# Time Decay Measurements of the Sextupole Component of the Magnetic Field in a 4-cm Aperture, 17-m-Long SSC Dipole Magnet Prototype

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## ABSTRACT

A systematic series of measurements of the time decay of the sextupole component of the magnetic field in a full-length SSC dipole magnet prototype was carried out in order to characterize the mechanisms involved. At least two mechanisms have been isolated. The first is a slow logarithmic decay which is independent of the excitation history of the magnet. This component is stopped by a decrease of the magnet temperature and is identified with flux creep. The second component, which is not yet fully understood, only appears when the magnet is pre-cycled to a high level of current, and cannot be stopped by decreasing the magnet temperature.

## INTRODUCTION

A major problem in the operation of superconducting particle accelerators is the time decay of the superconducting filament magnetization, which, at low currents, results in a drift of some of the allowed multipole components of the magnetic field. This effect is particularly disturbing at injection, during which, although the current is maintained at a constant level, the sextupole component of the dipole magnets, $b_2$, can decay by as much as 20% per hour, causing chromaticity changes which must be compensated. It also complicates the early stages of acceleration, for, as the current is increased at the end of injection, $b_2$ *snaps back* rapidly to values along the hysteresis curves. Understanding the decay is thus crucial to the reliability of a machine like the SSC.

The time decay of the multipole components was discovered during the first collider run of the Tevatron, and was characterized as being logarithmic.[1] Extensive studies were then carried out on a few Tevatron dipole magnets to determine the parameters influencing it. It was found that the decay rate strongly depended on the excitation history of the magnet, including the number of current pre-cycles, the pre-cycle maximum current, and the duration of the maximum current flattop.[2] Similar observations were made on the HERA dipole magnets, which were all measured prior to installation, and which exhibited large magnet-to-magnet variations.[3] Large variations were also observed on a sample of four early 1-m-long SSC dipole prototypes.[4]

The origin of the decay was first thought to be flux creep in the superconductor,[5] as suggested by the logarithmic time dependence. However, the decay rates measured in magnets after a pre-cycle to a high current are much higher than the flux creep rates measured on conductor short samples. Also, the flux creep theory cannot explain why magnets wound of the same cable can exhibit different time decays, as observed for the HERA dipole magnets. This suggests that, although the flux creep may always be present, another mechanism may take place when the magnet is pre-cycled to high current which boosts the decay rate. The present paper presents the results of a series of experiments that were carried out on a 4-cm aperture, 17-m-long SSC dipole magnet prototype that clearly demonstrates the existence of this second mechanism.

## MEASUREMENTS

### *Measuring Device and Procedure*

The measurements were performed on SSC dipole magnet prototype DD0028, which was built at BNL and cold-tested at Fermilab. The measurements were made using a BNL mole system,[6] which relies on a 0.6-m-long rotating coil, with a rotation period of 3.2 s. They were all taken at the same axial location, about 7 m from the magnet center, toward the lead end. The data are corrected for errors in the centering using the feedown from the 22-pole. The maximum data rate is one measurement per 20 s.

Since the decay rate strongly depends on the magnet excitation history, the measurements were made following a generic test sequence, representative of a SSC operating cycle. The sequence starts with a *cleansing quench* to erase all previous magnetizations. The magnet is then *pre-cycled* to a current $I_f$ for a duration $t_f$, simulating a colliding beam cycle. It is then ramped down to 120 A for 2 min, and ramped up again to the injection current of the SSC, 635 A. The excursion to 120 A is done to allow reaching the injection current on the up-ramp of the $b_2$ versus current curve, as is desirable for the operation of the machine. The measurements are then taken for several hours while sitting at 635 A, on what we shall refer to in the following as the *injection porch.* The generic current ramp rate is 6 A/s.

