OPTIMIZATION OF THE LHC BEAM CURRENT TRANSFORMERS FOR ACCURATE LUMINOSITY DETERMINATION

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Abstract

During the 2010 and 2011 LHC runs a series of dedicated fills were used for luminosity calibration measurements at each of the LHC experiments. A major contribution to the final precision of these luminosity calibration campaigns originated from the absolute accuracy of the bunch current population estimation. The importance of these measurements for the LHC physics community triggered a large and fruitful collaboration between the CERN Beam Instrumentation Group and the LHC Experiments to push the LHC Beam Current Transformers performance to their limit. This paper will report on the available instruments for beam current measurements, the methodology used to improve them and the results obtained.

INTRODUCTION

Beam and bunch intensity estimation is one of the most fundamental measurements for colliding rings. Use cases span from injection/extraction efficiency, lifetime, statistics... to machine and equipment protection issues. While operational needs were quickly covered by the standard LHC fast and DC BCTs, the subsequent needs of the LHC Experiments to calibrate their detectors required a lot more efforts and attention [1]. The ability to measure luminosity on an absolute scale is necessary to determine the absolute cross-section value of reaction processes. These measurements can then be used to constrain models of *pp* interactions and detect and quantify new phenomena. The required accuracy on the absolute value of the luminosity lies in the range 1-5%. Since luminosity is directly proportional to the colliding bunch populations, the request from the LHC Experiments was quite clear - not only to get the best possible performance from the beam current monitors but also to quantify precisely the uncertainty of these measurements.

The following document will present the available instrumentation for beam current measurements, the method used to assess and improve their performance and the results obtained.

THE AVAILABLE INSTRUMENTS

Several of the beam instrumentation systems available in the LHC can estimate absolute or relative bunch populations. Initial effort was mainly concentrated on the two types of beam current transformers but other systems were later also taken into accounts.

The LHC circulating beam current measurement is mainly provided by eight current transformers, two DC current transformers (DCCT) and two fast beam current transformers (FBCT) per ring.

The DCCTs, based on the fluxgate magnetometer principle [2], measure the mean current of the circulating beam (usually translated into the number of charges per revolution period).

The FBCTs [3], based on a Bergoz type transformer with a bandwidth from ~200 Hz to 1.2 GHz, provide both bunch-by-bunch (40 MHz) and total turn-by-turn beam intensity information, the latter also being used for beam lifetime calculations.

The main advantage of these instruments is that they could, in theory, be calibrated in situ with well known external current sources and thus provide accurate absolute measurements.

Other LHC instruments can also be used to estimate bunch populations. The longitudinal density monitors (LDM), based on single photon counting of synchrotron light [4], wall current monitors and the ATLAS beam pick-up based timing system (BPTX) [5] provide information on the beam longitudinal distribution in the LHC. The full beam structure, including filling pattern, relative bunch to bunch population, satellite to main bunch population and individual bunch properties such as bunch length can then be computed from these longitudinal profiles.

However, the only way to obtain absolute population estimations from these devices is to cross-calibrate them with calibrated ones such as beam current transformers.

THE METHOD

The main objective was to optimize the performance of our two main workhorses, i.e. the DCCT and FBCT, and to evaluate their uncertainties. It was decided to concentrate on the transformers absolute accuracy calibration and to rely on the other instruments to systematically check the relative behaviour of the transformers under various beam conditions.

The method consisted of three main activities:

- Gathering information on possible error sources and mitigation techniques
- Observing the (mis-)behaviour of the instrument
- Correlating measurement from the transformers and working on understanding, improving and quantifying the error sources.

An inventory has been made of all the potential error sources that could impact our measurement accuracy. The different layers of the systems were analysed separately with emphasis on pinpointing the different and distinct sources of error that could contribute at each stage.

In parallel to cataloguing the various error sources, the instruments were closely monitored to detect and rapidly diagnose potential misbehaviour.

To detect these problems, the different instruments were regularly cross-calibrated with the DCCTs and the

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evolution of the total beam current estimations from the different instruments, i.e. summing the bunch by bunch acquisitions of the FBCT, BPTX and WCM were then carefully monitored under various machine conditions. The procedure led to several issues being observed and consequently understood and mitigated:

- A filling pattern dependence (Fig. 1) was observed on the current measured by the DCCT which became evident through comparison with the FBCT.

