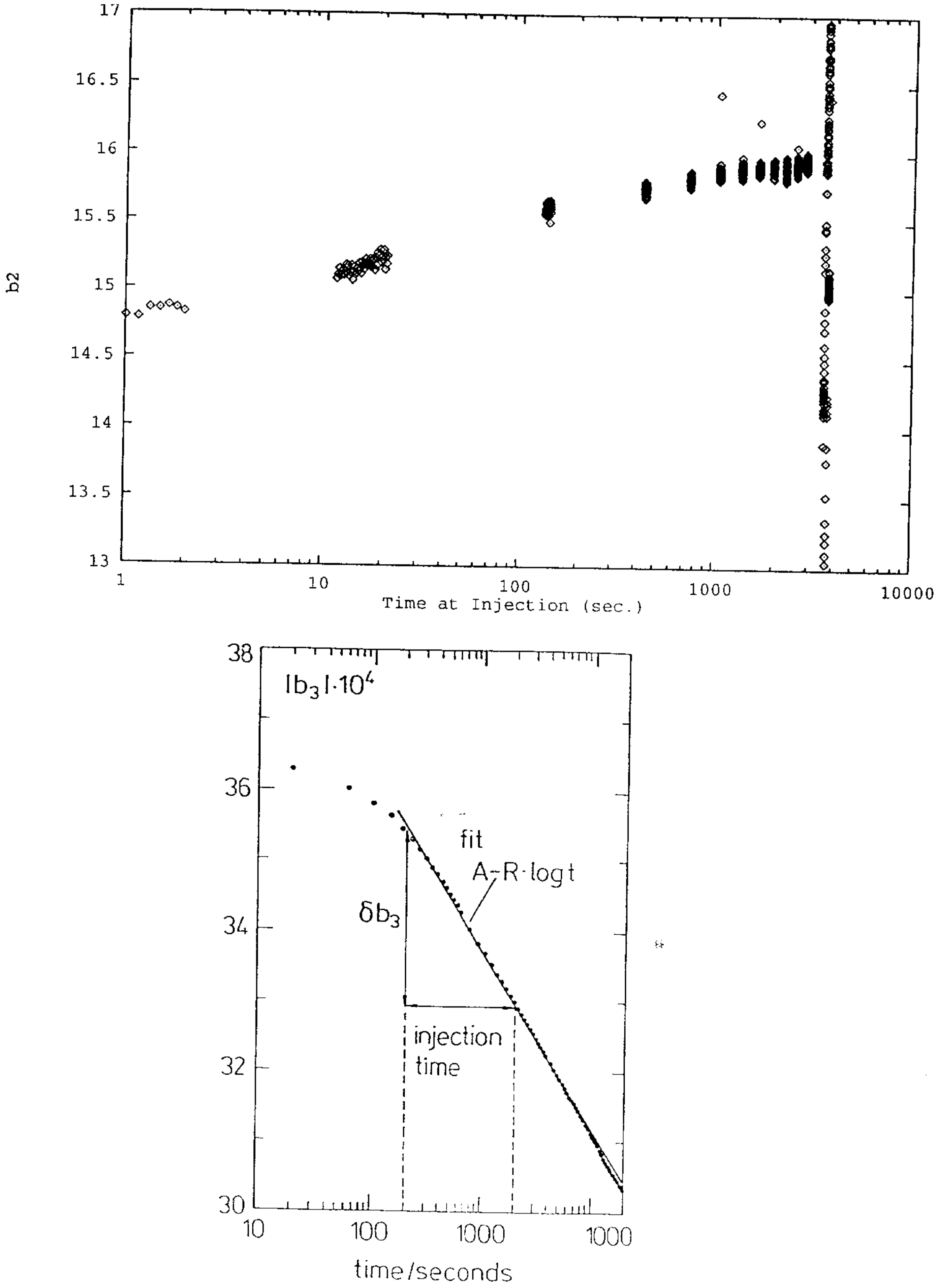

Figure 3. $b_2(t)$ on the injection front porch for **a** TEVATRON dipoles and **b** HERA dipoles.

