

# LHC BEAM CURRENT TRANSFORMERS STATUS AND PROSPECTS

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## Abstract

This document will present the main issues observed and results obtained with the LHC Beam Current Transformers (BCT) during 2010 along with the BE-BI strategy and prospects for 2011.

## MAIN ISSUES IN 2010

### Issues with the DC BCT

The DC BCTs performed well and within specifications at the beginning of the year with low intensity and unbunched beam (once we managed to regularly correct the offsets of the monitors via the LHC sequencer tasks). Unfortunately, things degraded significantly when we started to inject 75 ns batches in the machine. Depending on the filling pattern, the DC BCT started to sometimes over-estimate, sometimes under-estimate the number of protons stored in the machine (see Fig 1.). This effect has been diagnosed, simulated and then reproduced in our laboratory (see Fig 2.).

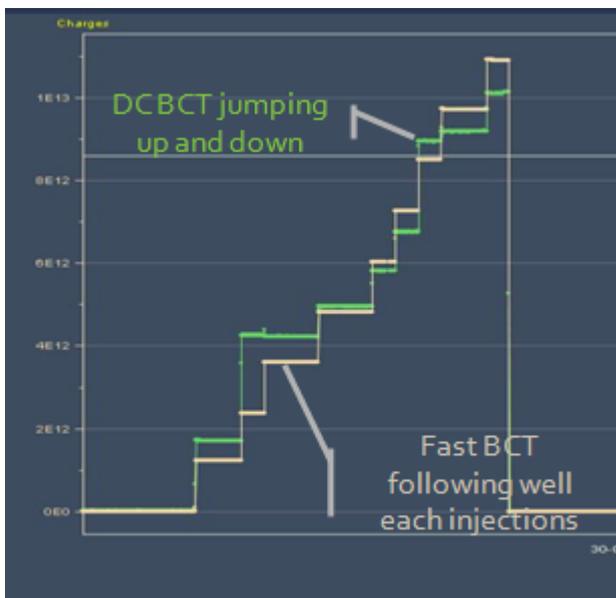


Figure 1: DC BCT dependency on the filling of the machine.

The source of this problem has been identified to be a combination of:

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

We made several attempts to mitigate this issue during 2010 but without real success.

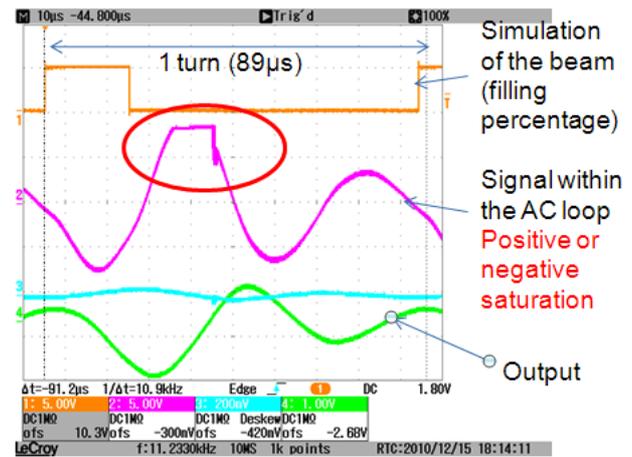


Figure 2: Plot showing a positive saturation of our 2010 AC loop with a given filling pattern. Same set-up with different filling pattern leads to a negative saturation, reproducing the observed over and under estimations seen with beam.

### Issues with the Fast BCT

We did not manage to make an independent calibration of our fast BCTs during 2010. Every attempt resulted in a difference of several % of the estimated intensity with respect to the DC BCT measurements.

We discovered that there are several effects which make accurate calibration difficult with these systems:

- A clear position dependence was demonstrated at the end of last year (>1% per mm), which was well outside the specifications given by the manufacturer of these toroids (see Fig. 3). The manufacturer acknowledges this issue, but there is no easy fix for this.

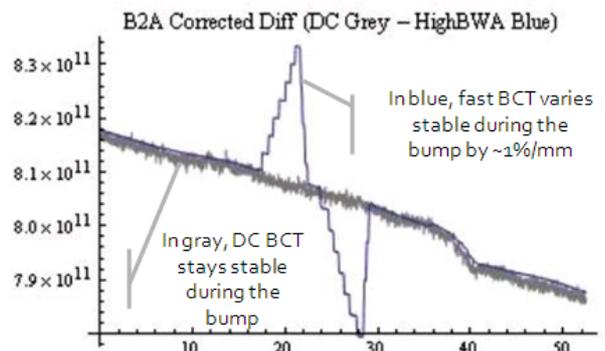


Figure 3: Fast BCT readings vary during controlled orbit bumps around our monitors while DC BCT behaves correctly.