### *Influence of the Pre-Cycle Flattop Current*

Figure 1 presents a series of time decay measurements of the sextupole component after pre-cycles of constant flattop duration ($t_f$ = 1 hour), and increasing flattop currents. The main feature of figure 1 is that the time decay exhibits two phases: 1) a transitory phase, lasting about 300 s, characterized by a logarithmic decay, with a rate independent of the pre-cycle flattop current, and 2) a long lasting phase, also characterized by a logarithmic decay, but with a rate depending on the pre-cycle flattop current.

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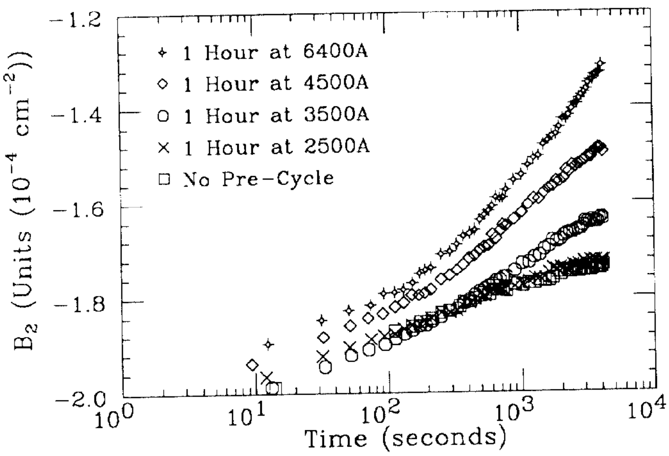


Fig. 1. Influence of the Flattop Current on the Time Decay of the Sextupole Component in Dipole Magnet DD0028.

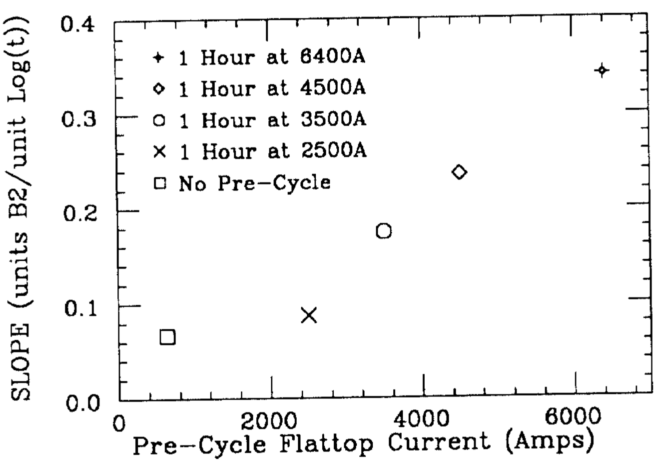


Fig. 2. Decay Rate as a Function of Flattop Current for Dipole Magnet DD0028.

The transitory phase is not of great concern, because soon after these measurements were taken, we found a way to eliminate it: namely, stopping at an intermediate current 10 or 20 A below the injection current for 5 to 10 min. This *pre-injection porch*, along with the snap back that is caused by the ensuing ramp to the injection porch, appears sufficient to kill the transitory. A trick of this nature can easily be introduced in the normal operation of the machine.

The second phase of the decay cannot be as easily eliminated, and is the one with which this paper is concerned. Figure 2 presents a plot of the decay rate of the second phase as a function of the pre-cycle flattop current. The main feature of figure 2 is that two domains can be delimited: 1) for pre-cycle flattop currents less than about 2000 A, the decay rate is constant, independent of $I_f$, while 2) for pre-cycle flattop currents larger than 2000 A, the decay rate increases linearly with $I_f$. The existence of a threshold above which the decay rate becomes dependent on the pre-cycle flattop current is consistent with what was observed on the Tevatron dipole magnets.[2] It also hints that two mechanisms may be involved here.

Having delimited these two domains, we now need to improve their characterization. This can be done by studying the influence of the temperature, which is an important parameter in both the magnetization and the flux creep theories.

