

## Chromaticity decay due to superconducting dipoles on the injection plateau of the Large Hadron Collider

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It is well known that in a superconducting accelerator a significant chromaticity drift can be induced by the decay of the sextupolar component of the main dipoles. In this paper we give a brief overview of what was expected for the Large Hadron Collider (LHC) on the grounds of magnetic measurements of individual dipoles carried out during the production. According to this analysis, the decay time constants were of the order of 200 s: since the injection in the LHC starts at least 30 minutes after the magnets are at constant current, the dynamic correction of this effect was not considered to be necessary. The first beam measurements of chromaticity showed significant decay even after a few hours. For this reason, a dynamic correction of decay on the injection plateau was implemented based on beam measurements. This means that during the injection plateau the sextupole correctors are powered with a varying current to cancel out the decay of the dipoles. This strategy has been implemented successfully. A similar phenomenon has been observed for the dependence of the decay amplitude on the powering history of the dipoles: according to magnetic measurements, also in this case time constants are of the order of 200 s and therefore no difference is expected between a one hour or a ten hours flattop. On the other hand, the beam measurements show a significant change of decay for these two conditions. For the moment there is no clue of the origin of these discrepancies. We give a complete overview of the two effects, and the modifications that have been done to the field model parameters to be able to obtain a final chromaticity correction within a few units.

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### I. INTRODUCTION

In a particle accelerator, chromaticity is the variation of the betatron tune with respect to (w.r.t.) the energy change: it is a crucial parameter since it can drive particles on betatron resonances, inducing beam losses [1]. The main sources of chromaticity in an accelerator are the quadrupoles, which give rise to the so-called *natural chromaticity*. When superconducting dipoles are used in the lattice, a sextupole component is generated at injection by (i) the geometric contribution of the coil and (ii) by the magnetization inside the filaments of the superconductive strands. The first component is constant, but the second one depends on the current, and has a non-negligible decay on the injection plateau.

In the Large Hadron Collider (LHC), as in many colliders, chromaticity has to be set to a few units above

zero, but not more. To achieve this, two corrector magnets are used: the lattice sextupoles to cancel the natural chromaticity and the so-called spool pieces to compensate for the sextupole component in the dipoles. The natural chromaticity of an accelerator is time independent, and is given by the lattice layout and by the optics, whereas the chromaticity generated by the magnetization in the dipole cables decays during a constant current plateau, such as at injection.

These *dynamic effects* and their strong influence on the accelerator operation have been discovered in the 1980's at the Tevatron [2]. The chromaticity decay has to be corrected dynamically, i.e., the current in the correctors has to follow and counterbalance the decay of the dipoles during the injection plateau, where all the other magnets are powered with constant currents, so that chromaticity is kept on the target value [3]. It was later observed that the chromaticity decay depends on the powering history of the magnets [4]. This complicates the operation since the chromaticity decay after a physics cycle can be considerably different from the decay after a beam abort during ramp or squeeze.

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In the LHC, natural chromaticity is  $\sim 70$  units, and chromaticity stemming from the dipole magnets is  $\sim 200$  units. The decay of the latter component, if left uncorrected, is expected to be  $\sim 50$  units, for 7 TeV operation, i.e., far beyond the required tight control limits of a few units. A full decay model, including the powering history dependence, was based on the magnetic measurements performed on the LHC dipoles: first on short models [5], then during series production [5–9].

In 2010–2011, the LHC ran at half of the energy, i.e., in different working conditions w.r.t. the design values [10]. Moreover, the precycling strategy has been modified to improve the accelerator availability. Because of this, the chromaticity behavior and the model precision under these new conditions had to be investigated.

The tune and chromaticity has been measured using passive monitoring of residual beam oscillations, i.e., the diode-detection-based base-band-Q detection techniques [11]. Using this technique the chromaticity has been measured in many cases during operation, especially in the early commissioning phases with low-intensity beams. These measurements confirmed the set of relevant physical quantities which determine the decay amplitude, i.e., ramp rate, flattop duration, flattop energy, and preinjection duration. Moreover, the measurements showed an unexpected result: both decay and powering history dependence have longer time constants in the accelerator w.r.t. what is measured on individual magnets.

In this paper we present in Sec. II a review on the chromaticity decay and fit used in the magnetic model based on magnetic measurements. We then discuss in Sec. III the magnetic measurements done with the LHC precycle used during operation in 2010–2011. In Sec. IV we present the beam measurements of chromaticity, and the comparison with the model. Conclusions are given in Sec. V.

## II. RECALL ON CHROMATICITY DECAY

### A. Operational conditions

The LHC main bending dipoles are twin-aperture magnets with separate coils contained in a common mechanical structure [10]. The coil geometry consists of six blocks separated by copper wedges, each block being made up of several turns of Rutherford-type cable. In the coil, three types of induced currents can be distinguished. The most relevant for this work are the persistent currents, i.e., eddy currents induced by an external field change, flowing within the superconducting filaments. Since there is no resistance in the filaments, these eddy currents flow forever in the filament, i.e., they *persist*. They generate a filament magnetization that has a hysteretic behavior as the external magnet field is ramped up and down. Moreover, one also has eddy currents between different strands in the cable and coupling currents between different filaments inside a strand. These currents flow in loops with nonzero

resistance due to the contacts between strands and between filaments, respectively.

