A NEW INTEGRATING CURRENT TRANSFORMER FOR THE LHC

D. Belohrad, M. Krupa, P. Odier, L. Søby, CERN, Geneva, Switzerland
J. Bergoz, F. Stulle, Bergoz Instrumentation, Saint-Genis-Pouilly, France

Abstract

The existing Fast Beam Current Transformers of the LHC have been shown to exhibit both bunch length and bunch position dependency. A new Integrating Current Transformers (ICT) has therefore been developed in collaboration with Bergoz Instrumentation to address these issues. As goals a 0.1%/mm beam position dependency and 0.1% bunch length dependency were specified, along with a bandwidth of 100 MHz. This paper describes the principles of ICT operation and presents the laboratory measurement results obtained with the first prototypes at CERN.

INTRODUCTION

The present fast beam intensity measurements for the LHC rings are provided by four Fast Beam Current Transformers (FBCT), two per ring. They measure both bunch-by-bunch and total turn-by-turn beam intensities. The LHC proton bunch intensity varies from 5e9 to 1.3e11 charges with nominal bunch spacing of 25ns and up to 2808 bunches. While operational needs are covered by the present performance of the LHC FBCTs, the needs of the LHC experiments in terms of knowledge of the absolute bunch to bunch population during luminosity calibration puts more stringent demands on the intensity measurements accuracy. In addition to providing bunch by bunch intensity information, the FBCTs also send signals to the Machine Protection System (MPS), via the LHC Fast Beam Current Change Monitor (FBCCM). The FBCCM [1] calculates the magnitude of the beam intensity signal provided by the FBCT, looks for a change over specific time intervals, and triggers a beam dump interlock if losses exceed an energy-dependent threshold. The present FBCTs exhibit bunch-length and beam-position dependencies (Figure 1), which exceed the requirements for luminosity calibration and the LHC MPS. It was therefore decided to develop new intensity monitors with minimized bunch-length and beam-position dependency.

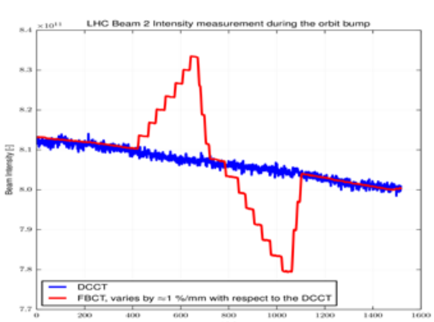

Figure 1: Beam position dependency in present LHC FBCTs with an orbit bump of ± 4mm.

PRINCIPLE OF OPERATION

The Integrating Current Transformer (ICT) and its respective read-out electronics are designed for accurate measurement of the bunch charge. To accomplish this, almost all information about the longitudinal bunch shape is sacrificed. Its working principle is based on the fact that the value of a pulse's time integral is contained in the lower end of its frequency spectrum. A precise bunch charge monitor may disregard information about the longitudinal bunch shape, which is contained in the high frequency part of the spectrum. That means, its bandwidth can be a lot narrower than the pulse spectrum.

This fundamental principle can be understood from the Fourier transform of a current pulse i(t), e.g. a particle bunch:

$$I(f) = \int_{-\infty}^{+\infty} i(t)\, e^{-i\,2\pi f\,t}\, dt \qquad (1)$$

For f = 0 we obtain:

$$I(0) = \int_{-\infty}^{+\infty} i(t)\, dt = q \qquad (2)$$

Eq. 2 proves that the value of the time integral of a current pulse i(t), i.e. its charge q, is carried by the DC component of the pulse spectrum. The ICT exploits exactly this principle, though reality is more complicated than this idealistic description.

A passive current transformer, including the ICT, can never transmit the DC component of the spectrum. In fact, any spectral content below the lower cut-off frequency is lost. The effect in time-domain is a droop, i.e. the signal amplitude drops with a certain time constant. To obtain a proper charge value, the integration time must be shorter than this time constant. Of course this implies that the output pulse length must be shorter than the time constant; speaking in frequency-domain terms the upper cut-off frequency must be sufficiently high.

