Prototype of an Integrating Current Transformer for Beam Intensity Measurements in the Large Hadron Collider

Michal Krupa*†, and Andrzej Napieralski†, *Senior Member, IEEE*

***Abstract*—The beam intensity (number of particles forming the beam) in the Large Hadron Collider (LHC) is measured by eight current transformers. The average beam current is monitored by the four DC Current Transformers (DCCTs) and the range from a few hundred hertz to over a gigahertz is covered by the four Fast Beam Current Transformers (FBCTs). During the early run of the LHC the beam intensity measured by the FBCTs was observed to be correlated to the beam position and charge distribution. To address the consequential limitations a prototype of an Integrating Current Transformer (ICT) has been developed at CERN as a possible future replacement of the FBCTs. In this article, its design, principle of operation along with results of first beam tests are presented. The measured beam-position-dependency of the ICT has been improved, compared to the FBCT, by a factor of 35 and 50 in the vertical and horizontal planes, respectively.**

***Index Terms*—Beam diagnostics, beam intensity measurements, Integrating Current Transformer (ICT), Fast Beam Current Transformer (FBCT).**

I. INTRODUCTION

PROTONS making up the two beams of the Large Hadron Collider (LHC) travel at speeds remarkably close to the speed of light. The particles of each beam are grouped in packets called bunches that form a bunch train sketched, along with the typical LHC time values, in Figure 1. Similarly to other sources, in this article it is assumed that the distribution of the electric charge of a bunch follows the Gaussian curve in the plane of motion with the standard deviation σ_b delimiting the bunch length.

The LHC beams typically circulate in the beam pipes for several hours before they are removed from the machine. This cyclicity allows the beam parameters to be monitored on different timescales, most commonly bunch-by-bunch, revolution-by-revolution and longer periods. In the first mode each individual bunch is treated independently, in the second one changes to the whole beam are considered, whilst in the last one longer time scales are taken into account.

The charged particles in motion constitute an electric current called the beam current. The average current of the nominal LHC beam, consisting of 2808 bunches with 1.15×10^{11} protons each, is in the order of hundreds of milliamperes with instantaneous peaks reaching tens of amperes. However, in some beam patterns the number of particles per bunch can be as low as 5×10^9 resulting in much smaller currents. [1]

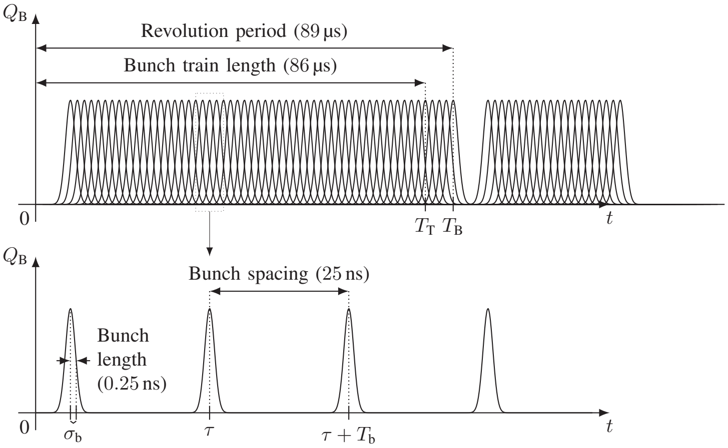

Fig. 1. Typical time structure of an LHC beam (not to scale)

The LHC beam intensity is measured with Beam Current Transformers (BCTs). These toroidal transformers are installed over a dielectric insert in the conducting beam line. The BCTs are enclosed in low-resistance housings connected to each end of the insert with RF contacts. In such configuration the beam is seen by the transformer as a single turn primary winding.

The BCTs measure the beam intensity indirectly by providing the value of the beam current which then can be integrated over time τ yielding the beam charge:

$$Q_\mathrm{B} = \int_0^\tau i_\mathrm{B} \cdot \mathrm{d}t \qquad (1)$$

The number of particles the transformer sees in the time τ is derived by dividing the integrated charge by the elementary charge:

$$N_\mathrm{p} = \frac{Q_\mathrm{B}}{q} \qquad (2)$$

Four DC Current Transformers (DCCTs) and four Fast Beam Current Transformers (FBCTs) are installed on the LHC to measure the beam intensity. Each of the two beam pipes is equipped with two BCTs of each kind. The first monitor serves as the main device with the second monitor being redundant.