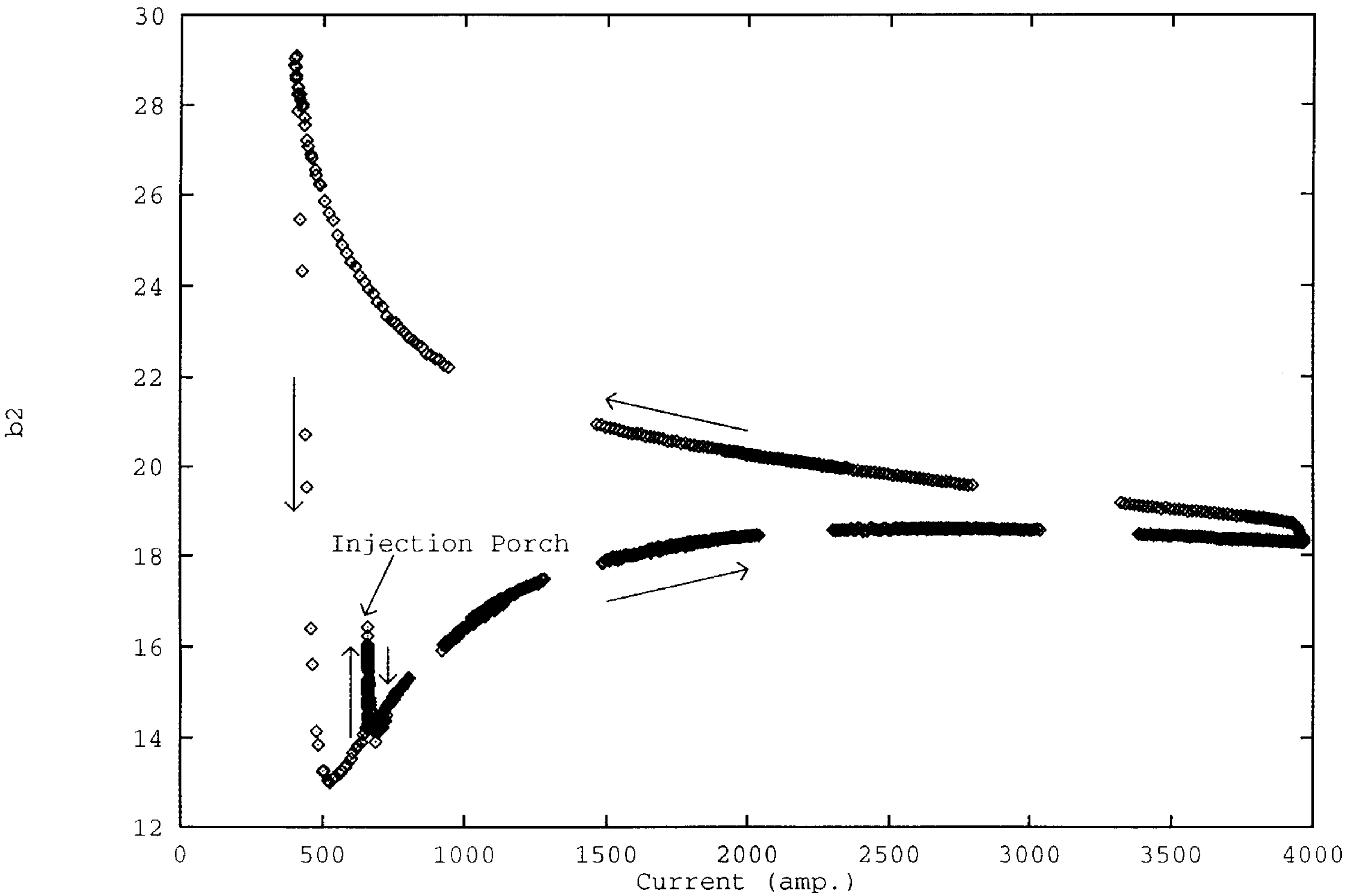

Figure 4. Sextupole hysteresis for a TEVATRON dipole. The arrows indicate the direction of the ramp.