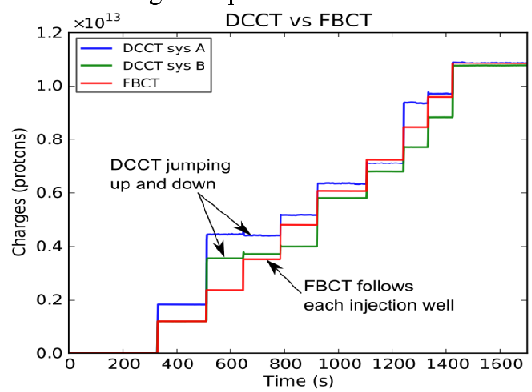

Figure 1: DCCT dependency on LHC filling pattern.

- A bunch length dependence was observed in the FBCT response again made evident by comparison with the DCCT data.
- A beam position dependence (Fig. 2) was revealed in the FBCT response due to the close monitoring of its response during a machine development session dedicated to other studies.

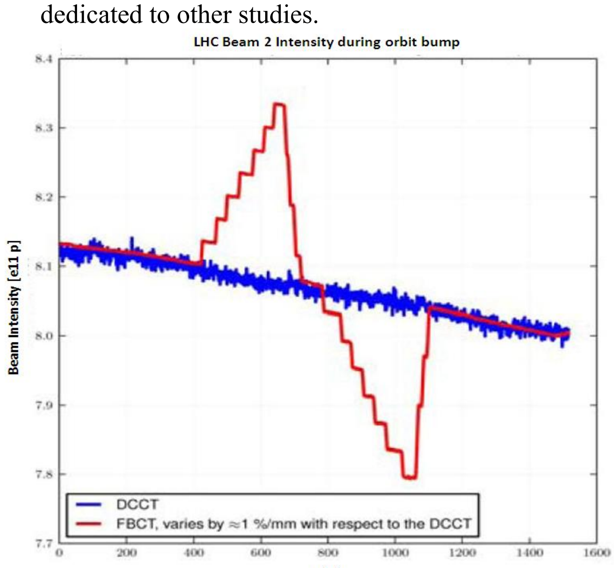

Figure 2: FBCT signal varies during controlled orbit bumps while DCCT signal behaves correctly.

Every disagreement in these beam current estimations was carefully analysed, with the assumed culprit often identifiable through comparison of three or more systems.

These effects were correlated with our potential error source inventory to guess their origin. The corresponding scenarios were then reproduced during specific beam tests or laboratory set-ups with the aim of identifying and quantifying the error source and targeting specific corrections or upgrades.

RESULTS

Using this approach it was possible to pin-point the main sources of error for the DCCT and FBCT. These were then either corrected whenever possible, or reduced to a minimum by choosing appropriate beam conditions for the LHC detector calibration campaigns.

The origin of the DCCT dependency to bunch filling pattern (Fig. 1) was traced to the design of the RF bypass and of the AC feedback loop resulting in saturation effects in the front end electronics [6]. These problems were fixed during the last winter shutdown and the modifications have been demonstrated to be successful both in the laboratory and in the LHC.

The evolution of the DCCT calibration factor has also been carefully followed by applying the same precise calibration procedure during every LHC technical stops. These factors have remained stable to within 0.05% since the improvement introduced to the system in early 2011 for all but the most sensitive gain (Range 4) more affected by the noise, as shown in Fig. 3.

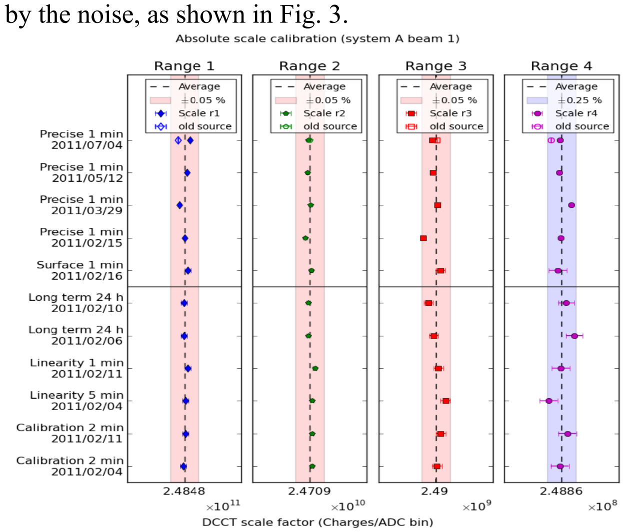

Figure 3: DCCT calibration factor evolution in 2011.