The four DCCTs measure the average beam current which is not visible to any other transformer-based monitor. The DC component is obtained by maintaining multiple toroidal cores of the monitor in the zero-magnetic-flux operation region [2].

The four FBCTs monitor higher-frequency components of the beam current. They are similar to a typical current

---

*CERN, Geneva, Switzerland, email: michal.krupa@cern.ch
†Department of Microelectronics and Computer Science, Lodz University of Technology, Lodz, Poland

transformer and were designed to provide bunch-by-bunch and revolution-by-revolution beam intensity information with accuracy better than 1 % for the nominal beam [3].

The Beam Instrumentation (BI) group of CERN extensively tested the FBCTs in 2010 and 2011. The monitors were observed to not be utterly bunch-length- and beam-position-independent [4]. A detailed analysis linked both issues to the magnetic toroids used in the FBCTs.

Due to the vast importance of precise and reliable beam intensity measurements, it was decided that a prototype of an Integrating Current Transformer (ICT) would be built and tested as a possible replacement of the FBCTs [5]. The ICT is expected to be less beam beam-position- and bunch-length-dependent than the FBCT.

II. INTEGRATING CURRENT TRANSFORMER

The ICT was designed at CERN for the Large Electron-Positron Collider (LEP) in 1989. Since then it has been used in many electron machines where bunches are typically a few-picoseconds-long and spaced by hundreds of nanoseconds [6].

The ICT is composed of two toroidal magnetic cores enclosed in a common copper shell with a non-conductive slit sketched in Figure 2. Some capacitors can be distributed over the slit influencing the capacitance of the shell. The secondary winding is installed over one of the toroid and loaded with a load impedance. A low-pass filter connects the monitor to the acquisition system.

The ICT significantly limits the frequency spectrum of the primary winding current, often by several orders of magnitude. When the particles pass through the monitor an equal but opposite charge ($Q_{\mathrm{ICT}} = -Q_{\mathrm{B}}$) is induced on the copper shell and stored by its capacitance. As the shell discharges, being loaded by the enclosed magnetic cores, the flowing electric current is seen by the toroid as a single turn primary winding [7]. The spectrum of this current, however, is narrower than the spectrum of the beam current and can be influenced by the shell capacitance and properties of the magnetic cores.

A simplified electrical model of the ICT has been developed [7], [8] and is shown in Figure 3, where:

- the current source I_{B} models the beam,
- capacitor C_{s} models the capacitance of the shell,
- inductors L_1 and L_2 model the inductance of the unwound and wound core, respectively,
- resistors R_{11} and R_{22} model the losses of the unwound and wound core, respectively,
- inductors L_{11} and L_{22} model the leakage inductance of the unwound and wound core, respectively,
- impedance Z'_{L} models the equivalent load impedance.

The model is a band-pass filter. Its corner frequencies can be influenced, by changing the value of the shell capacitance C_{s}, parameters of the cores, or the load impedance.

The low frequency cut-off of the ICT depends on the parameters of the magnetic cores and the load impedance. At low frequencies the impedance of the wound core $Z_{\mathrm{L2}} = \omega L_2$ is much smaller than the equivalent load impedance Z'_{L}. The output voltage signal V_{ICT} decreases by 3 dB when $Z_{\mathrm{L2}} = Z'_{\mathrm{L}}$. Hence the low cut-off frequency f_{low} on the ICT might be approximated by:

$$f_{\mathrm{low}} \approx \frac{Z'_{\mathrm{L}}}{2\pi \cdot L_2} \tag{3}$$

Both Z'_{L} and L_2 can be tuned with the number of secondary winding turns. Also, the core inductance L_2 depends directly on the permeability of the magnetic material.

