OPERATIONAL EXPERIENCE AND IMPROVEMENTS OF THE LHC BEAM CURRENT TRANSFORMERS

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Abstract

During the 2010 run the LHC continuously improved its performance. In particular the bunch charge and number of bunches were significantly increased, which revealed certain limitations of the LHC beam current transformers. The DC current transformers (DCCT), used to measure the circulating beam current, exhibited saturation related to bunch intensity, the number of batches in the machine and their spacing. Two major issues were also discovered on the fast beam current transformers (FBCT) used to measure the individual bunch charges: discrepancies in the measured intensities when compared to the DCCTs measurements and a bunch length dependence on the measured intensity. Further analysis showed that both problems are linked to the beam position dependence of the signal acquired from the toroids used in the FBCTs. This paper presents the observed issues, discusses possible solutions and reports on the results from modification made for the 2011 run.

INTRODUCTION

The progress of machine commissioning and operation has been fast and steady in 2010. New bunch intensities (from 2×10^{10} to 1.3×10^{11} charges per bunch), new filling patterns (from a few bunches to 600 bunches per beam), new particle type (fully-stripped lead ions) have been put into operation. In addition a variation of the bunch length from 0.6 to 1.7 ns has been observed during the acceleration up to 3.5 TeV. Beside the machine operation team, which is a classical user of the Beam Current Transformers (BCT), the experiments have shown a very demanding interest since the beam intensity is a key parameter for luminosity detector calibration [1].

MAIN ISSUES IN 2010

The beam parameters evolution revealed certain limitations of the BCTs.

Issues on DCCTs

After implementation of an offset reduction by software at the beginning of the year, the DCCTs [2] performed well and within specifications [3] with low intensity and unbunched beam. Unfortunately the quality of the measurements degraded significantly when batches of 75 ns spaced bunches were injected in the machine. Depending on the filling pattern, the DCCT over or under estimated the number of protons stored in the machine (Fig. 1). This effect has been diagnosed, simulated and then reproduced in laboratory (Fig. 2) on a test bench composed of a DCCT, a vacuum chamber of the LHC type and a coaxial antenna connected to a pulse current generator.

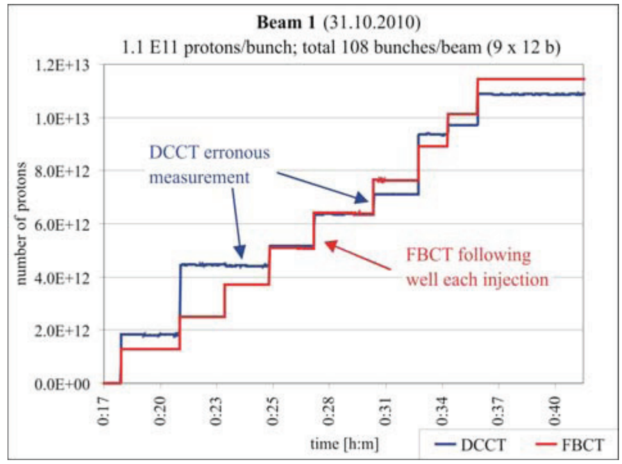

Figure 1: DCCT dependency on the filling pattern.

The source of the problem has been identified to be a combination of two causes worsened by the particularly low revolution frequency of the LHC (11 kHz):

- poor efficiency of the RF bypass foreseen to reduce the HF magnetic field induced by the beam, and which is seen by the DCCT
- inappropriate gain partition associated with operational amplifier limitations (current, voltage swing, slew rate) in the AC feedback loop

The RF bypass is essentially made of capacitors soldered on a flexible printed board wrapped around the ceramic gap of the vacuum chamber. Several attempts have been made to improve its efficiency during 2010 but without real success as the BCTs environment in the machine was not clearly understood.

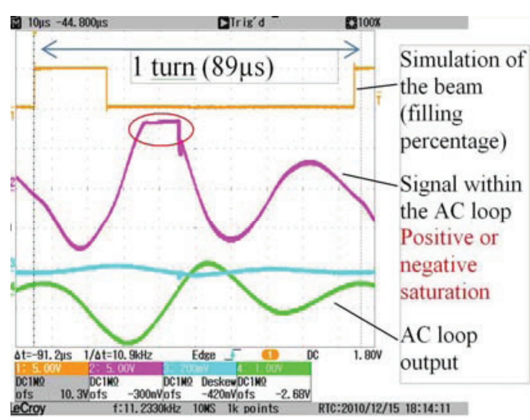

Figure 2: Plot showing a positive saturation of the 2010 AC loop with a given filling pattern simulated on the test bench.

