ANALYSIS OF THE B2 CORRECTION IN THE TEVATRON

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Abstract

Beam loss and emittance dilution during ramping from injection to collision energy is observed in the Tevatron, now in its collider run-II stage. It is well known that the sextupole (*b2*) components in the superconducting dipole magnets decay during the injection plateau and snap back rapidly at the start of the ramp. These so called dynamic effects, which were originally discovered in the Tevatron, are compensated with the chromaticity correctors, distributed around the ring. Imperfect control of the chromaticity during injection and snapback can contribute to the beam loss. Therefore a thorough investigation of the *b2* compensation in the Tevatron was launched, including beam chromaticity measurements and offline magnetic measurements on Tevatron dipoles. This paper reports the status of this investigation. A companion paper describes in detail the results of the magnet measurements [1]. This work was partly conducted as a collaboration between FNAL and CERN.

1 TEVATRON B2 COMPENSATION

Sextupole, *b2*, (and other) magnetic components are present in the 774 Tevatron dipole magnets at a level of several units of 10^{-4} of the main field. This is a well known feature of accelerator magnets. In fact, one differentiates between geometric, hysteretic and dynamic *b2* contributions. The simple, compact ends of the Tevatron dipoles have a strong negative *b2*, which is compensated by a built-in, positive *b2* of ~14 units in the body section, such as to give zero average geometric *b2* [2]. The hysteretic *b2* loop evolves around the geometric *b2*. The loop shape is more or less invariant (depending only weakly on magnet temperature and ramp-rate). During constant excitation such as at injection the *b2* drifts and snaps back rapidly whenever the ramp starts. These dynamic effects in superconducting magnets are the result of (slowly) changing current distributions among the superconducting strands forming the Rutherford cable from which the coils are wound. These changing current distributions cause local magnetic field changes that in turn cause changes in the magnetization response of the superconductor. The current imbalances within the cable also affect the bore field directly, producing a sinusoidal field pattern along the magnet, with the cable twist pitch as period. This, however, is believed to be irrelevant to the beam, because the cable pitch is short (~6.4cm).

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The chromaticity (ξ) correctors in the Tevatron compensate for all of the above effects as well as the natural chromaticity of the ring and provide a chosen ξ set-point (~8-20 units). They are placed next to the arc quadrupoles, therefore referred to as defocusing (SD) or focusing (SF). According to recent measurements 1 unit of *b2*, left uncompensated, produces 26.22/-23.92 units of horiz./vert. chromaticity, ξ_x/ξ_y [3]. The dynamic *b2* compensation has been fine-tuned over many years. It retained, however, the characteristic logarithmic time dependence of the drift amplitude during the injection porch, (1), where the offset and slope depend on the pre-cycle parameters (the time on the back-porch, t_{BP}, and the flat-top, t_{FT}). The beam-less pre-cycle is necessary to homogenize the ramping history of all magnets and hence bring the machine into a reproducible state that allows to use (1). A schematic of the pre-cycle is shown in Fig. 1.

$$b_2^{drift}(t, t_{FT}, t_{BP}) = b_{2,ini}(t_{FT}, t_{BP}) + m(t_{FT}, t_{BP})\ln(t) \quad (1)$$

The *b2* drift amplitude increases with shorter pre-cycle back-porch and longer pre-cycle flat-top. Further details regarding the trends of the *b2* drift parameters with the pre-cycle conditions can be found in [1]. During the first seconds of the ramp, the snapback occurs, which, on the basis of magnetic measurements performed in 1996, [4], is calculated for the Tevatron *b2* algorithm with (2),

$$b_2^{SB}(t) = b_2^{drift}(t_{IP}, t_{FT}, t_{BP})\left(1-\left(\frac{t}{t_0}\right)^2\right)^2 \quad (2)$$

where b_2^{drift} is computed with (1) for $t=t_{IP}$, the injection porch duration and t_0, the snapback duration (now 6 sec). Note that the dynamic *b2* correction in the Tevatron plays out on top of that for the geometric and hysteretic *b2* components. It is therefore customary to present the *b2* drift and snapback without the other contributions. This implies the removal of the small (~0.1 unit) change of hysteretic *b2* during the snapback phase (150-156 GeV).

2 MEASUREMENTS ON MAGNETS

Fig. 1 shows recent rotating coil measurements at Fermilab's Magnet Test Facility of the *b2* in the body of several Tevatron dipoles as a function of beam energy (transfer function: 980 GeV = 4332.57 A = 4.306 T). The measurements were taken after the same pre-cycle as for a usual Tevatron shot setup (t_{FT}=*20 min* "dry-squeeze" ,

t_{BP}=*1 min*, see insert in Fig. 1). The dynamic effects during the injection and back-porch plateaus are clearly visible (and they are shown more explicitly in Fig. 2). To be representative of the Tevatron the geometric *b2* for each magnet shown in Fig. 1 was removed and replaced by the average geometric *b2* of all Tevatron dipoles, as derived from the archived measurements performed during magnet production [5]. The average *b2* of all Tevatron dipoles installed, according to the archive data was calculated to be 1.47 units. Fig. 1 also shows the average hysteretic *b2* for all magnets installed as derived from the magnetic measurement archive. Note, however, that the measurements at production were performed only at 0.66/150, 2/452 and 4/905 kA/GeV, after stopping of the ramp. This resulted in an unknown amount of *b2* drift such that the archive data are expected to underestimate the width of the *b2* loop, especially at injection (150 GeV). The *b2* data in Fig. 1,2 were corrected, where needed, for temperature such as to be representative of the 4 K average Tevatron magnet temperature. The temperature correction consisted in removing the geometric and scaling the entire loop with an experimentally derived scaling factor (~-15%/°K, [1]).