During the tests, the simplified model did not to reflect the high frequency behaviour of the monitor very accurately. However, the high cut-off frequency can be roughly estimated assuming that the leakage inductance is small and the equivalent load impedance is much lower than the core losses:

$$f_{\mathrm{high}} \approx \frac{1}{2\pi \cdot C_{\mathrm{s}} \cdot R_{11}} \tag{4}$$

Obtaining reliable values for the core losses is very difficult, hence the optimal shell capacitance for a given configuration is usually an outcome of a number of iterations.

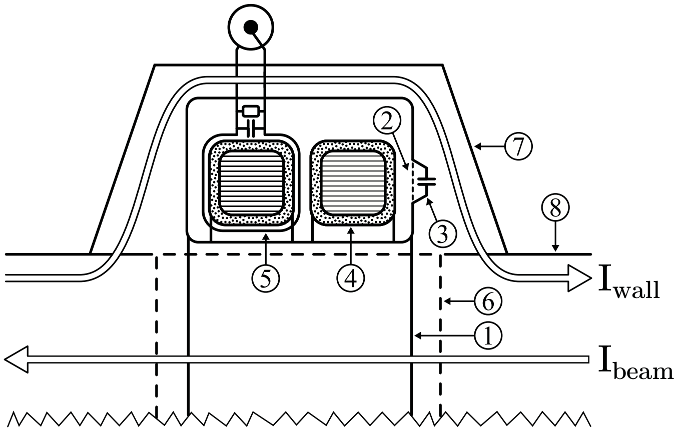

Fig. 2. ICT cross-section: 1 - Capacitive shell, 2 - Dielectric slit, 3 - Shell capacitors, 4 - Magnetic core, 5 - Winding with termination, 6 - Vacuum-tight ceramic insert, 7 - External enclosure, 8 - Beam pipe

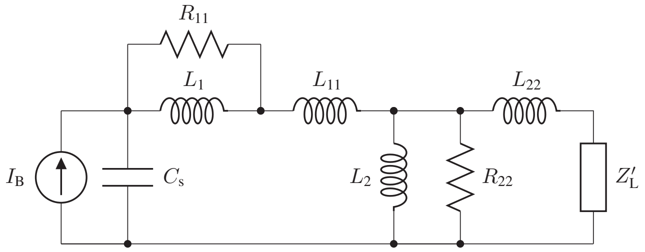

Fig. 3. Simplified electrical model of the ICT.

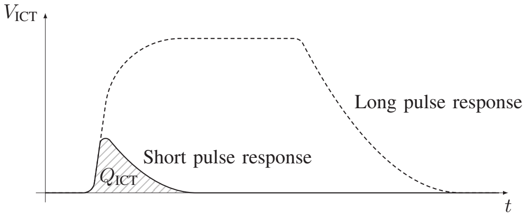

Fig. 4. Output signal of the ICT.

Both corner frequencies of a useful ICT should be minimised. A small low cut-off frequency reduces the drift of the output signal baseline. On the other hand, a small high cut-off frequency relaxes the requirements for the acquisition chain as well as limits beam-position-dependency of the device. A properly tuned ICT should work in the "short pulse response" mode shown in Figure 4, stretching the output pulse just enough not to leak into the following pulse. If the bunches exciting the ICT are always much shorter than the resulting output pulse, the length of the ICT output pulse is approximately constant. The ICT voltage measured with the acquisition electronics is proportional to the beam current. Hence, the ICT charge Q_{ICT} which was initially stored in the shell capacitance can be computed as:

$$Q_{\mathrm{ICT}} = \frac{1}{Z_{\mathrm{L}}} \cdot \int_{0}^{\tau} V_{\mathrm{ICT}}\,(t)\,\mathrm{d}t \tag{5}$$

III. ICT PROTOTYPE

Early LHC ICT work was carried out in the CERN BI group resulting in an ICT device measured with LHC beams in 2012. The work described in this article is the outcome of studies started in July 2012 resulting in an ICT prototype installed in the LHC in late 2012 and tested with beam during the first two months of 2013. The prototype was installed over a short technical stop during a regular operation period of the LHC. This imposed several mechanical constraints on the device.

The developed prototype ICT is shown in Figure 5. The prototype was cut in half to allow installation on the LHC without breaking the vacuum. Installing BCTs on the LHC typically requires breaking the vacuum, sliding the device onto its final location, followed by restoring the vacuum. Due to extremely pure vacuum (at the level of 10^{-8} Pa) this process typically takes up to several days and is scheduled well in advance.