The simulation of different filling patterns by a pulse of current injected into the antenna lead to a positive (Fig. 2) or negative saturation of the AC loop according to the pulse duration. This reproduces well the observed over and under estimations of the current measurement seen with beam.

Issues on FBCTs

The beam diagnostics team has used the 2010 LHC run to diagnose the issues related to the FBCT [4] calibration procedure, and correlation of the FBCT and DCCT measurements. It was found, that an independent calibration of the FBCTs results in a difference of several per-cent of the estimated intensity with respect to the DCCT measurement. Further measurement analysis revealed that this behaviour is caused by following effects:

- FBCT measurements are position dependent; this position dependency is in addition frequency dependent. Recent findings show, that a >1%/mm position dependence (Fig. 3) is caused by the measurement toroid itself. Such large value is far from the specification given by the toroid manufacturer (0.2%/mm).

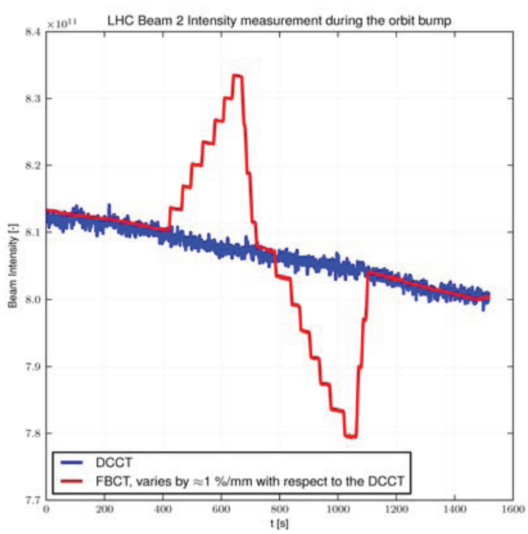

Figure 3: FBCT readings vary during controlled orbit bumps at the location of the FBCTs and DCCTs.

- A bunch length dependence at the 1% level has been observed (Fig. 4). The origin of this effect is under investigation. One of the possible causes could be related to the position dependence.

Another important remark for the functionality of the FBCTs is that the LHC experiments care about the bunch population in the nominal 2.5 ns RF bucket. The FBCTs however were not designed to provide such measurement [3], and thus they provide this information only with limited accuracy, mainly due to limited measurement bandwidth and used integration method. The integration over 25 ns does not allow to distinguish neither between the charges in the main bunch and in any satellite or ghost bunches, nor an unbunched beam, which is only seen by the DCCTs.

These problems affect negatively the DCCT-FBCT cross-calibration as it has to be assumed that the amount of unbunched beam and the ghost/satellite populations is negligible during the cross-calibration.

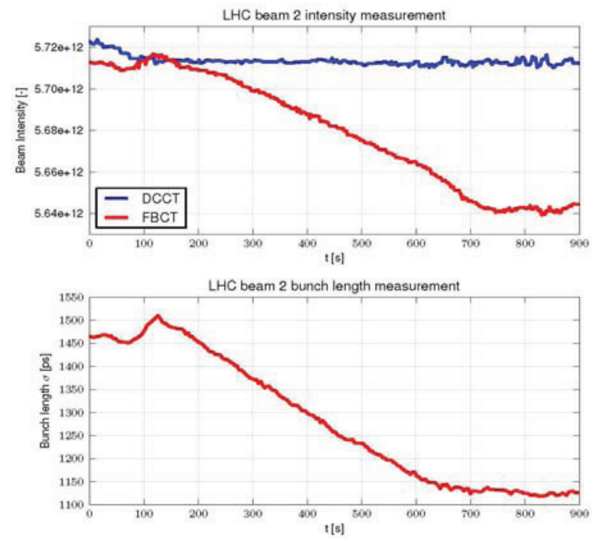

Figure 4: FBCT readings decrease with bunch length during the ramp while DCCT behaves correctly.