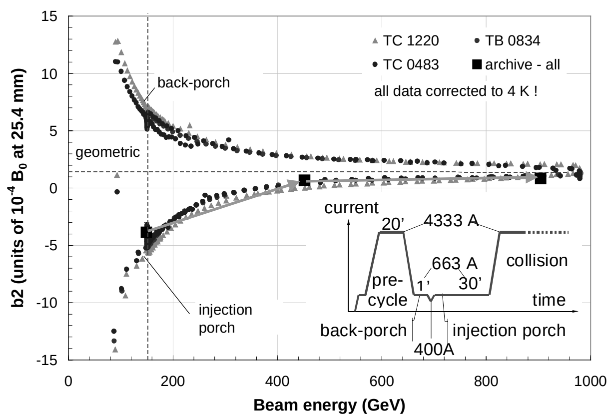

Figure 1: b2 loops measured in Tevatron dipoles and average b2 loop as expected from archive data.

Fig. 2 contains the same data as Fig. 1, except that it shows the *b2* drift during a 30 min injection porch, followed by the snapback together with the Tevatron *b2* fit (equations 1,2). In one case the measurement was obtained with Hall-probes, which were introduced through the other end of the magnet. The Hall-probe array, which reads data at 10 Hz, was supplied by CERN. All snapback data were baseline corrected, i.e. the geometric and hysteretic *b2* were removed from the data such as to show the pure snapback.

It is important to note that both Fig. 1 and Fig. 2 show a significant magnet-to-magnet spread in the *b2* characteristics. Magnetic measurement data from a small number of magnets are therefore not representative of the accelerator. A separate study of the *b2* using beam based methods is required to obtain the average *b2* characteristics of the machine. Such measurements will be discussed next. Fig. 2 indicates, however, that the snapback fit used in the Tevatron appears to underestimate the duration of the snapback. As discussed in [1] a Gaussian would fit better. The discrepancy of magnet data and the logarithmic fit at the start of the drift, however, is irrelevant for accelerator operation (and can easily be adjusted by shifting the time scale in the ln-function).

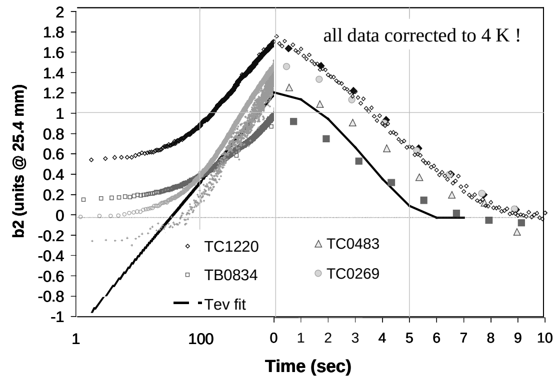

Figure 2: b2 drift and snapback measured in Tevatron dipoles after a standard pre-cycle. Note that the time for the drift data is on a log scale. For TC1220 both rotating coil and Hall probe snapback data are shown.

3 BEAM BASED MEASUREMENTS

The following describes beam based chromaticity measurements performed recently, not only during the injection porch, but also during the ramp [3]. The derivation of the average magnet *b2* from the beam chromaticity assumes that the measured chromaticity (ξ_{meas}) is given as the sum of the natural chromaticity (ξ_{nat}), the *b2* in the dipole magnets (ξ_{b2mag}) and the (compensating) *b2* supplied by the sextupole correctors (ξ_{b2corr}) as in (3).

$$\xi_{tot,i} = \xi_{meas,i} = \xi_{nat,i} + \xi_{b2mag,i} + \xi_{b2corr,i} \quad i = x, y \tag{3}$$

The natural chromaticity was calculated with a MAD Tevatron lattice model (-29 units). The *b2* corrector currents were converted to *b2* with: 1 unit of *b2* = ~-0.496 / -0.765 A in the SF / SD correctors [3]. The chromaticity measurements were performed with an un-coalesced proton beam on the center orbit. The Tevatron was prepared with a standard pre-cycle (20 min flat-top, 1 min back-porch). After injecting the beam, tunes were measured as a function of time during the injection porch as well as up the ramp with the Schottky pick-up. A sec-time resolution was obtained using a fast buffer digital oscilloscope in the time capture mode. This measurement (including the beam-less pre-cycle) was performed for different RF frequency settings (Δf=-20, 0, +20 Hz from nominal). The derivative of the tunes as a function of RF frequency gives the instantaneous chromaticity. Therefore each measurement required three Tevatron cycles (including the pre-ramp).

