THE WALL CURRENT TRANSFORMER – A NEW SENSOR FOR PRECISE BUNCH-BY-BUNCH INTENSITY MEASUREMENTS IN THE LHC

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Abstract

The Wall Current Transformer (WCT) is a new bunch-by-bunch intensity monitor developed by the CERN Beam Instrumentation Group to overcome the performance issues of commercial Fast Beam Current Transformers (FBCT) observed during Run 1 of the LHC. In the WCT the large magnetic cores commonly used in FBCTs are replaced with small RF transformers distributed around the beam pipe. Rather than directly measuring the beam current, the WCT measures the image current induced by the beam on the walls of the vacuum chamber. The image current is forced to flow through a number of screws which form the single-turn primary windings of the RF transformers. The signals of the secondary windings are combined and the resulting pulse is filtered, amplified and sent to the acquisition system. This paper presents the principle of operation of the WCT and its performance based on laboratory and beam measurements.

INTRODUCTION

During the LHC Run 1 (2008-2013) two commercial Fast Beam Current Transformers (FBCT) were installed on each LHC Ring: one used operationally and one spare used mostly for development. The bunch-by-bunch intensity measurements obtained with the FBCTs were observed to be sensitive to both the beam position at the transformer location and the bunch length [1]. This undesirable sensitivity was proven to be linked to the FBCT itself and significantly perturbed the bunch-by-bunch intensity measurements.

As an attempt to improve the situation, two new sensors were designed during the LHC Long Shutdown 1 (2013-2014) and subsequently installed for Run 2 (2015 onwards). The Integrating Current Transformer (ICT) [2], developed in collaboration with Bergoz Instrumentation, was installed on LHC Ring 1 while a Wall Current Transformer (WCT), developed by the CERN Beam Instrumentation Group, was installed on LHC Ring 2. In 2015 the two new monitors replaced the development FBCTs while the two operational FBCTs, upon which multiple intensity data users relied, were left in place to compare the three different technologies. This comparison showed that the best results were obtained with the WCT, leading to the operational systems being replaced with WCTs for the 2016 run.

The WCT design is derived from the Inductive Pick-Up (IPU) developed in 2003 at CERN for the CTF3 Drive Beam Linac [3]. Instruments applying similar ideas had also been developed in the past [4, 5]. Whilst the IPU was designed for beam position measurements, the WCT was carefully optimised for precise LHC bunch current measurements.

PRINCIPLE OF OPERATION

A simplified cross section of the WCT is shown in Fig. 1. The WCT uses small RF transformers instead of the large magnetic cores typically found in FBCTs. The transformers are mounted on internal Printed Circuit Boards (PCB) and uniformly surround the vacuum chamber. The image current is forced to flow through conducting screws connecting both sides of a dielectric insert brazed to the vacuum chamber. The screws go through the centre of each transformer to form single-turn primary windings. The secondary windings of the transformers are soldered to the PCBs and loaded with resistors of a few ohms, converting the secondary current into voltage. The signals of all RF transformers are passively combined into a single WCT output providing a signal proportional to the instantaneous beam current.

In parallel to the screws, both sides of the dielectric insert are connected by an RF bypass to provide a well-controlled image current path at frequencies above a few GHz, beyond the useful WCT bandwidth. The bypass consists of resistors and capacitors soldered to a flexible PCB that is mounted directly on the vacuum chamber.

The WCT is enclosed in a metal housing. The space between the housing and the conductive screws is filled with ferrite cores which increase the inductance of the housing as seen by the image current. This forces the low-frequency

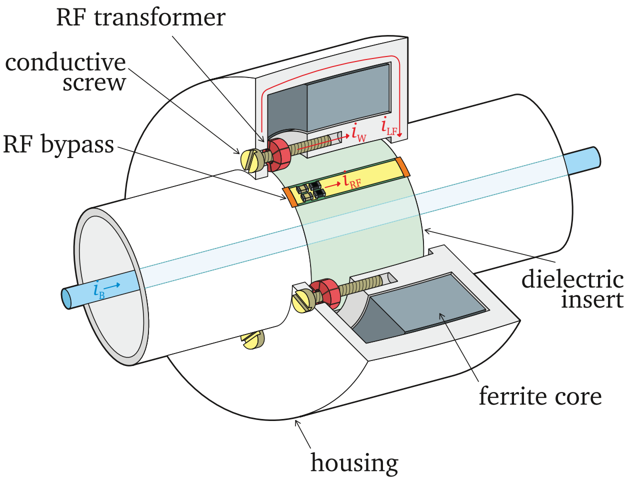

Figure 1: Cross section of the WCT.