All of these results lead us to reasonably believe that the absolute scale factor accuracy of LHC DCCTs will now be below 1% for all beam physics conditions currently foreseen in 2011.

The initially observed dependency of FBCT reading on bunch length has been substantially reduced to below the 1% level by adding 80MHz low pass filters at the input of the front-end electronics. However, the dependence on beam position is still present and has been demonstrated to come from the toroid itself. A new monitor is in preparation but will not be available for installation before the long LHC shutdown foreseen in 2013. Fortunately, the beam orbit at the BCT locations is kept sufficiently stable during standard physics fills to limit these effects to below a per-cent level, as shown in Fig. 4.

This dependence on beam position nevertheless prevents the absolute calibration of the FBCT using their

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own dedicated current source and integrated calibration windings. The only available solution for the moment is to cross-calibrate the FBCT with the DCCT. This is a valid option if the population of debunched beam (seen by the DCCT but not by the FBCT) is well known during the cross-calibration. Together with the LHC Experiments a concerted effort is therefore being made to assess instruments capable of measuring this population, i.e. the LDM and the LHC experimental detectors [7,8]. To mitigate this effect during the luminosity calibration campaign, dedicated filling patterns were used where the level of debunched beam was negligible.

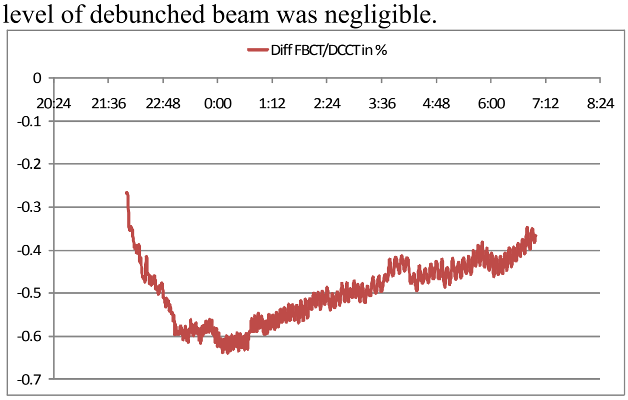

Figure 4: The percentage evolution of the difference between FBCT and DCCT total beam current estimations during a 12 hours physics period.

Bunch Measurement Accuracy

In addition to the uncertainty on the overall scale of the FBCT there is the relative error on the individual bunch population estimations.

To quantify this error, the FBCT has been compared with the BPTX as shown in Fig. 5.

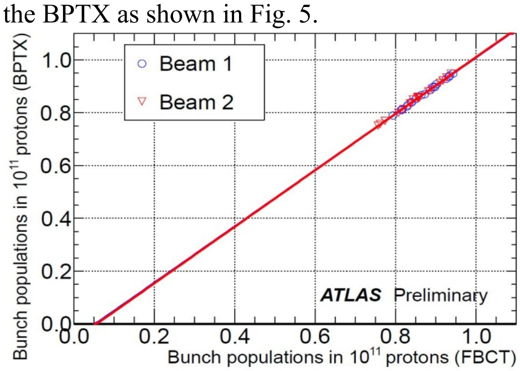

Figure 5: Bunch populations from ATLAS BPTX versus FBCT. The summed populations of each set were normalized to the current from the DCCT.

The uncertainty resulting from these comparisons imposes currently an upper limit on the FBCT relative error of 2% but work is currently in progress to allow a better understanding of FBCT and BPTX systems and reduce this systematic uncertainty.

CONCLUSIONS

Machine operation and optimisation can often rely on an absolute accuracy of beam instrumentation performance at a per-cent level. However, a pressure from the LHC Experiments to achieve the best accuracy of the absolute luminosity calibration has pushed the required performance of the LHC BCTs to well below the per-cent level. This has led to a much better understanding of these systems and resulted in improved performance.

During the October 2010 calibration campaign, the uncertainty on the bunch population used by the LHC Experiments came mainly from uncertainty on the absolute DCCT scale, the estimation of ghost/debunched populations and FBCT linearity. This was estimated to be around 3% [7,8] under the well defined and optimized conditions of this campaign. The improvements and progress made since then lead to a reasonable belief that the level of performance under all 2011 beam conditions is now well below this. The new luminosity calibration campaign foreseen for the autumn of 2011 should therefore result in a significant reduction in the uncertainty of the bunch population measurement.

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