IMPROVEMENTS AND OBSERVATIONS IN 2011

DCCTs

In order to eliminate the sensitivity to filling pattern, the following modifications have been made during the 2010/11 end of year technical stop:

- The RF bypass efficiency has been increased (damping resistors suppressed, higher value of capacitor) to limit any frequency components above 11 kHz, seen by the monitors
- The electronics has been modified (new operational amplifiers, new gain partition) to prevent saturation in the AC feedback loop
- The diagnostic capability from the surface building has been improved

$I_{mean\ batch}$ [mA]		$T_{bunch\ spacing}$ [ns]				
beam	$N_{charges/bunch}$	25	50	75	150	300
lead ion min	5.60E+08	3.6	1.8	1.2	0.6	0.3
lead ion max	5.60E+09	35.9	17.9	12.0	6.0	3.0
proton nominal	1.15E+11	736.9	368.5	245.6	122.8	61.4
proton ultimate	1.67E+11	1070.1	535.1	356.7	178.4	89.2

$I_{mean\ batch} = N_{charges/bunch} * e / T_{bunch\ spacing}$ with e = elementary charge

Figure 5: Tests performed in the laboratory for different filling patterns. Green numbers means successfully tested, i.e. no issues observed. Red numbers means still to be tested as the current set-up is not powerful enough to simulate such patterns.

The tests in laboratory have been repeated with these modifications and found efficient in eliminating filling pattern dependence for all the patterns that can currently be simulated. Figure 5 shows a summary of these tests, simulating the beam (average current over one batch) which covers the beams expected in 2011/12.

During the scrubbing run in April 2011 1020 nominal bunches were injected per beam (batches of 72 bunches spaced by 50 ns, 1.2×10^{11} charges per bunch on average, 368 mA average current per batch). Very good agreement (difference smaller than ±0.5 %) between the two DCCTs and one FBCT, previously cross-calibrated with the DCCT, confirmed the results obtained in laboratory (Fig. 6). With these conditions the voltage swing within the AC loop did not exceed 30% of the available dynamic, which leaves a comfortable margin for the operation with the beams expected in 2011/12.

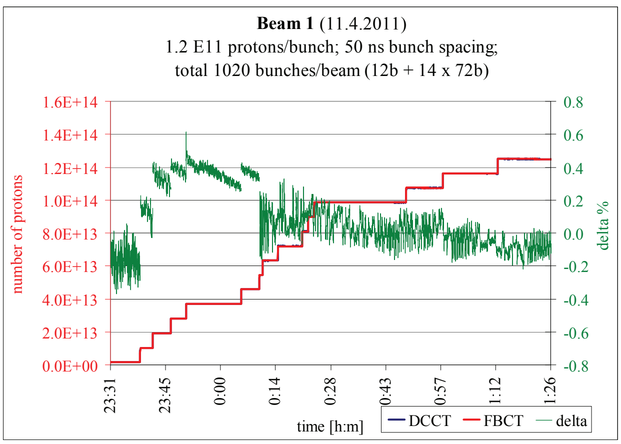

Figure 6: BCTs reading during a scrubbing run (highest number of bunches injected so far)

A further RF bypass improvement is being studied; it is required for the 25 ns bunch spacing operation with the ultimate number of charges per bunch (see lower rows in Fig. 5).

In addition, a new 24 bit ADC acquisition board is under development to cover the entire dynamic range avoiding range selection and to improve the resolution for the high intensity beams in 2012.

FBCT

The situation with the FBCTs is less favourable as the main error source is the toroid itself. Several ideas are currently under investigation to overcome the beam position dependency issue. Their efficiency is still to be determined. At the moment it seems that the best alternative to suppress the effect is the conversion of the LHC FBCTs into Integrating Current Transformers (ICT) [5]. There was already one such ICT constructed in the laboratory using one spare FBCT housing and an original FBCT toroid. Although this prototype seems to improve drastically the FBCT behaviour, its mechanical construction does not yet permit to install it easily on the LHC vacuum chamber without breaking the vacuum. Investigations lead towards a split-core design. The development is however time-consuming due to difficulties related to procurement of the nanocrystalline material.

The current situation implies that the quality of the FBCT measurements relies on a cross-calibration with the DCCTs to optimize the precision during the Van de Meer scans. Our aim is to construct an ICT measuring with an absolute accuracy of ±1 % of the nominal LHC beam (1.7×10^{11} charges per bunch).

In order to fulfil further requests of the experiments to provide an intensity measurement with a 2.5 ns temporal resolution the CERN BI section is now commissioning two new instruments: the Longitudinal Density Monitor and the Wall Current Monitor.

CONCLUSIONS

After the discovery of different issues in 2010 the effects have been diagnosed, simulated and then reproduced in laboratory. Solutions to improve the DCCTs were found and implemented at the beginning of 2011; they have proved to be effective with the beams observed so far. Investigations on the field of the FBCT measurements are on-going and the new ICTs are supposed to be installed during the long LHC technical shut-down in 2011-2012.

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