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currents to flow through the conductive screws and improves the low frequency cut-off of the sensor by more than two orders of magnitude.

The LHC WCT was designed to be installed over the existing FBCT dielectric insert brazed to the LHC vacuum chamber. The parts establishing the low-impedance path for the image current, including the conductive screws, are made of gold-plated copper. All the other parts are made of aluminium. The WCT can be installed, removed and modified with no impact on the accelerator vacuum. All mechanical parts are split in half and can be successively assembled around the vacuum chamber. This feature made it possible to replace the two operational FBCTs with new WCTs within a day during the 2015/2016 winter shutdown.

As the LHC WCT is designed for precise absolute bunch current measurement it can be calibrated with long current pulses. Each RF transformer features an additional single-turn calibration winding connected through a series resistor to the common WCT calibration input via a passive distribution network. The individual branches of the network are designed to be decoupled from the beam signal by increasing their high-frequency impedance with lossy inductive components. This significantly reduces the level of the signal induced on the calibration winding by the passing beam which would otherwise compromise the quality of the WCT output signal.

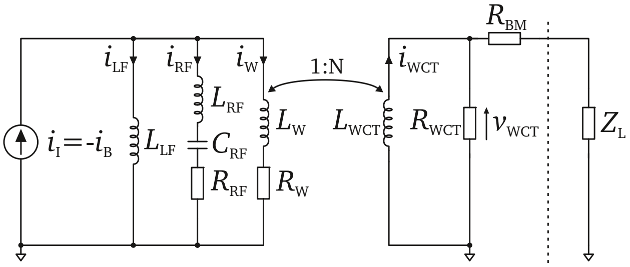

Figure 2: Electrical model of the WCT.

As shown in Fig. 2, upon arriving at the edge of the dielectric insert, the image current I_I (equal in value to the beam current I_B but with the opposite sign) can follow one of the three paths. These paths are designed to have appropriate impedances to conduct the desired frequency components of the image current. The very-low-frequency current flows through the ferrite-loaded housing L_{LF}. The high-frequency current passes through the RF bypass (L_{RF} + C_{RF} + R_{RF}) which is designed to have very low impedance at high-frequencies. The intermediate-frequency current flows through the conductive screws ($L_W + R_W$) and couples to the secondary winding of the RF transformers L_{WCT}.

Typically the LHC bunches are spaced by T_b = 25 ns. To ensure direct bunch-by-bunch measurements, with no signal leakage from one bunch to the other, the high frequency cut-off of the WCT must be greater than $1/T_b$ = 40 MHz. In practice it should be much larger to leave margin for the limited bandwidth of the acquisition chain.

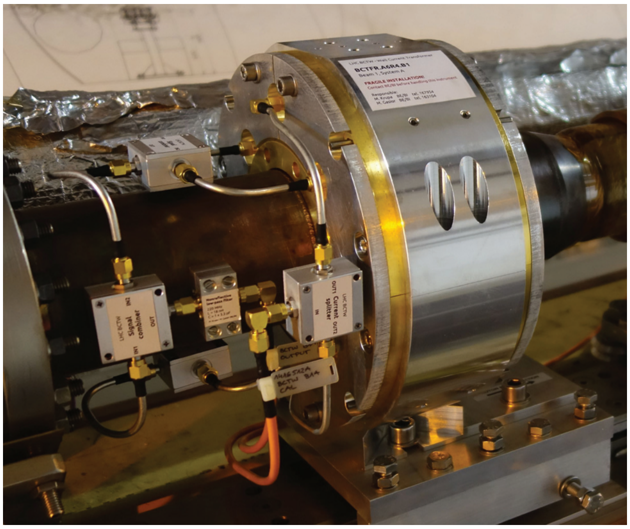

Figure 3: The WCT installed in 2016 as the operational LHC Ring 1 bunch-by-bunch intensity monitor.