There are two sources of decay of the magnetization: the flux creep, which are linear in the logarithm of time [4], and the boundary induced coupling currents (BICC) which give rise to a decay which is a sum of exponential in time, with different time constants [5,6,12]. The first mechanism, which was the first hypothesis considered to explain phenomena in Tevatron, is negligible in the LHC.

The change in magnetization is visible as a decay of the allowed harmonics during a constant current plateau. This effect is strong in the sextupole ( $b_3$ ) component, giving a change in the chromaticity. The series expansion of the 2D magnetic field  $\mathbf{B}$  in the magnet aperture is given by

$$\mathbf{B}(x, y) = \sum_{n=1}^{\infty} (C_n) \left( \frac{z}{R_{\text{ref}}} \right)^{n-1} = \sum_{n=1}^{\infty} (B_n + iA_n) \left( \frac{x + iy}{R_{\text{ref}}} \right)^{n-1}, \quad (1)$$

where  $z = x + iy$  is the complex coordinate in the transverse plane ( $x, y$ ),  $C_n$  are the harmonic coefficients,  $B_n$  the normal harmonics,  $A_n$  the skew harmonics, and  $R_{\text{ref}}$  is the reference radius. The normalized multipoles  $b_n$   $a_n$  are given by

$$b_n + ia_n \equiv 10^4 \frac{C_n}{B_1}. \quad (2)$$

Since the magnetization is proportional to the critical current, the decay is much larger at low field, i.e., at injection. As soon as the current is ramped up, the magnetization reestablishes itself to the value it had at the beginning of the current plateau and thus snapback occurs [2–9]. In most cases in LHC operation, beam injection takes between 1–2 hours during which the current is kept at a constant value of about 757 A. The current in the magnets is then ramped up as the beam is accelerated to collision energy. The decay and snapback as a function of time of the normal sextupole together with the current in the main bending dipoles are shown in Fig. 1.

### B. Fit of the decay

The decay of the magnetization component due to BICC can be modeled by an infinite series of exponentials with time constants

$$\tau_n = \frac{\tau}{(2n - 1)^2}. \quad (3)$$

Keeping the first two terms and neglecting the higher order modes, a model of the decay can be obtained,

$$\Delta = [d(1 - e^{(t_{\text{inj}} - t)/\tau}) + (1 - d)(1 - e^{(t_{\text{inj}} - t)/9\tau})], \quad (4)$$

which gives the normalized decay (i.e.,  $\Delta = 1$  at infinite time) from the beginning of the injection period  $t_{\text{inj}}$ , where  $\tau$  is the time constant, and  $d$  is the weight between the fast and the slow mode.

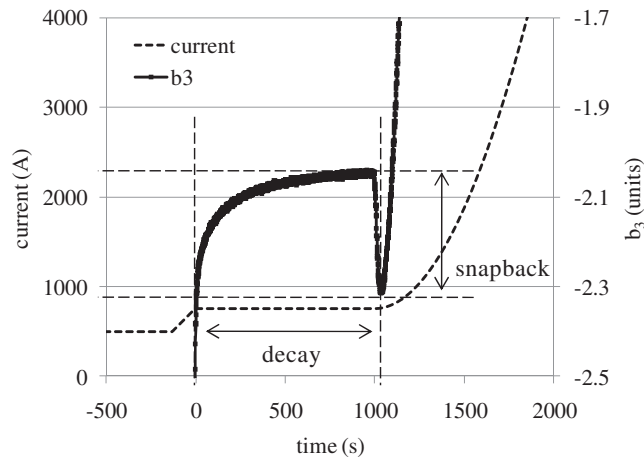


FIG. 1. The dipole current and the normal sextupole  $b_3$  as a function of time. Magnets reach injection current at  $t = 0$ , and energy ramp starts at  $t = 1000$  s.

Based on a series of magnetic measurements during the LHC magnet production, the two fitting parameters of Eq. (4) plus an amplitude  $\delta^{\text{std}}$  were found [8,9]. The values of these parameters are given in Table I: the decay time constant is about 200 s, the ratio between the fast and the slow modes is 2:1 and  $\delta_n^{\text{std}}$ , which is the decay amplitude at a reference time  $t_{\text{inj}}^{\text{std}}$ , is 2 units of  $b_3$ . This amplitude is referred to a 50 A/s precycle ramp rate, which was used to speed up the magnetic measurements, whereas in the LHC the ramp rate is fixed to 10 A/s. Having a time constant of about 200 s implies that after an injection time of 15 minutes ( $\sim 1000$  s) the decay is over and  $b_3$  is asymptotic as shown in Fig. 2. The typical injection time in the LHC is between one and two hours, with the minimum time of 30 minutes: this implies that the correction applied for chromaticity decay does not need to be dynamic (i.e., change with time), as the dynamic part of the decay is already over after 30 minutes and can be corrected by a constant trim.