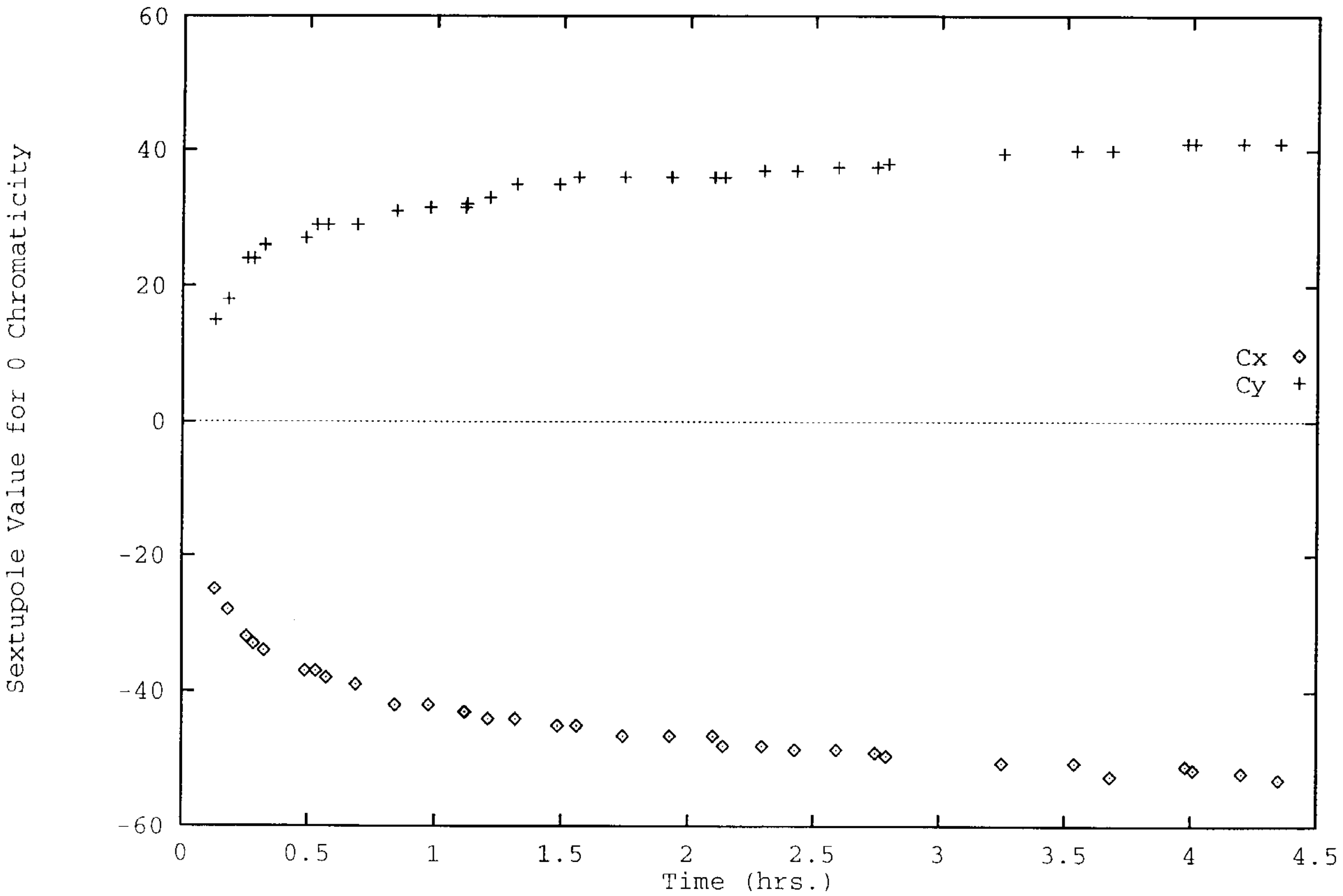

Figure 5. Chromaticities on the injection front porch measured during the 1987 Collider run.