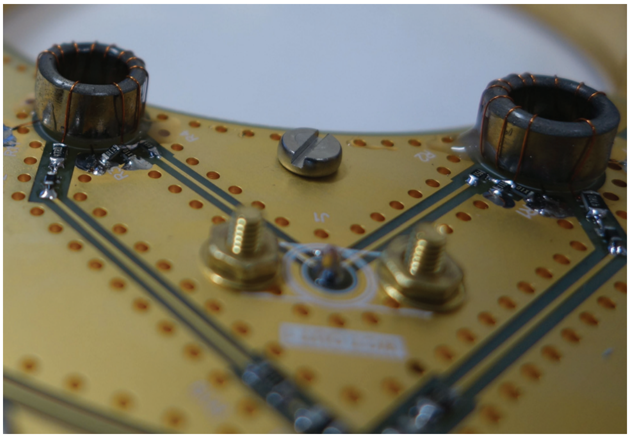

Figure 4: Two of the eight internal WCT RF transformers.

Being a transformer-based instrument, the WCT has no DC response. However, the low cut-off frequency of the WCT must be low enough that the baseline of the output signal does not drift significantly over the baseline sampling period. Currently, in the LHC, this is performed once per revolution $T_r \approx 89\,\mu s$. Therefore, the low cut-off frequency of the WCT has to be much lower than $1/T_r \approx 11$ kHz.

The LHC WCT was therefore designed in such a way to ensure that the image current components in the range from a few hundred Hz up to over 100 MHz would flow through the conductive screws (L_W + R_W).

A picture of the WCT installed in March 2016 is shown in Fig. 3 with two of its eight internal RF transformers shown in Fig. 4.

The output signal of the LHC WCT is filtered at 400 MHz directly at the output of the combiner network with a non-reflective low-pass filter built and optimised for this application. The filter lowers the peak amplitude of the output signal and stretches it to adapt it to the acquisition system. The output pulse length can be easily modified by replacing the external filter. The LHC WCT is also equipped with a front-end amplifier located approximately 1 m away from the monitor. The output signal of the amplifier is sent over some 25 m of a good quality coaxial cable to a distribution amplifier installed in the acquisition rack. Each channel of the distribution amplifier has an independently controlled gain and a bandwidth adjusted to the proceeding acquisition systems. The distribution amplifier additionally compensates the low cut-off frequency of the WCT extending the monitor's bandwidth down to 100 Hz.

LABORATORY MEASUREMENTS

The frequency response of the FBCT, ICT and WCT measured in the laboratory is shown in Fig. 5. The measurements were performed with the sensors installed on a spare LHC vacuum chamber containing a brazed dielectric insert. The chamber was used to build a 50 Ω matched coaxial setup allowing high frequency measurements to be carried out. Due to the size of the chamber, measurements at frequencies above 2 GHz were very challenging.

The FBCT and WCT were measured in two configurations: with their full bandwidth and in the actual configuration used in the LHC. The FBCT was connected to an 80 MHz filter as used during LHC Run 1 to reduce its beam position sensitivity. The LHC WCT output is filtered at 400 MHz to stretch the output pulses and limit their peak amplitude.

As seen in the measurements, the bandwidth of the FBCT extends up to 1 GHz with ±1 dB fluctuations starting at 40 MHz and a strong 18 dB notch at 450 MHz. The bandwidth of the WCT extends over 2 GHz with ±1 dB fluctuations starting at 400 MHz. The ICT bandwidth is significantly lower, having a high frequency cut-off at 100 MHz. The low cut-off frequency of all sensors is in the order of a few hundred Hz.

The longitudinal impedance of the FBCT and WCT was measured with the same coaxial setup by comparing the transmission through the setup with the sensors installed and with the sensors replaced by a shunt bypass [6].