### C. Dependence on powering history

The decay amplitude depends on the powering history [2–9]. As shown in Fig. 3, in Ref. [8] four parameters which affect decay were identified: (i) the precycle ramp rate  $dI/dt$ , (ii) the precycle flattop (FT) current  $I_{\text{FT}}$ , (iii) the precycle flattop time  $t_{\text{FT}}$ , and (iv) the time spent on the preinjection plateau  $t_{\text{prep}}$ .

TABLE I. Parameters obtained to fit the sextupole decay in the main dipoles according to Eq. (4), based on magnetic measurements.

Parameter	Dimension	$b_3$
$\tau$	(s)	189
$d$	(-)	0.66
$\delta^{\text{std}}$	(units)	2.01

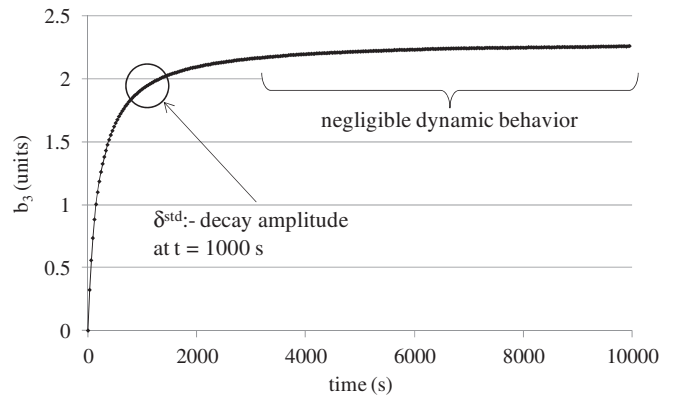


FIG. 2.  $b_3$  behavior during a 10000 s injection plateau as measured in MB3028. The values have been shifted along the y axis to cancel the initial value.

The powering history scaling law relates the new decay amplitude  $\delta_n$  at a new operating condition, with the standard decay amplitude  $\delta_n^{\text{std}}$  at the standard operating condition according to [8,9]

$$\delta_n = \delta_n^{\text{std}} \frac{T_0^n - T_1^n e^{-[(t_{\text{FT}})/(\tau_T^n)]} \frac{P_0^n - P_1^n e^{-[(t_{\text{prep}})/(\tau_P^n)]}}{T_0^n - T_1^n e^{-[(t_{\text{FT}}^{\text{std}})/(\tau_T^{\text{std}})]} \frac{P_0^n - P_1^n e^{-[(t_{\text{prep}}^{\text{std}})/(\tau_P^{\text{std}})]}}, \quad (5)$$

where for the sake of simplicity we removed the dependence of the decay amplitude on the ramp rate  $dI/dt$  and flattop current  $I_{\text{FT}}$ . This scaling law is required for the current LHC operation because the precycle flattop time  $t_{\text{FT}}$  and the time spent on the preinjection plateau  $t_{\text{prep}}$  varies from cycle to cycle. For instance, under optimal conditions, the flattop time is between 10 to 20 hours, but one can have beam aborts during the ramp or during collision time which considerably reduce the flattop time. Therefore the applied correction has to change according to the powering history. This is done by applying the scaling factor (5) to the standard correction  $\delta_n^{\text{std}}$ .

The time constants  $\tau_T^n$  and  $\tau_P^n$  describe the length of the magnet memory with respect to the flattop time and preinjection time, respectively. These time constants

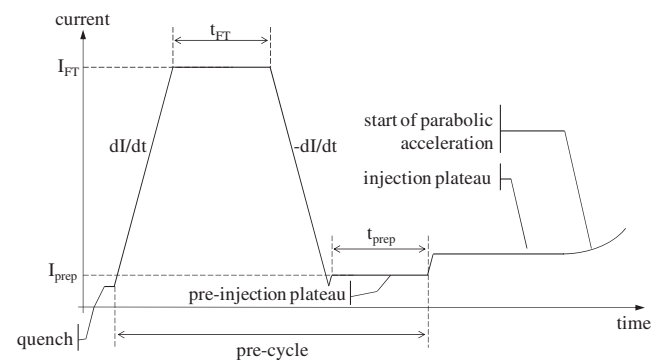


FIG. 3. Definition of the parameter affecting decay during LHC injection.

TABLE II. Parameters of Eq. (5).