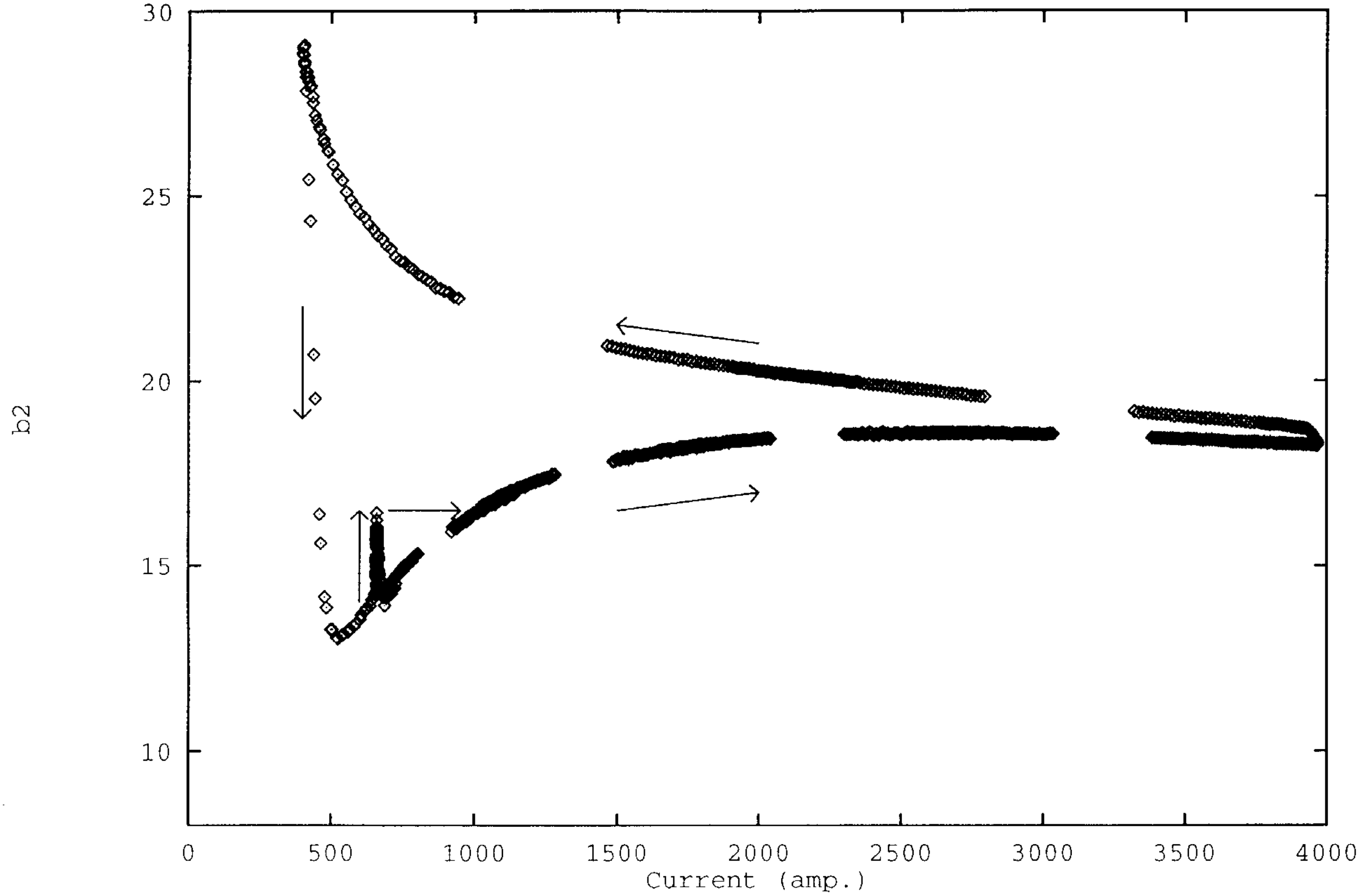

Figure 6. b_2 waveform used to calculate the sextupole corrections during the 1987 Collider run. The arrows indicate the actual ramp used.

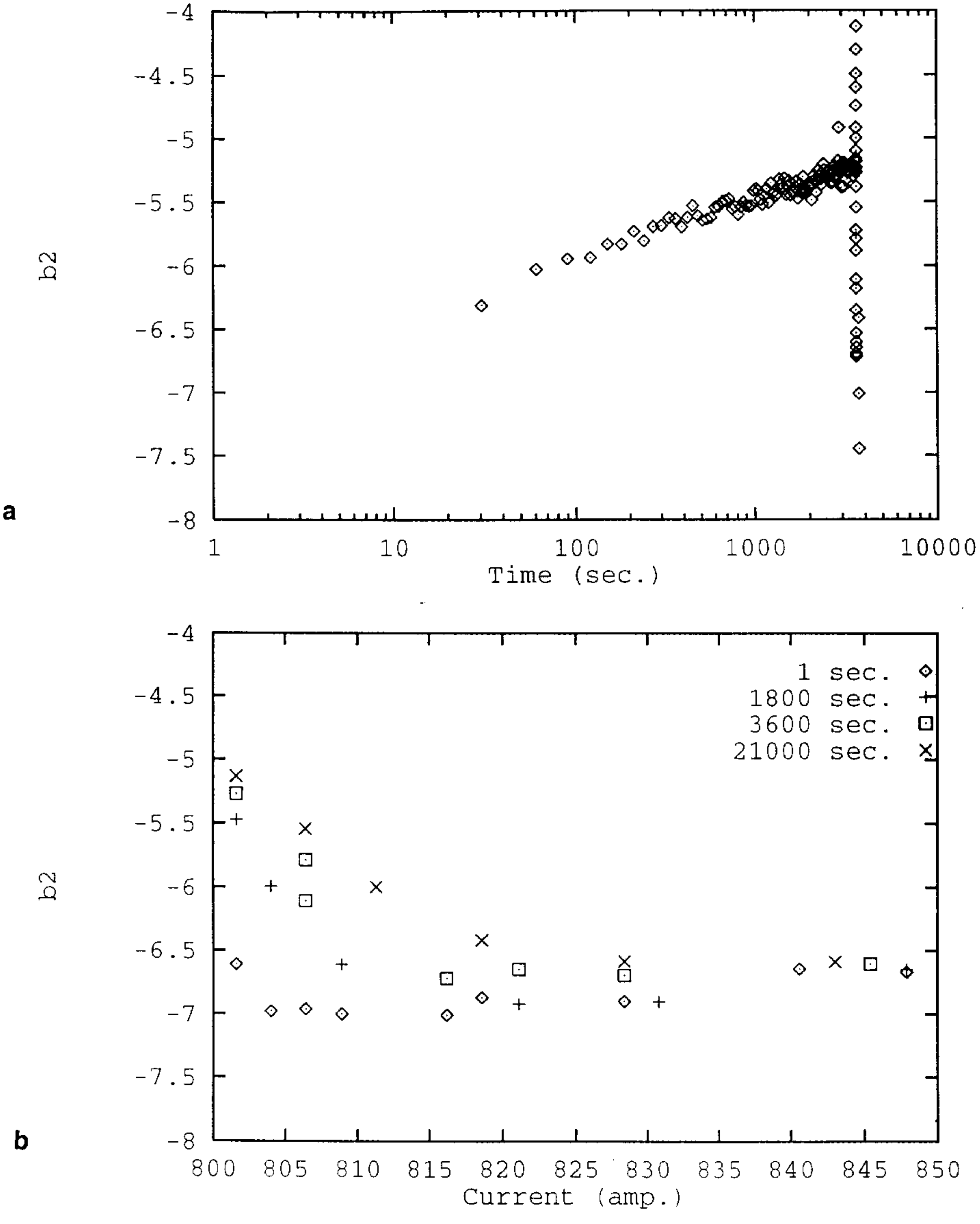

Figure 7. Data taken with the 1-meter long prototype dipole showing **a** the drift in b_2 on the injection front porch and **b** the behavior at the start of acceleratio