A practical limit of the low frequency cut-off for the ICT has been chosen to be 500 Hz, which at LHC is sufficiently low for the Base Line Restitution (BLR) circuit to work correctly during batch injections of up to 288 bunches spaced by 25ns. The BLR corrects for any base line drifts before bunch integration.

Even though the information about the bunch charge is contained in the very low frequency components, the bandwidth of the ICT has to be wide enough to perform bunch-by-bunch measurements. In order to fulfil this requirement the ICT output pulse must settle at a steady baseline before the monitor is excited by the next bunch. The nominal bunch spacing in the LHC is 25 ns and a safe higher cut-off frequency of a bunch charge monitor was estimated to be in the order of 100 MHz.

ISBN 978-3-95450-141-0

Limiting the upper cut-off frequency and thus neglecting higher frequency components in the beam spectrum is beneficial as the beam-position and bunch-length dependent components are mainly present in that region. Moreover, as the signal frequency increases, core permeability and magnetic coupling diminish and core losses get stronger. Spurious resonances also become more likely.

Disregarding the high frequency effects mentioned above, the ICT can be described as an ideal transformer with three windings: the beam is the primary winding, the box with the integrating capacitors is the secondary winding and the wire wound on the core is the tertiary winding, see Figure 2. The two magnetic cores of the ICT, of which only one is wound, are enclosed in a box with gap that is closed by capacitors C_2. The read-out winding is terminated by a resistor R_3.

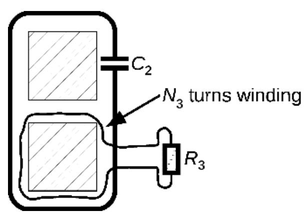

Figure 2: Cut through an ICT with an unwound core (top) and a read-out core with the read-out winding (bottom). The beam passes outside the box which encloses the cores.

Assuming that all the components of the ICT sketched in Fig. 1 are perfect and disregarding the unwound core, the voltage over the load resistor can be calculated by applying standard transformer equations:

$$U_{R3}(\omega) = -\frac{1}{N_3} I_1 \left(\frac{1}{i\,\omega\,L_3} + \frac{1}{R_3} + \frac{i\,\omega\,C_2}{N_3^2} \right)^{-1} \quad (3)$$

where I_1 is the amplitude of an incoming harmonic current, ω is the signal angular frequency and L_3 is the inductance of the read-out winding. Eq. 3 is in fact the response of a damped parallel resonant circuit.

While this equation properly describes the basic ICT functioning, it is insufficient to describe the output waveform as seen in Figure 3. At the very least the imperfect magnetic coupling of the windings should be taken into account. This can be described by inductances in series with the windings. Although their values will be very small, they do have an important influence on the output waveform, especially on resonances.

One would arrive at the same result by adding parallel capacitors to a standard transformer output. But such a design is prone to spurious resonances and position dependence. Unwound cores and capacitors over the box gap are therefore included as they modify signal propagation from the beam to the read-out winding. They help to ameliorate imperfections.

LABORATORY MEASUREMENTS

Bergoz Instrumentation delivered two ICTs to CERN in 2013, which were then thoroughly tested prior to their installation on the LHC. They are now pending beam measurements in early 2015.

Measurement Setup

The test bench used for all measurements performed by CERN, with the exception of beam position dependency measurements, was based on a 50 Ω transmission line consisting of the LHC beam pipe with a ceramic insert, an inner conductor and conical transitions maintaining the line impedance on each end of the beam pipe. The distinct difference to the actual LHC beam pipe is the lack of a thin metallisation layer on the ceramic insert in the laboratory test bench which serves as a bypass for the high-frequency end of the beam spectrum.

The ICT was excited by bunch-like pulses from custom made avalanche generators [2]. The equivalent bunch intensity delivered was in the order of a few 1e9 protons per pulse similar to an LHC pilot bunch. Although these pulses were not Gaussian and were followed by some fast decaying reflections they were believed to be a good approximation of an LHC bunch.

For each measurement, 100 ns of the test bench input and output signals as well as the ICT output response were recorded with a 12-bit, 1 GHz analogue bandwidth oscilloscope running in the Random Interleaved Sampling (RIS) mode with an equivalent sampling rate of 125 GS/s. The pulse integration, where necessary, was performed offline [3]. A satisfying signal to noise ratio was achieved by averaging, resulting in an integration precision of the order of 0.1%.