The developed prototype uses two very high-permeability magnetic cores supplied by an external company. Halving the cores reduced their permeability by a factor of 10 to $\mu_{\mathrm{r,10kHz}} \approx 10^4$ and significantly increased their losses and leakage inductance.

A secondary 6-turn winding was installed on one of the cores. The cutting plane and mechanics aligning the split cores limited the winding to about a third of the core's circumference. The winding was loaded with $2.7\,\Omega$ placed directly on the core. The optimal shell capacitance was found to be extremely low. No additional capacitors were placed over the dielectric gap and only its self capacitance of $7\,\mathrm{pF}$ was used.

Some high frequency resonances in the output signal were attenuated with a good quality non-reflective low-pass filter tuned to $200\,\mathrm{MHz}$. The filter was connected directly to the ICT's output port. Its measured reflection coefficient did not exceed $-20\,\mathrm{dB}$ up to $1\,\mathrm{GHz}$.

A coaxial test-bench closely copying the real LHC vacuum chamber with the ceramic insert was used to measure the frequency characteristic of the prototype. In order to maintain the $50\,\Omega$ impedance domain, two conical transitions from 80-millimetre-wide vacuum chamber to the N connectors were added at both ends.

TABLE I
DESIRED PARAMETERS OF THE ICT

Parameter	Desired value
Sensitivity	$3\,\mathrm{V}$ / 3×10^{11} charges
Beam position dependency	$0.1\,\%\,\mathrm{mm}^{-1}$
Bunch length dependency	$0.1\,\%\,\mathrm{ns}^{-1}$
Output pulse duration (6σ)	$< 25\,\mathrm{ns}$
Input dynamic range	5×10^9 to 3×10^{11} charges
Resolution	1×10^9 charges
Accuracy	1×10^9 charges

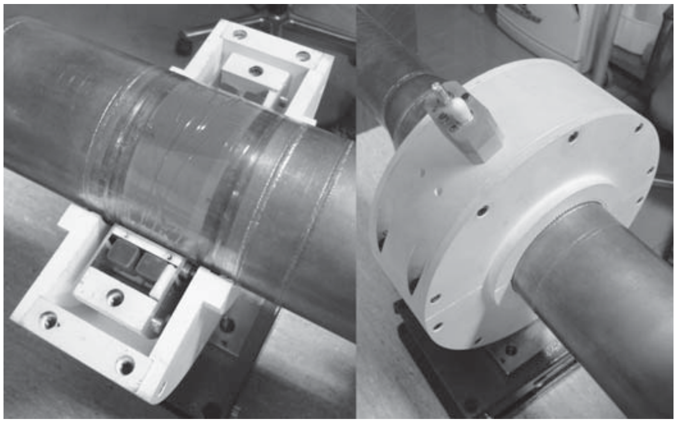

Fig. 5. The prototype ICT

The prototype was tested in the range from $100\,\mathrm{Hz}$ to $200\,\mathrm{MHz}$. The measured magnitude of the frequency characteristic is shown in Figure 6. The $3\,\mathrm{dB}$ bandwidth spans from $4\,\mathrm{kHz}$ to $40\,\mathrm{MHz}$ with $42\,\mathrm{dB}$ attenuation in the passband. Some high-frequency resonances were observed and partially mitigated by the low-pass filter.

Cutting the cores had a negative effect on both corner frequencies of the ICT. The low cut-off frequency is inversely proportional to the inductance of the wound core, i.e. its permeability. Decreasing permeability by 10, increased the low cut-off frequency by the same factor. On the other hand, small core losses and leakage inductance are essential for the high frequency behaviour of the ICT. Increasing them, decreased the high cut-off frequency. It is also believed that cutting the cores contributed to the high frequency resonances.

The same coaxial test-bench was used also for the time domain measurements. The prototype was excited by a trapezoidal pulse of $3.9\,\mathrm{ns}$ FWHM and $1.9\,\mathrm{ns}$ slopes. The measured response is shown in Figure 7.