*Influence of the Temperature after a Single Ramp to Injection (no Pre-Cycle)*

Figure 3 presents a series of time decay measurements that were done after the sequence: cleansing quench and single ramp to injection (no pre-cycle). The top data (squares) correspond to a run at a constant, nominal temperature of 4.35 K. The bottom data (diamonds) correspond to a run at a constant, nominal temperature of 3.8 K. For the intermediate data (crosses), the ramp to injection and the early measurements were made at a nominal temperature of 4.35 K, but after about 600 s on the injection porch, the temperature was dropped by about 0.5 K. The main features of figure 3 are: 1) the data from the runs at 4.35 K and 3.8 K lie on parallel lines, 2) the 3.8 K line lies below the 4.35 K line (more negative $b_2$), and 3) lowering the temperature by 0.5 K while sitting on the injection porch effectively stops the decay.

The respective positions of the 3.8 K and 4.35 K lines simply result from the fact that, for a given current sweep (like that from zero to injection), the induced magnetization of the superconducting filaments is larger at the lower temperature, due to the higher critical current density. As we shall now discuss, the two other observations are consistent with what can be expected from the flux creep theory.

The starting point of the flux creep theory is that, in the mixed state of the type II superconductors, the effective depth of the pinning wells, $\Delta U_e$, is reduced by the presence of the electromagnetic potential, enabling thermally activated flux bundles to *creep* from one pinning site to the other. This flux creep results in a demagnetization of the superconductor, which can be shown to be logarithmic in time, with a rate proportional to $\exp(-\Delta U_e/kT)$. The parameters influencing $\Delta U_e$ are: 1) the slope of the electromagnetic potential, which is determined by the critical current density at the time of the critical state formation, and 2) the actual temperature of the superconductor.

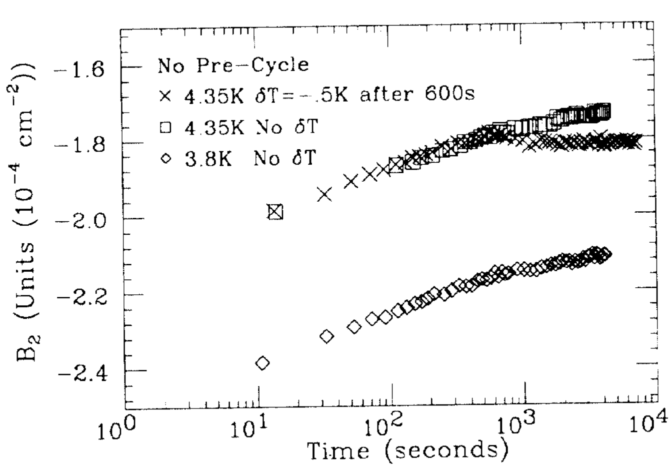


Fig. 3. Influence of the Temperature on the Time Decay of the Sextupole Component after a Single Ramp to Injection.

For the run at 3.8 K, the pinning wells are deeper than at 4.35 K, but the electromagnetic potential slope, at the time of the critical state formation, is also larger. These two effects are known to compensate each other, resulting in an unchanged $\Delta U_e$, and, thus, similar creep rates. On the other hand, when the temperature is lowered while sitting on the injection porch, the slope of the electromagnetic potential does not change, but the pinning wells deepen, resulting in a larger $\Delta U_e$. Due to the presence of the exponential, this increase of $\Delta U_e$ can strongly decrease the creep rate, eventually stopping it.