Parameter	Dimension	$b_3$
$T_0$	(-)	1.3406
$T_1$	(-)	0.3436
$\tau_T$	(s)	504.9
$P_0$	(-)	1.7472
$P_1$	(-)	-0.7568
$\tau_P$	(s)	375.4
$t_{FT}^{std}$	(s)	1000
$t_{prep}^{std}$	(s)	0

together with the variables  $T_0^n$ ,  $T_1^n$ ,  $P_0^n$ , and  $P_1^n$  are the fitting parameters of Eq. (5). Although these are six parameters, in reality only four are independent as  $T_0^n$  and  $T_1^n$  (and similarly  $P_0^n$  and  $P_1^n$ ) can be reduced to one parameter.

The values of the fitting parameters as obtained from the magnetic measurements [8,9] together with the standard values of the precycle parameters are shown in Table II. Since the time constants are of the order of 500 s, one can conclude that for a  $t_{prep}$  of 20 minutes or more at the preinjection plateau, the decay amplitude is approximately constant. A similar consideration can be done for the flat-top time. This implies that as long as the  $t_{FT}$  and  $t_{prep}$  are longer than 20 minutes the scaling factor obtained by computing Eq. (5) is constant. Thus, in operation the powering history can be neglected in most of the cases, the only exception being flat-top times of the order of a few minutes.

### III. MAGNETIC MEASUREMENTS AT NEW OPERATIONAL CONDITIONS

At the beginning of 2011, the operation cycle of the LHC was modified such that the reset current and the preinjection current value had the same value of 100 A, i.e., eliminating the preinjection plateau (see Fig. 4). This is different to the baseline used in 2010 where the reset value was 350 A and the preinjection plateau was at 500 A. This modification was introduced to allow access to the machine while keeping the machine powered—thus avoiding a successive precycle—since a stored energy of 100 kJ in the machine (equivalent to 100 A) or less is considered to be safe for access [13].

The impact of the change of powering cycle on the  $b_3$  decay during injection was investigated by magnetic measurements of an LHC dipole magnet (MB1132). The average (between the two apertures) measured  $b_3$  is shown in Fig. 5, where the values have been shifted along the y axis to compensate for different initial values. These measurements showed that the time constant of the decay does not vary significantly from the 2010 to the 2011 cycle. A difference of 15% was observed in the decay amplitude; although this is not negligible, it is within the general accuracy of the whole magnet model, which is  $\sim 20\%$  [14].

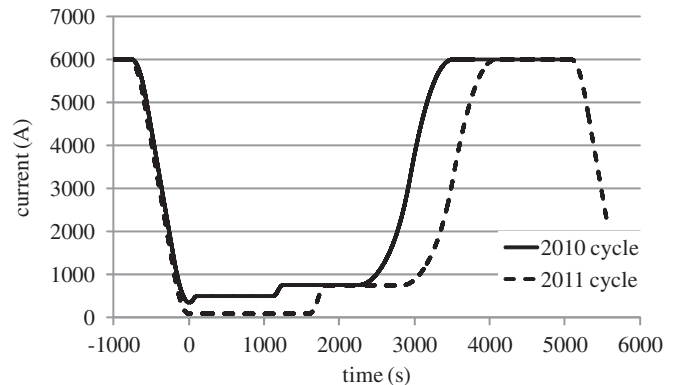


FIG. 4. Difference between the operation cycle used in 2010 and 2011. The 0 s mark represents the point where the reset current is reached.

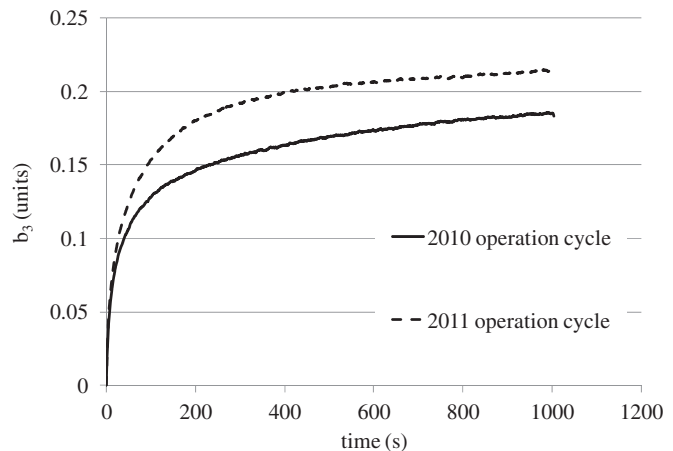


FIG. 5. Comparison of the  $b_3$  behavior as measured in magnet MB1132. The values were shifted down along the y axis to cancel the initial value.

The measurements also showed that the change in the decay amplitude induced by different precycling parameters is only 10%, w.r.t. the 30% found with previous measurements. On the other hand, the time constants  $\tau_T$  and  $\tau_P$  were similar to previous measurements.