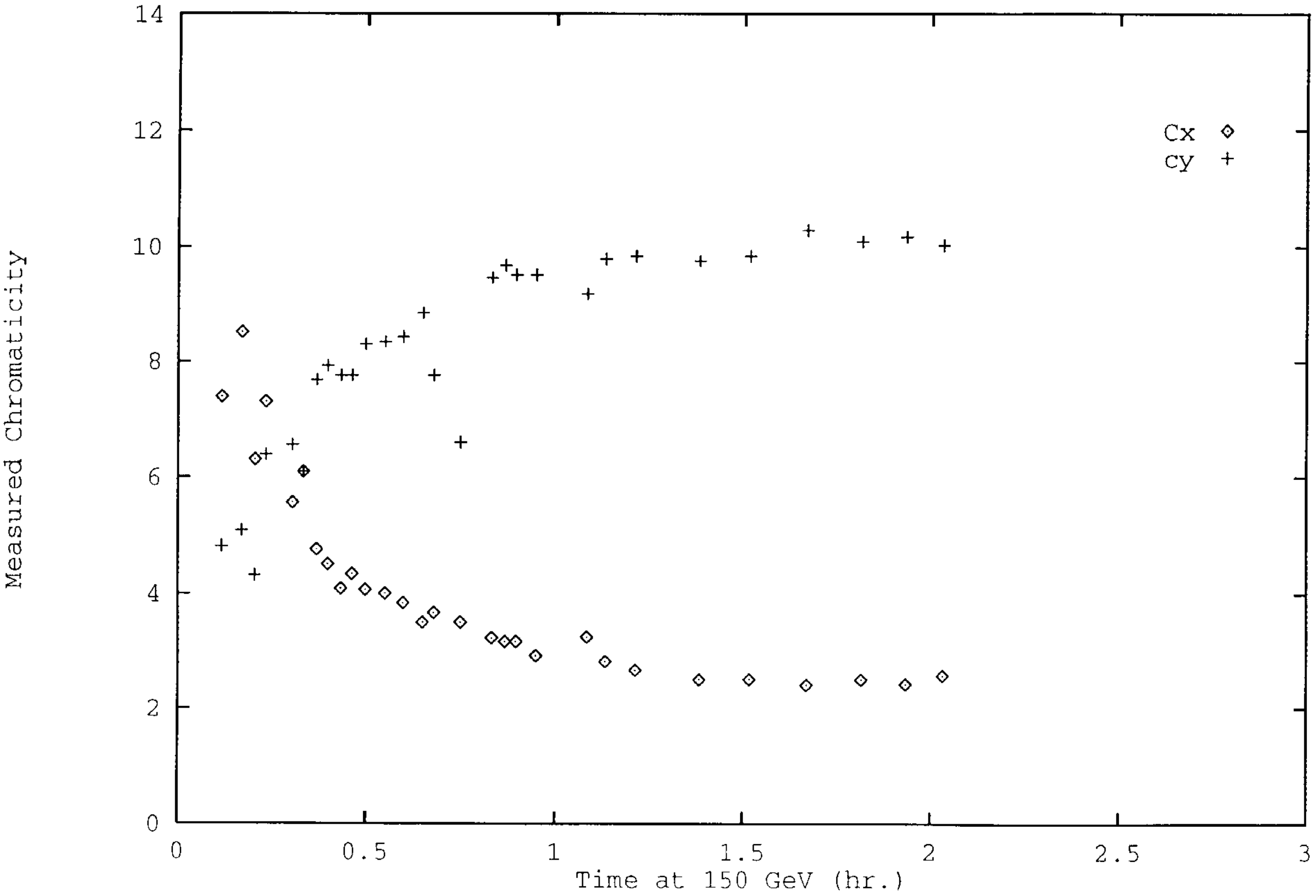

Figure 8. Measured chromaticities on the injection front porch, 1988-1989 Collider run.