As shown in Fig. 6 the longitudinal impedance of the WCT is much lower than that of the FBCT. For high frequencies the mechanical housing of the FBCT can be excited by the beam and can resonate. The housing of the WCT is filled with ferrite cores which are lossy at high frequencies and therefore prevent any resonant modes.

BEAM MEASUREMENTS

Beam position sensitivity of the FBCTs, ICT and WCT was determined during a dedicated beam study session in 2015 [8]. At the location of the instruments, vertical, horizontal and diagonal beam position scans were performed. Due to limitations of the LHC optics it was not possible to introduce offsets of equal amplitudes in both planes for all monitors. The beam was displaced by 1.5 mm to 3 mm. The results obtained are shown in Fig. 7 and summarised in Table 1. Both FBCTs suffered from a significant sensitivity to beam displacement, up to 8.2×10^{-3} mm^{-1} depending on the offset plane. The ICT showed a slight sensitivity to horizontal beam offsets, in the order of 0.2×10^{-3} mm^{-1} while no position sensitivity could be observed for the WCT within the measurement resolution of 0.05×10^{-3} mm^{-1}.

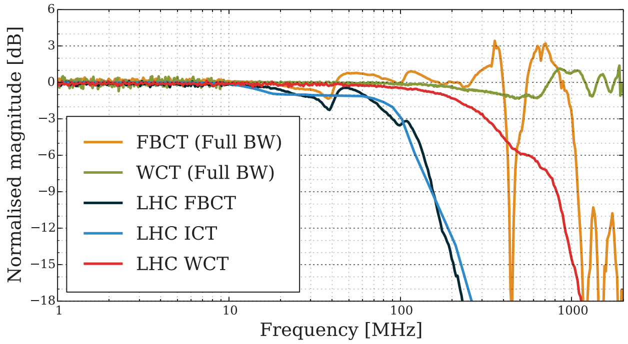

Figure 5: Laboratory measurements of the frequency response of the FBCT, ICT and WCT.

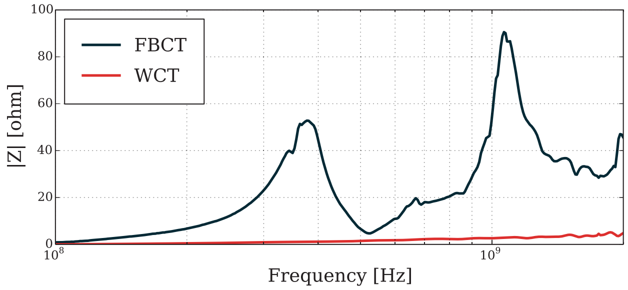

Figure 6: Laboratory measurements of the longitudinal impedance of the FBCT and WCT.

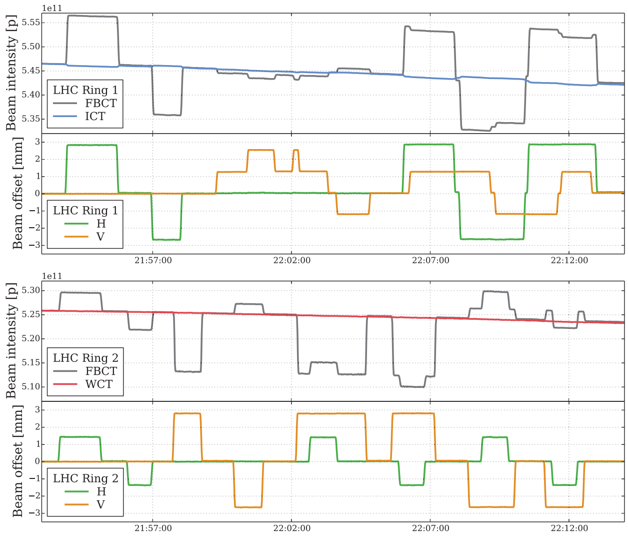

Figure 7: Beam position sensitivity of the FBCT, ICT and WCT. The intensity plots show the last 5% of the total beam intensity.