### IV. CHROMATICITY DECAY MEASURED IN THE MACHINE

#### A. Time constants

Chromaticity beam measurements were used to establish the accuracy of the models that describe the  $b_3$  decay behavior during injection and its dependence on the powering history. In the LHC, the contribution from misalignment to chromaticity is small since  $b_4$  is close to zero. Therefore the measured chromaticity has a constant term plus a part proportional to the  $b_3$  in the main dipoles, and a part proportional to the sextupole correctors (two lattice sextupoles families and one family of spool pieces). These measurements were performed during the routine

operation: this ensures that the typical operation modes were studied in detail, but it was harder to get the complete picture of the parametric dependence w.r.t. an *ad hoc* study.

The measured decay of chromaticity is well fitted by the double exponential (4) used in the magnetic model (see Fig. 6). The amplitude of the decay agrees well with the expected value of  $\sim 0.4$  units in asymptotic conditions for the 3.5 TeV operation, i.e.  $\sim 22$  units of chromaticity. On the other hand, the time constants were much longer ( $\tau = 1000$  s instead of 200 s) than what was measured on a single magnet during series measurements. The slower decay takes place for both beams, and both horizontal and vertical chromaticity. This difference is shown in Fig. 6, where the chromaticity decay measured from the beam is compared to the average equivalent chromaticity decay extracted from magnetic measurements on a wide sample of magnets ( $b_3$  units are converted to chromaticity units using the standard model of the optics). Note that the magnetic measurements were performed using a measurement cycle consisting of a precycle of 50 A/s and at 7 TeV. For this reason, the chromaticity behavior from the magnetic measurements is scaled accordingly to match the current operation cycle, that of a precycle of 10 A/s and at 3.5 TeV.

Having observed this difference in the time constants, it was decided to analyze the dependence of the time constant on the ramp rate and on the flat-top current. A set of magnetic measurements, using the same powering cycle ( $dI/dt = 10$  A/s,  $I_{FT} = 6$  kA) as used in the 2011 LHC operation, showed a time constant  $\sim 30$  s, which is less than that observed in the machine ( $\tau = 1000$  s) and also less than that observed in the magnetic measurements carried out during the dipole production ( $\tau = 200$  s,  $dI/dt = 50$  A/s,  $I_{FT} = 11.85$  kA). The difference between the three sets of measurements is shown in Fig. 7, where  $\Delta b_3$  is normalized at  $t = 1000$  s.

With time constants of the order of 1000 s, after 30 minutes one still has a large chromaticity decay of  $\sim 10$  units (see Fig. 6), not tolerable for operation: therefore, a dynamic chromaticity correction is needed. A discrepancy between magnetic measurements and accelerator behavior was also observed in HERA [15], where the chromaticity in the reference magnet did not match the chromaticity found by the sextupole correction settings. A discrepancy up to 6 units was observed, with worse cases happening after magnet quenches or interruptions for access or maintenance.

Until March 2011, the accelerator operated with reduced bunch intensity, continuous chromaticity measurements were possible, and chromaticity trims were applied. After reaching nominal beam intensity, chromaticity measurements were possible only on the pilot beam, and then operators were blind once the full beam was injected. For this reason the correction of the decay had to be implemented to avoid beam losses during injection.