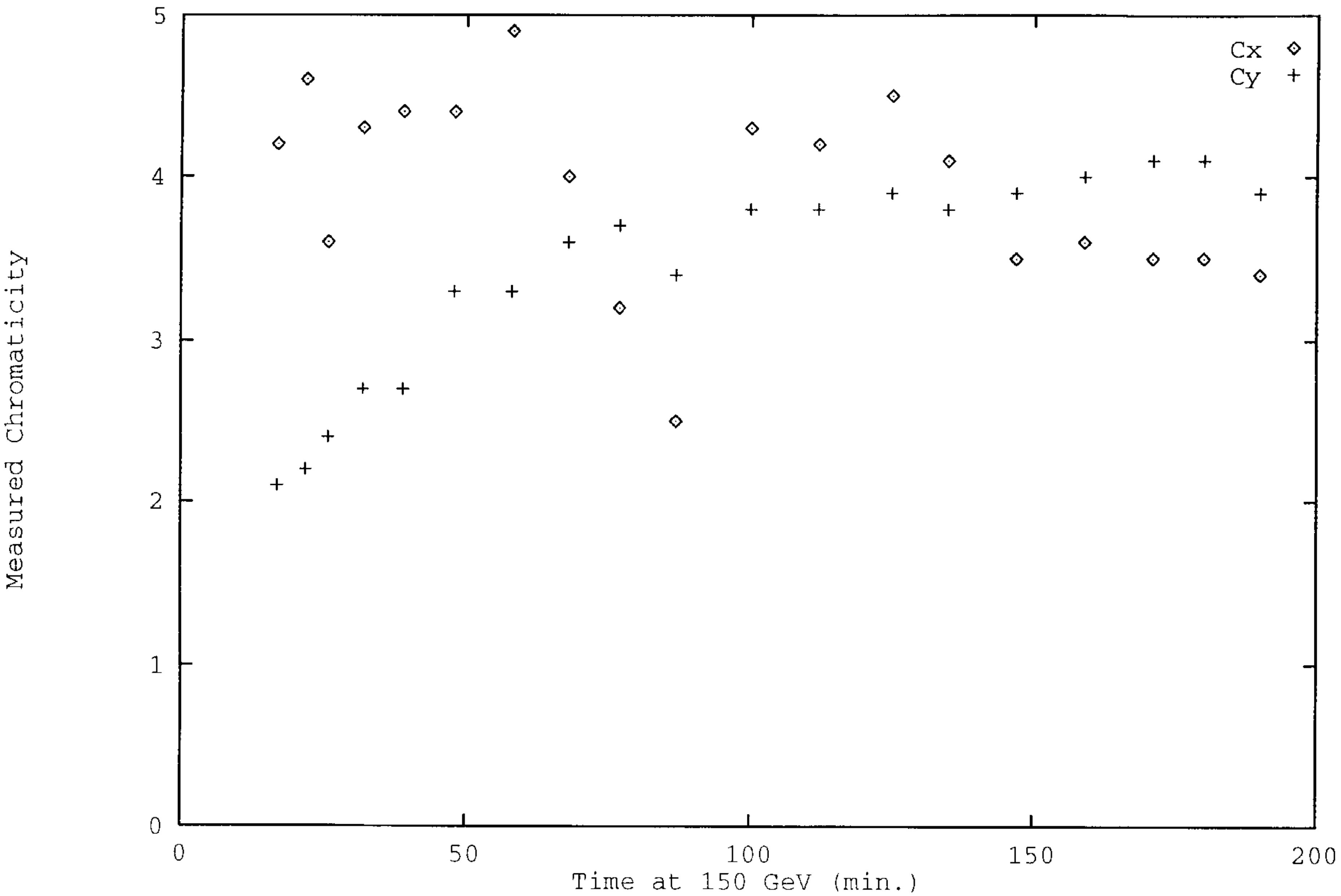

Figure 9. Measured chromaticities on the injection front porch, 1992-1993 Collider run.