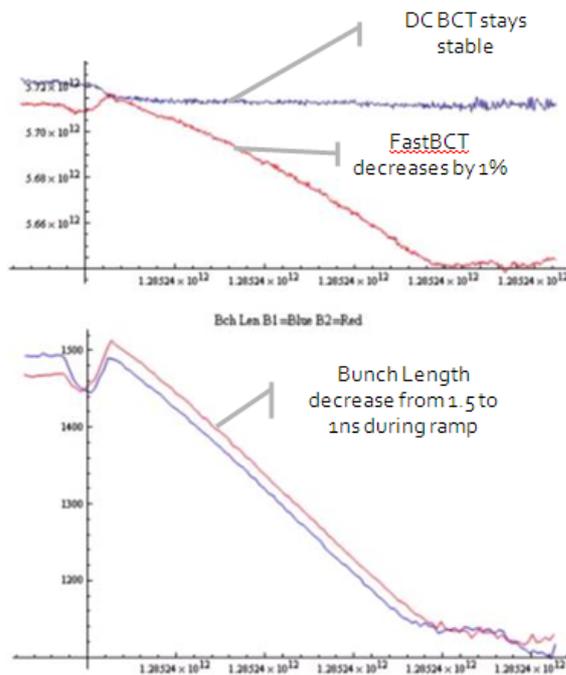


Figure 4: Fast BCT readings decrease with bunch length during the ramp while DC BCT behaves correctly.

- A bunch length dependence has also been seen at the 1% level. This can have many sources, one of which is related to the position dependence mentioned above (see Fig 4).

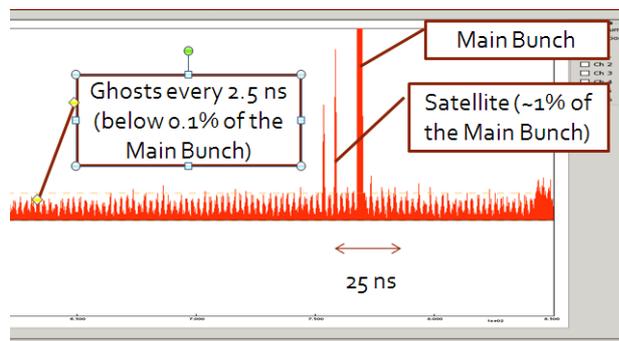


Fig 5: RF bucket population around one main bunch estimated with the Longitudinal Density Monitor during the ion run proves that these satellites and ghost bunch populations cannot always be neglected.

- The bandwidth of the transformer and the acquisition chain do not allow the system to distinguish between charges in the main bunch and in any satellite or ghost bunches. All

charges in 21ns out of every 25ns slot is integrated. It is important to remind ourselves that the experiments care about the bunch population in the nominal 2.5ns RF bucket. In addition, fast BCTs are totally insensitive to unbunched beam.

All of these effects meant that we had to rely on cross calibrating the fast BCT with the DC BCTs assuming that the amount of unbunched beam and the ghost/satellite populations were negligible.

### OUR STRATEGY AND RESULTS IN 2010

Based on these observations, our strategy to achieve the best possible accuracy during the 2010 luminosity calibration measurements has been the following:

- Define and use filling patterns where the DC BCT was known to be free of issues
- Check and fine tune if necessary the DC BCT offsets before the fill
- Cross-calibrate fast BCT with DC BCT just before stable beam, once orbit and bunch length are stabilized, assuming ghost, satellite and unbunched beam populations were negligible (any unbunched beam is lost during the ramp and satellite populations in the vicinity of the main bunches were measured by the experiments. ).

Despite our issues and thanks to our close collaboration with PH and the well defined context of the dedicated Van de Meer scans, we managed to achieve a performance level which is already close to the targets defined in the original LHC functional specifications for beam intensity monitoring [1].

These results are described in details in these proceedings and in 2 notes dedicated to the April-May [2] and October [3] luminosity calibration measurements.

### THE SITUATION WITH BEAM CURRENT TRANSFORMERS ELSEWHERE

We took the opportunity of this Lumi workshop to bring together at CERN BCT experts from DESY, GSI and Industry to share our experiences and results. We had many fruitful discussions on how to improve our current systems and some of these actions will be described in the following chapters. But it was also interesting to hear that:

- Similar issues have been observed in all laboratories on many different machines (lepton/hadron, linac/synchrotron)
- These instruments are still poorly understood for phenomena below the % level
- LHC experiments are quite demanding clients

- People tend to be reluctant to mention absolute accuracy as soon as they have more than one intensity monitor in the ring.

## OUR STRATEGY AND PROSPECTS FOR 2011

### Our Plans for the DC BCTs

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

- We improved the RF bypass to limit any components above 11kHz seen by the monitors
- We modified our electronics to prevent saturation in the feedback loop.
- We improved our diagnostic capability in SX4.

We repeated our tests in the laboratory with these modifications and found that they were successful in eliminating fill pattern dependence for all the patterns we can currently simulate. Fig.6 shows a summary of these tests which covers the beams we may expect in 2011/12.