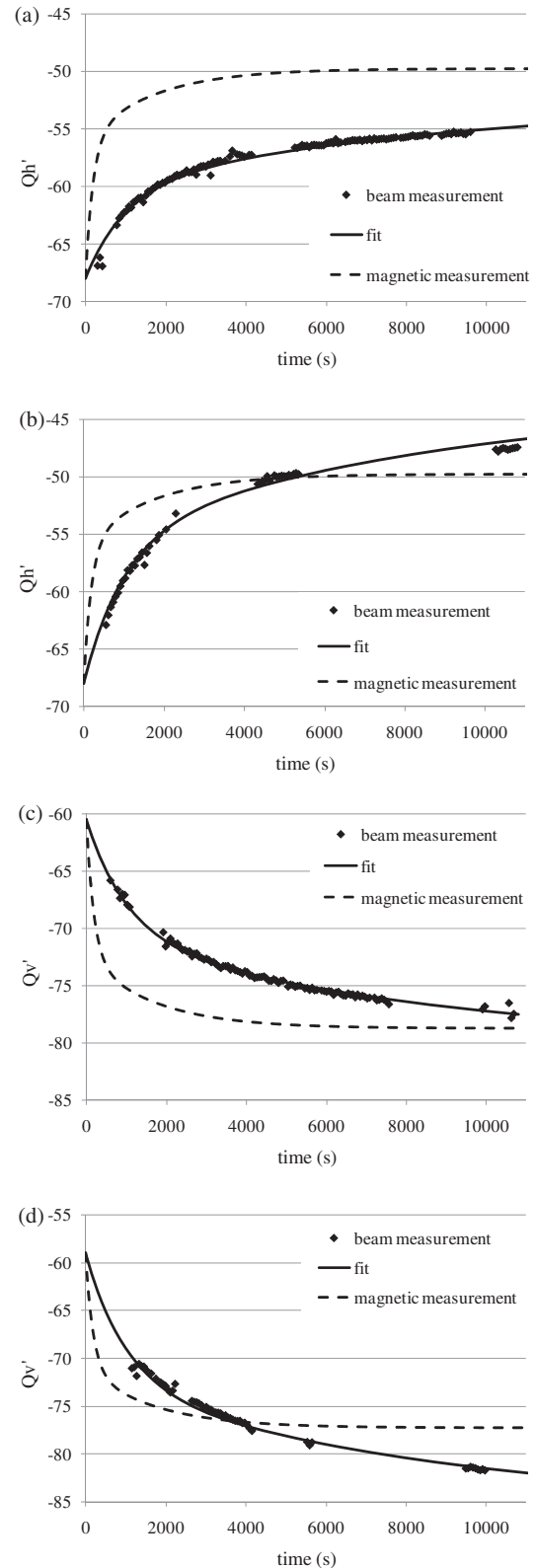


FIG. 6. Average chromaticity as measured during magnetic measurements (dashed line) compared with the measured chromaticity during beam measurements (dots) and its respective fit (continuous line). Parts (a) and (b) are the horizontal chromaticity for beam 1 and beam 2, respectively, and (c) and (d) are the vertical chromaticity for beam 1 and beam 2, respectively.

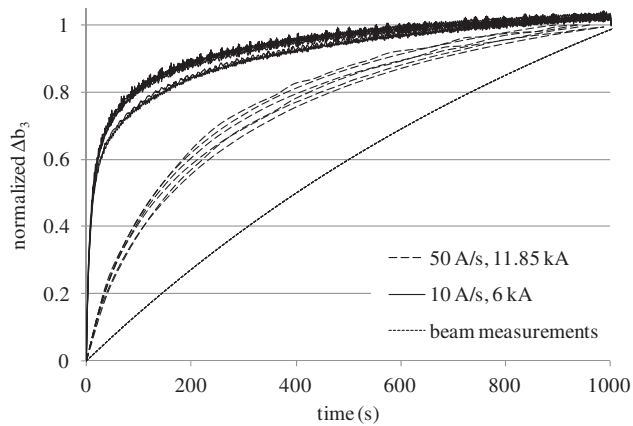


FIG. 7. Decay of  $b_3$  for series measurements (50 A/s precycle and 11.85 kA flattop), in LHC operational condition of 2010–2011 (10 A/s and 6 kA flattop), and derived from beam measurements.

The dynamic correction of the decay was implemented in April 2011, with time constants estimated through beam measurements. Thanks to this correction, the chromaticity has been stabilized within 5 units at injection plateau. In Fig. 8 we show the chromaticity behavior and the current in the spool pieces during the injection plateau before and after the implementation of the decay correction. Indeed, the level of correction of the order of 1–2 units as shown in Fig. 8(b) can be obtained only taking into account the powering history, as it is explained in the next section.

### B. Dependence on powering history

As mentioned in Sec. II, the decay amplitude depends on the flattop time and on the preinjection time, which change from run to run. This difference in the flattop time and preinjection time is due to the use of previous physics runs as a precycle, and the use of the real precycle only in exceptional cases (such as power abort, beam dump caused by external events, ...).

Typical powering history parameters, i.e., flattop time and preinjection time, that occurred during operation in May–June 2011 are shown in Fig. 9. Each point represents a chromaticity measurement performed during the standard LHC operation. Note that most of the cases had a preparation time of  $\sim 20$  minutes and a flattop time ranging from a few minutes to several hours. These chromaticity measurements were used to analyze the dependence of the decay on the flattop time. Another group of points lie on the 10 minutes flattop time line. These points were used to analyze the dependence of the chromaticity behavior on the preparation time.

The amplitude of the  $b_3$  decay versus the flattop time and versus the preparation time, as extracted from the chromaticity measurements during beam operation, are shown in Figs. 10 and 11, respectively. Normalization is done with respect to the  $b_3$  decay amplitude at the standard