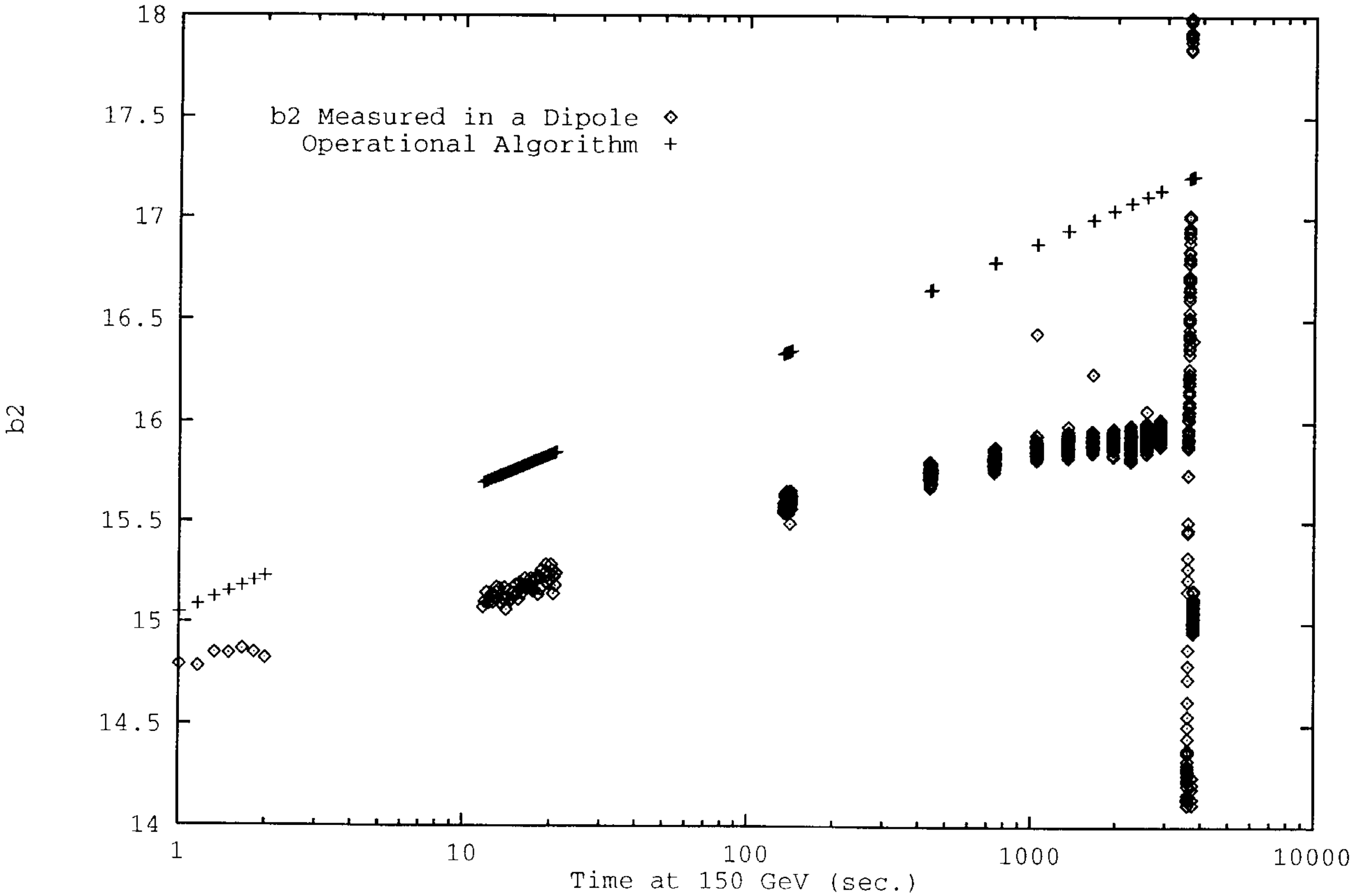

Figure 10. b_2 measured in a TEVATRON dipole and the logarithmic function used to calculate the sextupole currents on the injection front porch.