$I\_mean\_batch = \#charges\_per\_bunch * elementary\_charge / bunch\_spacing$

Elementary charge [C]: 1.60E-19

I_mean_batch [mA]	Bunch spacing [ns]					
	25	50	75	150	300	
Pb min	5.60E+08	3.59	1.79	1.20	0.60	0.30
Pb max	5.60E+09	35.88	17.94	11.96	5.98	2.99
p nominal	1.15E+11	736.92	368.46	245.64	122.82	61.41
p ultimate	1.67E+11	1070.14	535.07	356.71	178.36	89.18

Fig 6: Tests performed in the laboratory for different filling patterns. Green box means successfully tested, i.e. no issues observed. Pink box means still to be tested as our current set-up is not powerful enough to simulate such patterns.

In addition, during the second half of the year, it is planned to test a new 24 bit ADC acquisition board to cover the entire dynamic range without gain switching to improve our resolution for high intensity beams in 2012.

Finally, we will continue to work in collaboration with PH on the reduction of the BCT DC scale factor uncertainty.

### Our Plans for the Fast BCTs

The situation with the fast BCTs is less favourable since the main source of errors comes from the monitor itself. Several ideas are currently under investigation to overcome this issue without replacing the monitor itself but their efficiency is still to be determined. We will therefore again have to rely on cross-calibration with the BCT DC to optimize precision during the Van de Meer scans.

In addition, a good estimation of the parasitic population (ghost, satellite, unbunched beam) will be

important and BI will commission two new instruments (the Longitudinal Density Monitor and the Wall Current Monitor) for this purpose.

### The New Players

#### The Longitudinal Density Monitor (LDM)

The LHC LDM uses the light from the Beam Synchrotron Radiation Telescopes to produce a high-dynamic-range longitudinal profile. An avalanche photodiode operated in Geiger mode detects the arrival of single photons and a time-to-digital converter is used to make a histogram of their arrival times.

Correction algorithms need to be applied to these systems (to cancel afterpulsing and adjust for the effects of the detector's deadtime) but first measurements look promising and we plan to achieve a dynamic range better than  $10^4$  with an integration time of 5-10 minutes (see Fig 5). This would be sufficient for the characterization of unbunched beam and satellite and ghost bunches. A measurement with lower dynamic range showing the length, shape and relative current of all 'main' bunches around the ring could be made in a few seconds.

Both rings will be equipped in 2011 (only beam 2 was equipped at the end of last year) and efforts are ongoing to incorporate the LDMs into our standard control system (via a FESA server) and have relevant data logged for offline studies.

#### The Wall Current Monitor (WCM)

The WCMs are acquired via fast oscilloscopes controlled by a standard FESA server. The instrument is already linked to the LHC database and should be able to provide relative population of the main bunches at 0.1 Hz whilst also providing other parameters such as bunch length.

Neither the LDM or WCM can be directly calibrated and hence both will also rely on cross-calibration via the DC BCT. It is also not clear what additional systematics and non linearities these methods introduce. We have some studies ahead of us there but the first results look promising.

### Outlook for 2011

In 2011 the DC BCT will remain our main source of absolute calibration. We will push its performance as much as we can with the current hardware and can reasonably think to reduce the absolute scale factor uncertainty below 1% in all 2011/12 physics beam conditions.

We saw during the October Van de Meer scans that we can achieve a 1% relative uncertainty between bunches with the fast BCTs but we will have to ensure this is still the case if we mix pilot and nominal bunches during the future scans.

In addition to this, the final fast BCT absolute accuracy will depend on:

- The LHC injectors' ability to deliver satellite free bunches
- A proper estimation of the ghost and unbunched beam population contributions to fast and DC measurements
- The stability of the bunch length and bunch position at the monitor

Even if all these conditions are met it will be difficult to guarantee an absolute accuracy of the fast BCT scale factor below 1% at all times. However, it should be able to achieve it on request for dedicated luminosity calibration measurements.

Finally, we will commission and assess the LDM and WCM in 2011. These instruments may play a key role in the evaluation of ghost, satellite and unbunched beam populations or even eventually become good alternatives to the fast BCT for precise bunch population measurements (albeit with much longer integration times).

## CONCLUSIONS

To conclude, we would like to take the opportunity of this workshop to thank the experiments for:

- Their unreasonable accuracy requirements and constant pressure, which significantly speeded up our progress in fully understanding our instruments.

- Their trust in our capacity to solve our issues
- Their patience
- Their help in analysing the results from our instruments. Special thanks go to the BCNWG members and in particular Carolina Gabaldon Ruiz, Gabriel Anders, Thilo Pauli and Colin Barschel for their extremely valuable analysis of our data.

Despite all the issues encountered, we are satisfied to see that the results of these luminosity calibration measurements look amazingly precise and coherent for a first year of physics and we will keep working hard to achieve even better results in 2011..

## REFERENCES

- [1] "On the Measurements of the Beam Current, Lifetime and Decay Rate in the LHC Rings." (<https://edms.cern.ch/file/359172/1.0/LHC-BCT-ES-0001-10-00.pdf>)
- [2] "LHC Bunch Current Normalisation for the April-May 2010 Luminosity Calibration Measurements" (<http://cdsweb.cern.ch/record/1325370?ln=en>).
- [3] "LHC Bunch Current Normalisation for the October 2010 Luminosity Calibration Measurements" CERN-ATS-Note to come.