Pulse Response and Sensitivity

The pulse response of the ICT is shown in Figure 3 for a 250 mA peak current pulse of about 500 ps (one sigma length) injected into the test bench. This corresponds to a bunch consisting of approximately 2e9 protons i.e. 320 pC of electric charge. The ICT output pulse amplitude reached 220 mV yielding an ICT sensitivity of approximately 0.7 V_{peak}/nC. For the ultimate LHC bunch of 3e11 protons the ICT is therefore expected to output pulses with amplitudes exceeding 30 V.

The main output pulse is 7 ns long and followed by damped oscillations lasting some 25 ns. It was attempted to reduce the oscillations by applying different reflective and absorptive filters but no better results could be achieved.

The ICT was designed to perform precise bunch by bunch intensity measurements in the LHC where the nominal bunch spacing is 25 ns. Therefore the amount of charge leaking into the next bunch slot had to be measured and is shown in Figure 4. These integrals were obtained from the data seen in Figure 3.

ISBN 978-3-95450-141-0

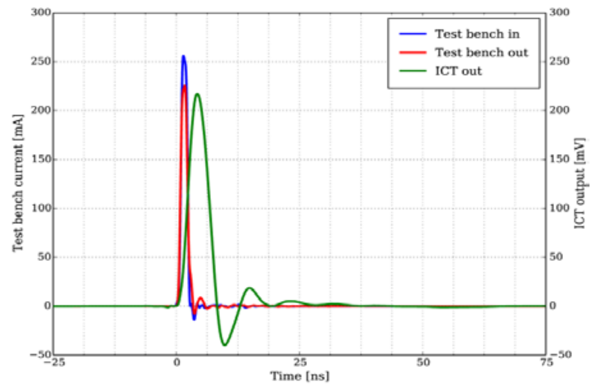

Figure 3: Time response of the ICT to an LHC bunch-like pulse.

The numbers on the top of each graph show how much of the total charge has been accumulated when looking at the first three 25 ns bunch slots. During laboratory evaluation the ICT was demonstrated to confine 98.6% of the total pulse integral within the first 25 ns slot, with the output pulse integral at 100% after 60 ns. This means that there is an influence on the two bunch slots following the main bunch slot. Nevertheless, it must be noted that the charge leakage is deterministic and can be accounted for in signal the processing.

The bandwidth of the ICT was measured to span over five decades up to 100 MHz. The lower cut-off frequency is at around 550 Hz, which translates into a droop of 0.35%/µs.

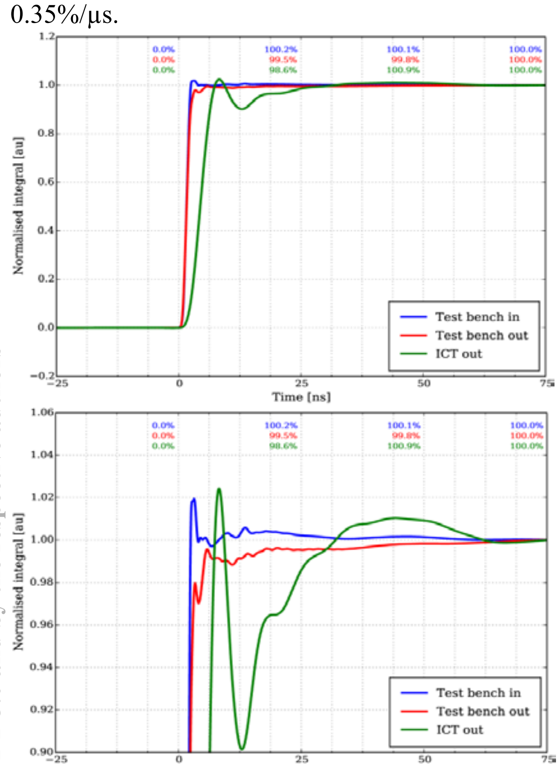

Figure 4: Normalised time integral of the ICT output pulse, with a zoom in to the region of interest in the lower plot.