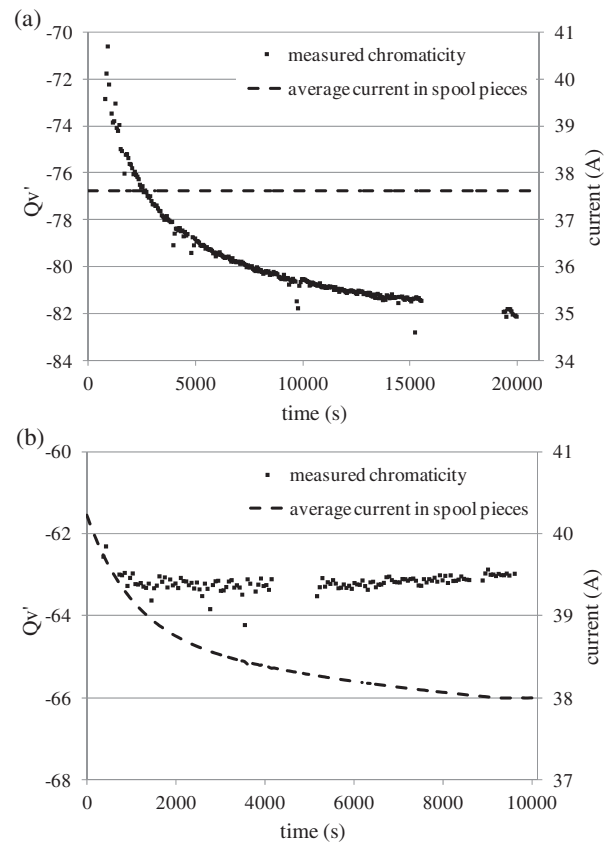


FIG. 8. Chromaticity behavior and current in the spool pieces during the injection plateau before (a) and after (b) the implementation of the dynamic decay correction. Data shown in (a) was measured on 21/02/2011 and the data shown in (b) was taken on 02/05/2011.

condition, i.e., 10 minutes flattop time and 20 minutes preparation time. The updated list of parameters is given in Table III. Measurements show that the change in the decay w.r.t. these two parameters is more than what is expected from magnetic measurements: 130% and 56% in comparison with 10%. Moreover, the time constants  $\tau_T$

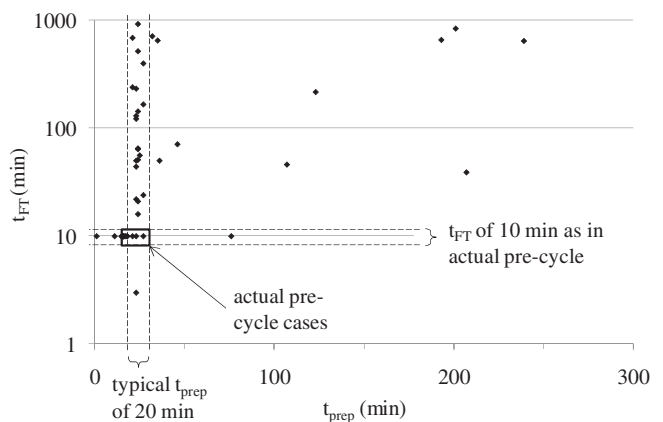


FIG. 9. Precycle parameters used for each ramp in the LHC during May–June 2011. Each point represents a ramp.

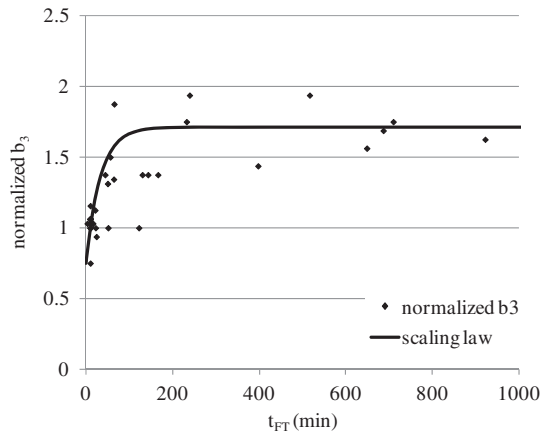


FIG. 10. Normalized  $b_3$  decay amplitude and the scaling law against the flattop time.

and  $\tau_P$  are of the order of 1000 s, i.e., a factor 3 to 4 larger than those observed in the magnetic measurements (see Table II). This implies that magnetic memory in the LHC is longer than 20 minutes: for instance, the  $b_3$  decay amplitude observed after a preinjection plateau of one hour will be 30% smaller than that observed after 20 minutes on the preinjection plateau. This forced us to activate the powering history dependence in the control system, using the coefficients estimated through beam measurements. After this update of the model, in most of the cases, chromaticity was constant over the injection plateau within 1–2 units as shown in Fig. 8.

In the present powering history scaling law, it is assumed that there is no coupling between the two precycle parameters on the decay amplitude. From the first few measurements which were obtained, we have indications of some coupling, and additional measurements would be needed to fully characterize the powering history.

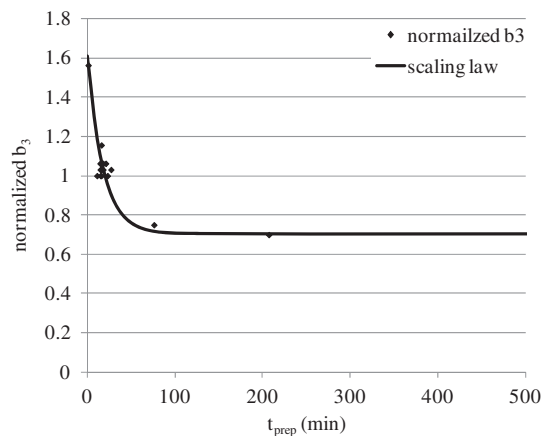


FIG. 11. Normalized  $b_3$  decay amplitude and the scaling law against the preparation time.