The output pulse stretches over $27\,\mathrm{ns}$. Most of the visible high-frequency oscillations were attenuated by the low-pass filter. The reflected pulse at $25\,\mathrm{ns}$ after the original pulse is believed to come from the mismatch between the ICT and the $50\,\Omega$ cables used to transmit the output signal but more research is needed to fully understand it.

Beam-position-dependency of the prototype was measured with LHC beam in February 2013 with give bunches of very low intensity spaced by several microseconds.

The measured intensity signal was integrated every full LHC revolution period of 89 µs, then averaged in the acquisition chain each second and stored.

The beam was off-centred independently in both axes from -2.5 to 2.5 mm with 0.25 mm steps.

Beam-position-dependency of the ICT and the FBCT is compared in Figure 8. The ICT showed a great improvement to the FBCT. The dependency has been improved from $0.73\,\%\,\mathrm{mm}^{-1}$ to $0.02\,\%\,\mathrm{mm}^{-1}$ in the vertical plane and from $0.51\,\%\,\mathrm{mm}^{-1}$ to below $0.01\,\%\,\mathrm{mm}^{-1}$ in the horizontal plane.

IV. CONCLUSIONS AND FUTURE WORK

The ICT prototype developed in late 2012 and tested with beam in the beginning of 2013 showed promising results in terms of beam-position-dependency. Closed LHC vacuum resulting in some mechanical constraints contributed to some significant limitations of the monitor's performance. Another prototype using uncut cores is expected to perform much better.

Beam intensity measurements in the LHC require the bandwidth of a useful ICT to be wider than achieved so far. A low cut-off frequency at the level of 400 Hz and high cut-off frequency at the level of 100 MHz are needed for compatibility with the presently used acquisition systems. Experience with the prototype shows initially that the low frequency requirement can be met by using uncut high-permeability cores. However, additional research is needed to fully understand the high frequency behaviour of the ICT.

At the moment, studies focus on a precise electromagnetic computer model of the ICT to broaden the understanding of the device. Also, different winding and loading techniques are being investigated to mitigate the leakage inductance and mismatching.

ACKNOWLEDGMENTS

The authors are grateful to Silvia Aguilera, William Andreazza, Jerome Belleman, David Belohrad, Marek Gasior, Patrick Odier, and Lars Soby of CERN for their insightful contribution to the project. They would also like to acknowledge Bergoz Instrumentation for sharing their experimental knowledge of the ICT technology.

REFERENCES

[1] O. S. Bruning, P. Collier, P. Lebrun, S. Myers, R. Ostojic, J. Poole, and P. Proudlock, *LHC Design Report*. Geneva: CERN, 2004.

[2] P. Odier, M. Ludwig, and S. Thoulet, "The DCCT for the LHC Beam Intensity Measurement," CERN, Geneva, Tech. Rep. CERN-BE-2009-019, May 2009.

[3] D. Belohrad and P. Kaspar, "Fast Beam Intensity Measurements for the LHC," Ph.D. dissertation, Prague U., 2010, presented on 05 Oct 2010.

[4] P. Odier, D. Belohrad, J. J. Gras, and M. Ludwig, "Operational Experience and Improvements of the LHC Beam Current Transformers," *Conf. Proc.*, vol. C11-05-16.4, no. CERN-BE-2011-015, May 2011.

[5] J. J. Gras, D. Belohrad, M. Ludwig, P. Odier, and C. Barschel, "Optimization of the LHC beam current transformers for accurate luminosity determination," no. CERN-ATS-2011-063, Sep 2011.

[6] Bergoz Instrumentation, "Integrating CT & Beam Charge Monitor," March 2013. [Online]. Available: http://www.bergoz.com/

[7] K. B. Unser, "Design and preliminary tests of a beam intensity monitor for LEP," no. CERN-LEP-BI-89-07, Mar 1989.

[8] L. Vos, "The LEP monitor for the measurement of bunch intensity," CERN, Geneva, Tech. Rep. CERN-SL-94-18-BI, Jun 1994.