Both the parallelism of the 4.35 K and 3.8 K lines, and the turning off of the decay while sitting on the injection porch can therefore be interpreted as signs that, in the present case, the mechanism driving the decay of the sextupole component is flux creep. Another fact pointing towards the same direction is that the amplitude of these decays is of the same order of magnitude as the creep rates measured on short samples of SSC cables, similar to the cables wound in magnet DD0028.[7]

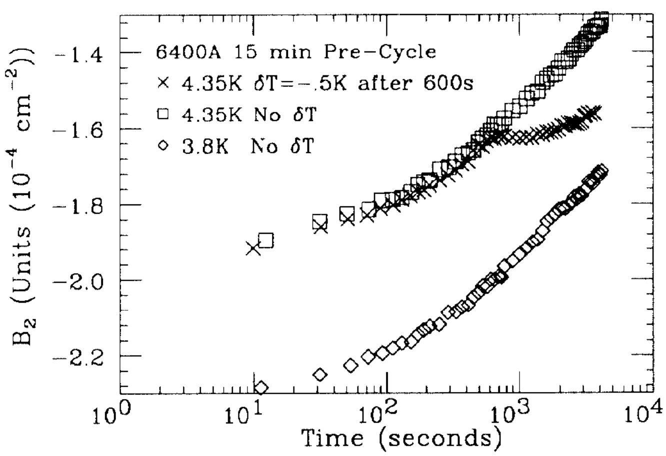


Fig. 4. Influence of the Temperature on the Time Decay of the Sextupole Component after a Pre-Cycle to 6400.

*Influence of the Temperature after a Pre-Cycle to 6400 A*

Figure 4 presents a series of time decay measurements, similar to the one described above, but performed after the sequence: quench, pre-cycle to 6400 A for 15 min, ramp down to 120 A, and ramp up to injection. Once again, the top data (squares) correspond to a run at a constant nominal temperature of 4.35 K. The bottom data (diamonds) correspond to a run at a constant nominal temperature of 3.8 K. The intermediate data (crosses) correspond to a run where the temperature, which initially was 4.35 K nominal, is lowered to 3.8 K nominal after about 600 s on the injection porch. In comparison to figure 3, the main features of figure 4 are: 1) the data from the runs at 4.35 K and 3.8 K still lie on parallel lines, but their slopes are much larger than for the runs with no pre-cycle, and 2) lowering the temperature by 0.5 K while sitting on the injection porch reduces the decay but *does not* stop it.

In the run with no-pre-cycle, the fact that lowering the temperature while sitting on the injection porch turned off the decay was interpreted as a sign that the decay was driven by flux creep in the superconductor. In this run, the fact that the decay is initially larger, and is only reduced, and not stopped, by lowering the temperature can be interpreted as a sign that the decay has now two components: a flux creep component, which is still turned off by the deepening of the pinning wells when the temperature is lowered, and a second component, which initially boosts the decay, and which is not affected by the temperature change.

Other evidence that the second mechanism is not affected by the temperature can also be found in the fact that the 4.35 K and 3.8 K lines are parallel. As we saw in the previous paragraph, the creep rates for the 4.35 K and 3.8 K runs are similar. Subtracting the data of figure 3 from that of figure 4 therefore lead to two curves which are still parallel. The decay rate associated with the second mechanism is therefore the same at the two temperatures.

## CONCLUSION

The experimental facts gathered in this paper are: 1) there is a pre-cycle current threshold above which the decay rate of the sextupole component becomes dependent on the magnet excitation history, 2) if the magnet was not previously excited above this threshold, the time decay can be turned off by lowering the magnet temperature, and 3) if the magnet was previously excited above this threshold, the time decay is only reduced, but not stopped by lowering the temperature. This leads us to the conclusion that the time decay has two components: 1) a component that does not depend on the excitation history, and that can be stopped by a decrease of the temperature, and 2) a component that only appears when the magnet is pre-cycled to a high level of current, and that cannot be stopped by decreasing the temperature. The first component is attributed to flux creep in the superconductor. We are currently developing a model of demagnetization caused by shifting transport currents in the superconducting cables that could account for the second component.


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[2] R. W. Hanft, B. C. Brown, *et al.*, "Studies of Time Dependent fields in Tevatron Superconducting Dipole Magnets," *IEEE Trans. Magn.*, **25, No. 2**, 1989, pp. 1647-51

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[7] A. Ghosh, private communication.