Fig. 3 shows the results of different chromaticity measurements performed during the ramp to collision. Note that the first part of the beam derived *b2*-curve is the snapback, which is shown again in Fig. 4 in the case of the Dec 4th data. The drift amplitude in the Sept 18th case is larger, presumably due to a longer dwell at injection (this parameter was not recorded in this measurement). The average hysteretic up-branch as derived from the Tevatron magnetic measurement archive (such as in Fig 1) is shown also. The brackets ascribed to each point represent the σ of the width-distribution of the *b2* loops of all dipoles installed. One can see that the average magnet *b2* predicted on the basis of the ξ measurement is close to the expected. Also note that the measurement performed on Sept 18th did not use the oscilloscope time capture mode to record the tune data, but the tunes were read from the oscilloscope display, therefore introducing a larger error (estimated at ± 0.5 *b2* units).

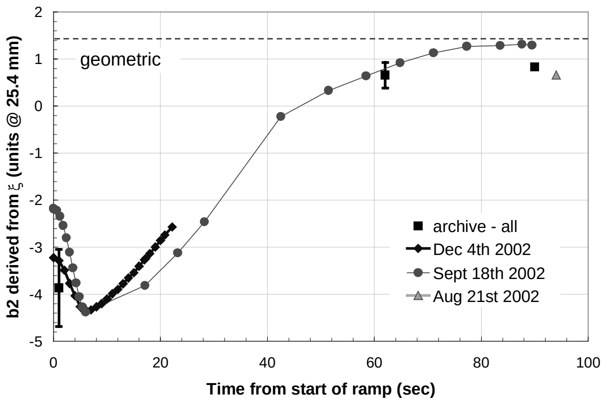

Figure 3: *b2* up the ramp as derived from beam chromaticity measurements and expected average of all magnets installed derived from magnetic measurement archive (brackets represent σ of loop width distribution).

Fig. 4 shows the *b2* snapback measured during one of the beam studies presented in Fig. 3, for 2 different injection porch (IP) durations (20, 120 min). As with the magnet data the hysteretic and geometric *b2* were removed from the data by extrapolation of the 160 and 200 GeV data to the lower energy snapback phase. These tests were performed to see the effect of different drift amplitudes on the Tevatron *b2* compensation (in the 120 min IP case the *b2* drifts 25% more than in the 20 min case). A correlation between drift amplitude and the field (current, beam energy) at which the snapback is complete is expected on the basis of the existing dynamic effect models and was observed in the LHC dipoles. In fact this correlation allows for a novel approach in b2 compensation, which consists of predicting the snapback on the basis of *b2* measurements just before ramping. Fig. 4 indeed shows that the snapback takes slightly longer in the 120 min IP case. The difference is not as distinct as the difference in drift amplitude because the parabolic current ramp time-compresses the end of the snapback. A plot of the snapback in terms of magnet current reveals that the 120 min IP case takes 25% more current to snap back [5]. The two curves in Fig. 4 also show a difference between the fit and the data for the drift amplitude.

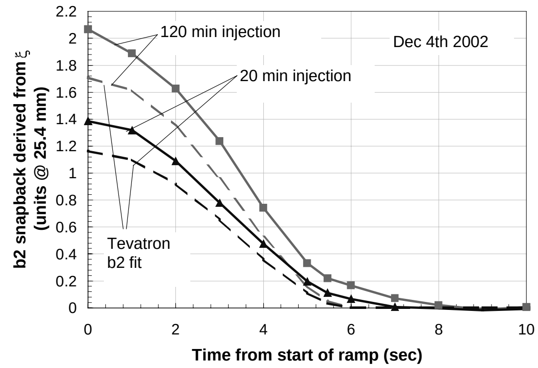

Figure 4: b2 snapback derived from chromaticity measurements after a 20 min and a 120 min IP. Dashed lines: Tevatron b2 compensation algorithm (equation 1,2).

4 SUMMARY AND OUTLOOK

The comparison of magnetic measurements on some Tevatron dipoles, the expected average Tevatron magnet characteristics derived from the magnetic measurement archive and beam based *b2* measurements have so far shown that the current Tevatron *b2* compensation works reasonably well in what refers to the geometric and hysteretic *b2* components. There is, however, experimental evidence suggesting that the dynamic *b2* compensation can be improved. In particular magnet measurements indicate that the *b2* snapback is better described by a Gaussian function than the polynomial that is currently in use and that today's fit under-estimates the snapback duration. It is hoped that the implementation of an improved functional form of the *b2* compensation will reduce emittance growth and beam loss. The measurements also confirmed that the *b2* drift amplitude and the snapback time are correlated as observed in LHC dipoles. This allows for a novel *b2* compensation scheme, which was actually proposed for the LHC, and which uses on-line chromaticity measurements during injection to predict the snapback. Such an approach could also be of interest for the Tevatron, making use of the recently developed head-tail chromaticity monitors, [6].

5 ACKNOWLEDGMENTS

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6 REFERENCES

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