TABLE III. Parameters of Eq. (5) based on beam-based measurements.

Parameter	Dimension	$b_3$
$T_0$	(-)	1.78
$T_1$	(-)	1
$\tau_T$	(s)	2000
$P_0$	(-)	-0.78
$P_1$	(-)	1
$\tau_P$	(s)	1100
$t_{FT}^{std}$	(s)	600
$t_{prep}^{std}$	(s)	1200

## V. CONCLUSIONS

The decay of  $b_3$  in the main dipoles of the Large Hadron Collider is a source of chromaticity change that affects operation. First estimates carried out during the production phase gave a  $b_3$  decay at injection plateau of about 2 units, corresponding to 90 units of chromaticity. More recently, it has been observed that a 10 A/s precycle, as in the LHC operation, instead of at 50 A/s, as done during the magnetic measurements, reduces decay by about a factor 2. With operation at 3.5 TeV instead of 7 TeV, magnetic measurements showed a further factor 2 of decay reduction, i.e.  $\sim 0.4$  units of  $b_3$  decay and  $\sim 22$  units of chromaticity. These values have been confirmed by beam measurements, see Sec. IVA, Fig. 6.

The chromaticity measurements performed during routine operation also showed that the functional form used for the fit also works very well; the time constants of decay are about 30 times larger than expected by the magnetic measurements in similar conditions, i.e., about 30 s (see Fig. 7). A direct consequence is that injecting after one or three hours makes a relevant difference, and a dynamic correction of decay at the injection plateau is needed. It has been activated in the LHC control system in April 2011, with the time constants estimated through beam measurements.

The chromaticity measurements also confirmed that the flattop time and the preinjection plateau time are the key parameters ruling the powering history dependence of the decay. Indeed, we found that decay amplitude has a larger dependence on the powering history 50%–100% variations w.r.t. 30% expected from magnetic measurements. Moreover, the saturation takes place for much longer times, and a flattop time of 1 hour instead of 10 hours makes a relevant difference (see Fig. 10). This lack of fast saturation of the powering history dependence obliged us to implement the powering history model in the LHC control system in May 2011, with the coefficients estimated through beam measurements. For the moment there is no explanation why decay time constants measured in the accelerator are considerably larger than expected from measurements on single magnets.

With the present corrections, the chromaticity is stable within 1–2 units at injection plateau, i.e., we manage to correct the  $b_3$  component within 0.02–0.04 units. This impressive capability of correction is considered to be sufficient for the present operation.

### ACKNOWLEDGMENTS

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- [1] A. Chao and M. Tigner, *Handbook of Accelerator Physics* (World Scientific, Singapore, 1999).
  - [2] D. A. Finley, D. A. Edwards, R. W. Hanft, R. Johnson, A. D. McInturff, and J. Strait, in *Proceedings of the 12th Particle Accelerator Conference* (IEEE, Washington, DC, USA, 1987), pp. 151–153.
  - [3] O. Brüning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, “LHC Design Report Volume I The LHC Main Ring,” p. 74, CERN, Geneva, 2004.
  - [4] R. W. Hanft, B. C. Brown, D. A. Herrup, M. J. Lamm, A. D. McInturff, and M. J. Syphers, *IEEE Trans. Magn.* **25**, 1647 (1989).
  - [5] M. Schneider, Ph.D. thesis, University of Twente, Netherlands, 1998.
  - [6] M. Haverkamp, Ph.D. thesis, University of Twente, Netherlands, 2003.
  - [7] L. Bottura, G. Ambrosio, P. Bauer, M. Haverkamp, T. Pieloni, S. Sanfilippo, and G. Velev, *IEEE Trans. Appl. Supercond.* **15**, 1217 (2005).
  - [8] N. J. Sammut, L. Bottura, P. Bauer, G. Velev, T. Pieloni, and J. Micallef, *Phys. Rev. ST Accel. Beams* **10**, 082802 (2007).
  - [9] N. J. Sammut, L. Bottura, G. Deferne, and W. Venturini Delsolaro, *Phys. Rev. ST Accel. Beams* **12**, 102401 (2009).
  - [10] L. Rossi, *Supercond. Sci. Technol.* **23**, 034001 (2010).
  - [11] R. J. Steinhagen, CERN Yellow Report No. 2009-005, pp. 317–359.
  - [12] L. Krempasky and C. Schmidt, *J. Appl. Phys.* **78**, 5800 (1995).
  - [13] W. Venturini Delsolaro, in Proceedings of the Chamonix LHC Performance Workshop (CERN Yellow Report No. 2011-005), pp. 70–74.
  - [14] L. Bottura *et al.*, in *Proceedings of the 23rd Particle Accelerator Conference, Vancouver, Canada, 2009* (IEEE, Piscataway, NJ, 2009), p. 241.
  - [15] B. Holzer and C. Montag, in *Proceedings of the European Particle Accelerator Conference, Vienna, 2000* (EPS, Geneva, 2000).