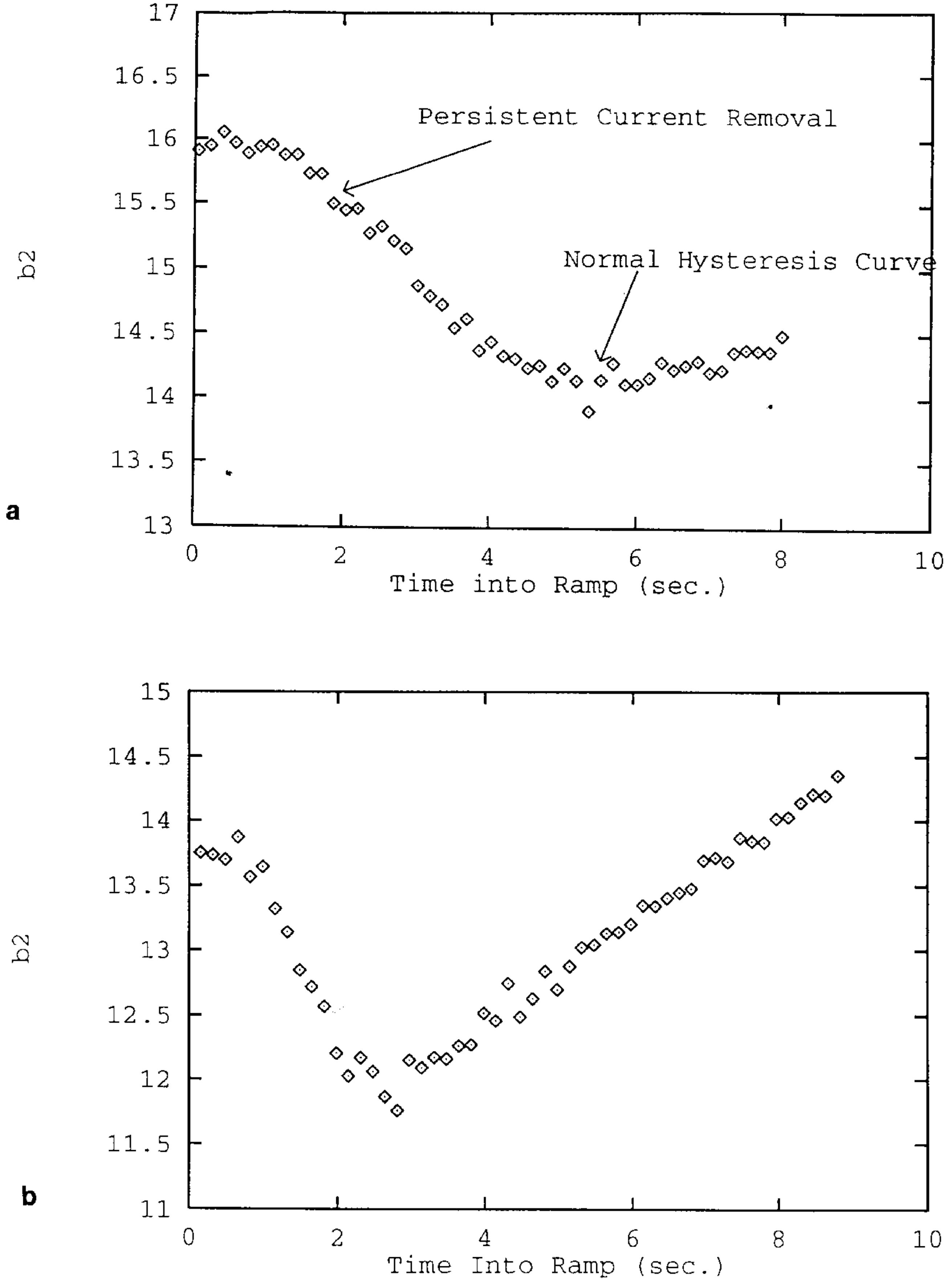

Figure 11. a Behavior of b_2 at the start of the ramp, 1992-1993 waveform. **b** b_2 at the start of ramp, 1988-1989 waveform.

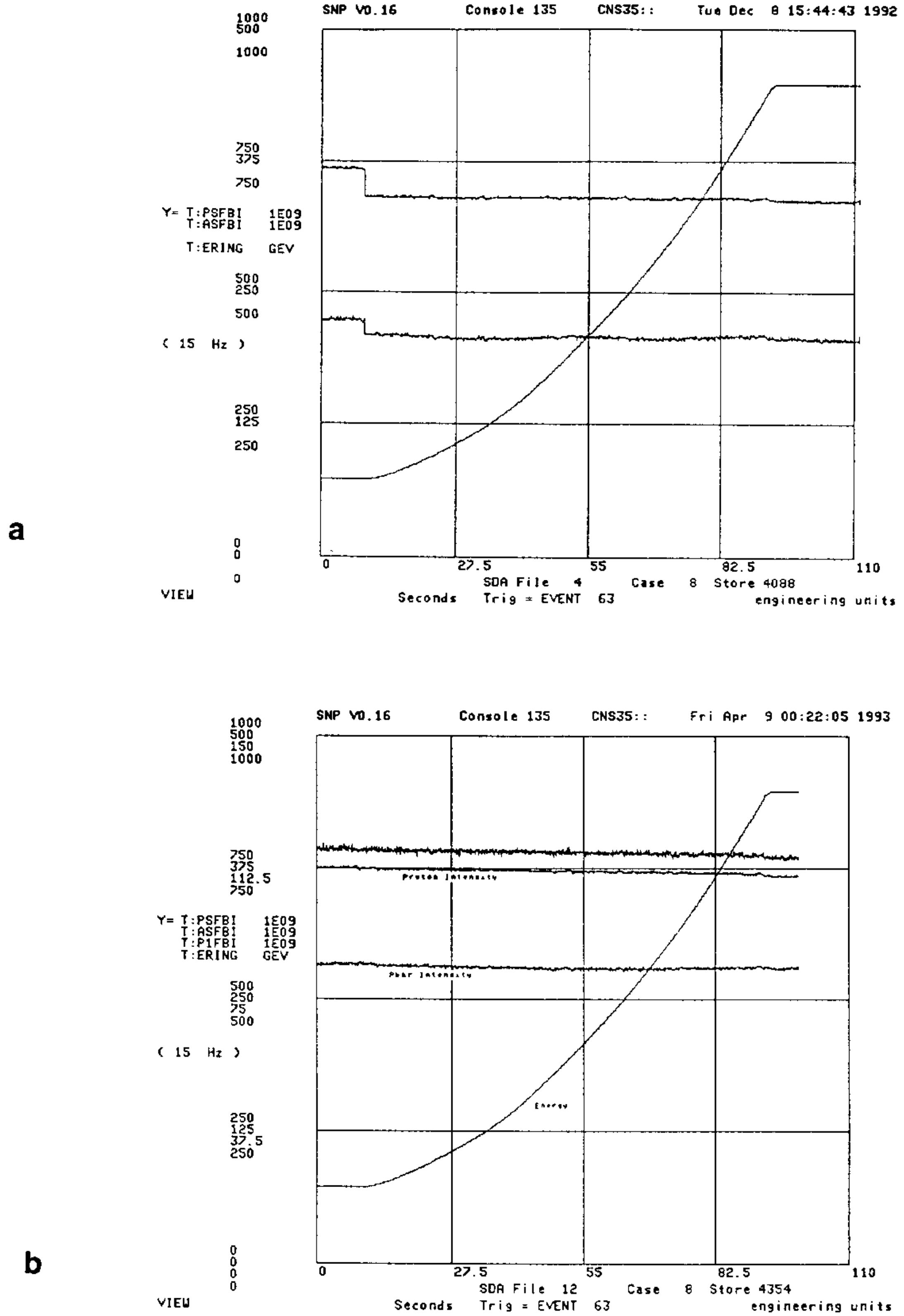

Figure 12. a Intensities during the ramp, original 1992-1993 waveform, showing the loss of proton intensity. **b** The same plot with the corrected waveform based on TEVATRON dipole measurements.