Beam Position Dependency

In order to study the beam position dependency of the ICT a non-coaxial test bench of similar dimensions as the LHC beam pipe was designed and assembled at CERN. The inner conductor of the 300 Ω transmission line was off-centred by 7 mm which translated to about 20% of the beam pipe radius. The line was matched to 50 Ω on either end to minimise possible reflections. The test bench was evaluated to provide viable results up to a few 100 MHz.

To simplify the measurements the ICT orientation was fixed. The beam position dependency of the monitor was measured by radially displacing the inner conductor with respect to the monitor. This was done by rotating the antenna azimuthally in steps of 30 degrees. The signals of interest were integrated over 100 ns to account for any possible charge leakage into the following bunch slots.

The results seen in Figure 5, shows that the ICT exhibits no quantifiable beam position dependency down to the 0.1% level, the limit given by the measurement set-up, for radial displacements of up to 7mm. From Figure 5, it can also be seen that when rotating the antenna the transmission in the antenna changes, due to imperfect impedance matching.

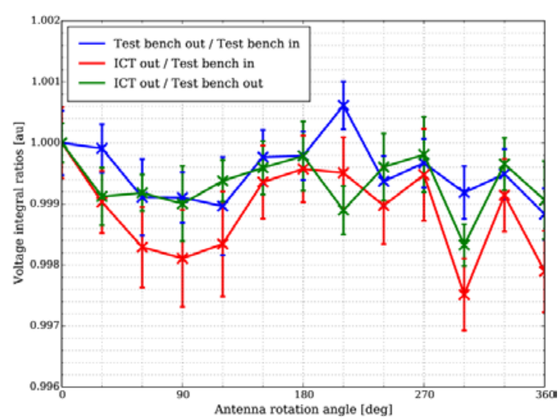

Figure 5: Measured beam position dependency.

Bunch Length Dependency

The avalanche generators used to test the system allowed the standard deviation of the pulse to be controlled with a resolution of about 50 ps. However, since they maintained their amplitude, the total pulse charge was different for each measured bunch length. Hence, in order to estimate the ICT bunch length dependency, the ratio of the ICT output integral to the transmission line output integral was computed for each tested bunch length. Similarly to the beam position dependency measurements, both integrals were obtained over 100 ns.

Pulses with standard deviations of approximately 250, 300, 350 and 500 ps were generated as input to the coaxial setup. These values were chosen to simulate the typical range of LHC bunch lengths, which during normal operation have an RMS bunch length in the order 300 ps.

The ratio of the integrals remained constant over this entire range down to the 0.1% accuracy given by the test set-up. In addition, the percentage of electric charge contained within the first 25 ns of the ICT output pulse was not observed to be influenced by the pulse length. The charge leakage into the following bunch slots is therefore believed to be independent of the bunch length.

CONCLUSIONS AND OUTLOOK

Two ICTs manufactured by Bergoz Instrumentation were installed in the LHC in June 2014, and are pending measurements with beam by beginning of 2015. The new design, which has been optimized to reduce beam position and bunch length dependency on the measured intensities, is based on filtering frequencies above 100 MHz before the signal reaches the magnetic readout toroid. Laboratory tests have shown very promising results, with less than 0.1%/mm beam position dependency, and 0.1% bunch length dependency. The charge leakage from one bunch slot to the next is slightly higher than desired and will need to be corrected for.

ACKNOWLEDGMENT

The authors would like to thank M. Gasior for his input to the discussions and his invaluable help in the design of the test circuit.

REFERENCES

[1] J. Belleman, D. Belohrad, L. Jensen, M. Krupa, A. Topaloudis, "The LHC Fast Beam Current Change Monitor", WEPF29, IBIC 2013, Oxford, UK, Sept 2013.
[2] M. Krupa and M. Gasior "Application of Avalanche Generators in Laboratory Measurements", MIXDES 2014, Lublin, Poland, June 2014, http://www.mixdes.org
[3] M. Krupa and M. Gasior "Precise Digital Integration of Fast Analogue Signals Using a 12-bit Oscilloscope", IBIC 2014, these proceedings.

ISBN 978-3-95450-141-0