The time response of the three instruments to a single nominal bunch is shown in Fig. 8. The main pulse is 9 ns long for the ICT and 12 ns long for the FBCT when filtered at 80 MHz. In both cases the pulses are followed by tails extending to 40 ns and 50 ns, respectively. The response of the WCT is a single pulse stretched by the filters of the amplification chain to around 22 ns as required by the current acquisition system. The full-bandwidth WCT response is about 2 ns long followed by a 1 ns reflection. It should be

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Table 1: Beam position sensitivity of the LHC Ring 1 (R1) and Ring 2 (R2) FBCTs, ICT and WCT. The unit is [10^{-3} mm^{-1}], i.e. 1 in the table translates to 0.1 % change of the intensity reading for a 1 mm beam position change.

Axis	FBCT R1	FBCT R2	ICT	WCT
Horizontal	6.5	5.1	0.2	< 0.05
Vertical	1.4	8.2	0.1	< 0.05

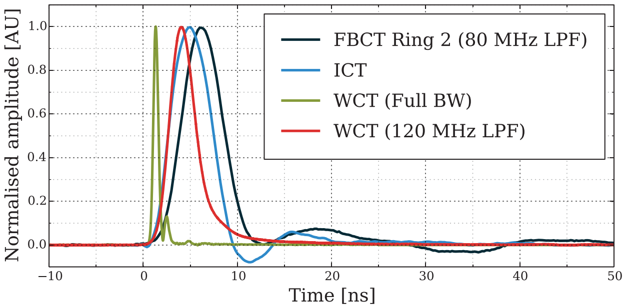

Figure 8: The response of the FBCT, ICT and WCT to a single nominal LHC bunch.

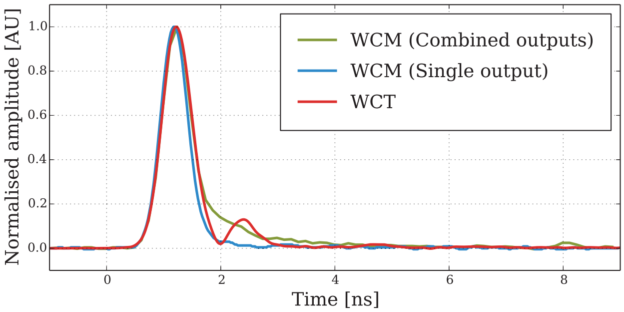

Figure 9: The response of the WCM and WCT to a single nominal LHC bunch.

noted that in case of the LHC any signal leakage outside of the 25 ns window is measured as belonging to the following bunch and compromises the measurement.

The full-bandwidth response of the WCT with beam was also compared to that of a “traditional” LHC Wall Current Monitor (WCM) [7]. The WCT and WCM output signals were acquired with a 3 GHz-bandwidth oscilloscope.

The results of measurements performed on a nominal LHC bunch with a 1 ns 4σ bunch length are shown in Fig. 9. The WCM response can be improved by using a single output and avoiding mismatches introduced through combination of all 8 of its outputs. The WCT pulse is seen to match the single output WCM response but suffers from a 15 % reflection coming 1 ns after the main signal, suspected to be caused by the internal WCT PCB signal combiners. An improvement to this would therefore be required if the WCT were also to be used for longitudinal diagnostics.

CONCLUSIONS

The LHC Wall Current Transformer is based on a relatively unknown technology which is well-suited for bunch-by-bunch intensity measurements. Due to its relatively simple mechanical design it can be installed, removed and modified with no impact on the accelerator vacuum. The WCT developed for the LHC has 400 MHz bandwidth, is optimised for the precise measurement of nanosecond bunches spaced by 25 ns and can be calibrated with long current pulses.

After a year of testing and commissioning of the new instruments, it was concluded in 2015 that the WCT was the most suitable sensor to measure bunch intensity in the LHC. During the 2015/2016 winter technical stop the two operational FBCTs were therefore replaced by WCTs. As of 2016, the WCT became the operational bunch-by-bunch intensity monitor in the LHC. Installation of the WCTs has led to a significant improvement in LHC bunch-by-bunch intensity measurements. It is the only sensor to show no measurable sensitivity to the beam position and no signal leakage outside the 25 ns window. In addition, longitudinal bunch measurements with a full-bandwidth WCT give very similar results to that of the operational LHC Wall Current Monitor.

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