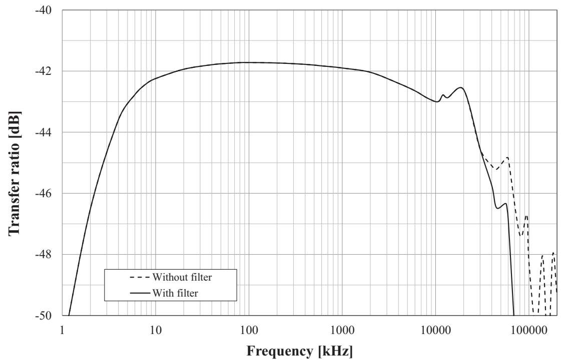

Fig. 6. ICT prototype frequency characteristic

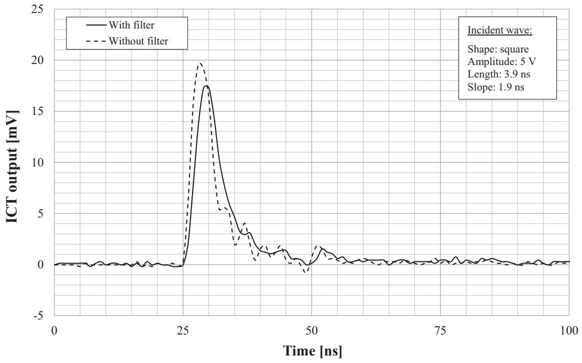

Fig. 7. ICT prototype transfer function

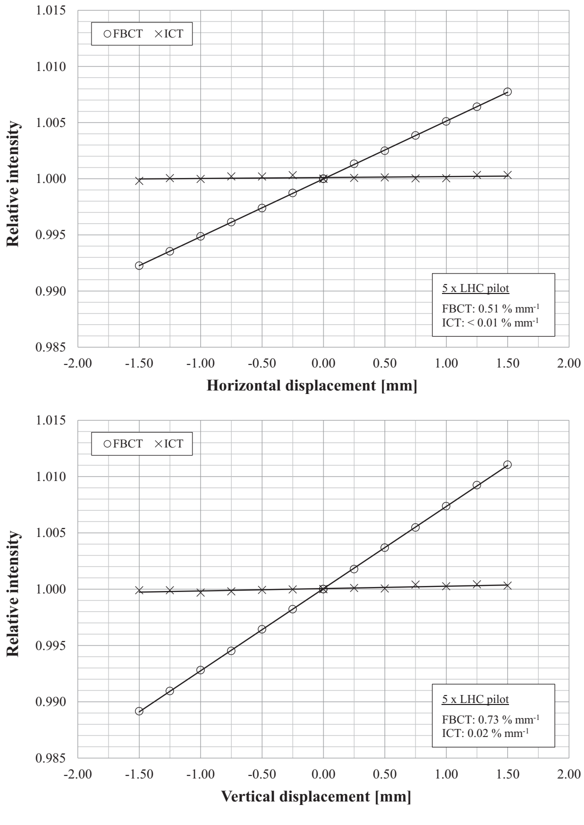

Fig. 8. ICT prototype beam-position-dependency

Michal Krupa is a graduate student at the Department of Microelectronics and Computer Science of the Lodz University of Technology, Poland. Since 2010 he has been working at CERN, Switzerland with the Beam Instrumentation group on beam current and position measurement systems. He received the B.Sc. degree in February 2012 for a study of an acquisition chain for a beam position monitoring system for one of CERN's accelerators. Currently, he is developing new devices for precise fast beam intensity measurements in the Large Hadron Collider.

Andrzej Napieralski received the M.Sc. and Ph.D. degrees from the Lodz University of Technology (TUL) in 1973 and 1977, respectively, and a D.Sc. degree in electronics from the Warsaw University of Technology (Poland) and in microelectronics from the Universit de Paul Sabati (France) in 1989. Since 1996 he has been the Director of the Department of Microelectronics and Computer Science. Between 2002 and 2008 he held a position of the Vice-President of TUL. He is an author or co-author of over 920 publications and editor of 20 conference proceedings and 12 scientific Journals. He supervised 48 PhD theses; six of them received the price of the Prime Minister of Poland. In 2008 he received the Degree of Honorary Doctor of Yaroslaw the Wise Novgorod State University (Russia).