

UPGRADE OF THE CERN PSB/CPS FAST INTENSITY MEASUREMENTS

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Abstract

The CERN Proton Synchrotron Booster (PSB) and Proton Synchrotron (CPS) complex fast intensity measurement is undergoing a major upgrade. The old analogue electronics no longer provides enough accuracy, resolution and versatility to perform accurate beam intensity measurements. It has also become less reliable due to the ageing equipment. A new measurement system - Transformer Integrator Card (TRIC) - replaces these obsolete acquisition systems. TRIC is a generic platform used to measure the intensity in different transfer lines at CERN.

Five TRICs were installed during the year 2010 in order to evaluate their performance with different beam types, from the low intensity pilot (5×10^9 charges per bunch) to high intensity beams (1×10^{13} charges per bunch). The aim of this article is to present the technical aspects of the new system and the different measurement scenarios. It discusses possible sources of measurement errors and presents some statistical data acquired during this period.

INTRODUCTION

The Transformer Integrator Card (TRIC) has been designed to replace the obsolete analogue integrators used to acquire the beam intensity from the Fast Beam Current Transformers (FBCT) in the PSB and CPS [1].

The TRIC is an acquisition system equipped with two analogue inputs having switchable attenuators; sampled at 200 MHz. Together with on-board calibrators the TRIC serves as a universal measurement platform for the Fast Beam Intensity Measurements (FBCT). It is realised in a VME64x 6U form-factor card. The advanced beam signal processing as well as remote programmability is assured by on-board Altera CycloneII series FPGA.

The on-board calibrator offers a precise calibration pulses generated by either constant current source or by discharging a high precision capacitor into the FBCT through a calibration turn. Two calibration measurement types are provided:

- **Online calibration:** sending and acquiring a calibration pulse after each measurement acquisition.
- **Offline calibration:** using fixed calibration constant, obtained by long term averaging of online calibration.

In order to assure a smooth transition to the TRIC system, both original and new system were running in parallel from August to December 2010, at the CERN PSB ejection transfer lines, when the old electronics was finally dismantled.

MEASUREMENT ALGORITHMS

The TRIC provides the beam intensity by means of a numerical integration. Due to the different user requirements the TRIC provides the intensity measurement using four different integrators (Fig. 1) and a mathematical unit to generate a calibration constant and calculate the total intensity.

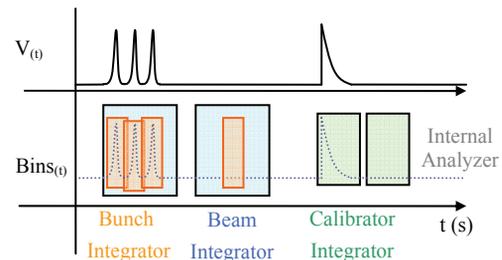


Figure 1: Integrator methods supported by TRIC.

The **Beam** and **Calibrator Integrators** are equipped with two measurement gates, one measuring the beam or calibration, the other to measure the offset. The offset measurement suppresses the DC signal component generated by the amplifiers and the ADC. It also compensates the transformer droop

The second type of integrator is the **Bunch Integrator**. This integrator consists of a set of 32 gates that can be positioned independently (series, parallel, partially overlapping) to acquire the intensity bunch by bunch.

The **Internal Analyzer** is an integrator with 1024 consecutive integration gates of programmable width. This integrator allows observing the incoming signals together with the status of all the integrators. This permits the instrument expert to set up the integrators remotely with high precision and visualize beam signals of long duration e.g. Linac beams.

The **Normaliser** is a state machine that uses the results of the beam and calibration integrator, together with the calibration parameters, to calculate the total intensity measured by the TRIC.

Combining all these elements together with an expert GUI, the TRIC system offer:

- Total intensity measurement.
- Bunch by bunch measurement.
- Beam Shape together with integrator status (Fig. 2).
- Remote settings and diagnostics.

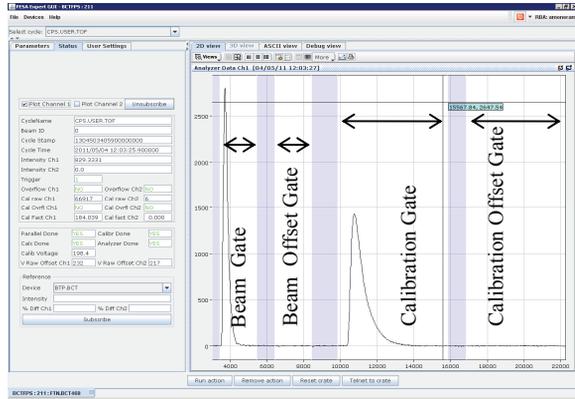


Figure 2: Expert GUI used for remote settings and diagnostics.

precision to less than 0.1 %. For this reason the offline calibration is often used when the calibration signal to noise ratio is low.

In order to maximise the usage of the TRIC ADC dynamic range it was decided to change the attenuation of the currently used passive input attenuators from 0, 20 and 40 dB to 0, 14 and 28 dB.

TRIC MEASUREMENT ERROR

This article discusses only the measurement errors caused by the TRIC. The errors due to external sources (e.g. EM interference) are ignored. The following components are addressed:

- Calibration error
- Acquisition error
- Calculation error

Calibration Error in Calibration by Charge

In this case, a known capacitor gets discharged through the calibration turn of the FBCT.

$$Np = \frac{V \cdot C}{e} \tag{Eq. 2}$$

MEASUREMENT RESULTS

During the transition period in 2010, the TRICs in the PSB-ISOLDE transfer line was monitored to analyze their performance. However, because the original electronics was found improperly calibrated with respect to the DCCTs, it was decided to evaluate only the closeness of the FBCT measurement to the DCCT:

$$C_{FBCT,DCCT} = stdev \left(100 \cdot \frac{DCCT - FBCT}{DCCT} \right), \tag{Eq. 1}$$

where $C_{FBCT,DCCT}$ represents a precision of a FBCT to DCCT measurement closeness.

Table 1: Closeness Measurement over one Thousands Measurement

Measurement System	$C_{FBCT1,DCCT}$	$C_{FBCT2,DCCT}$
Original System	0.362 %	0.14 %
TRIC	0.65 %	1.16 %
Online Calibration		
TRIC	0.074 %	0.189 %
Offline Calibration		

Table 1 summarises the results of one thousand beam measurements performed by both TRIC and analogue electronics. The measurement results show good agreement between the original electronics and the TRIC. Using an online calibration a TRIC precision better than 1 % can be assumed from the fact, that the $C_{FBCT,DCCT}$ lower than 1 % is a combination of DCCT and FBCT precision. Offline calibration improves the assumed

Here V is the calibration voltage (limited from 10 to 200 V) which is acquired by a 12-bit ADC (ADC_{HV}) through a resistor network. C is a 10 nF high precision capacitor and e the elementary charge. The charges stored in the capacitor are discharged into the FBCT and acquired with the calibration integrator. The charge calibrator permits to send calibration pulses from 62.4×10^{10} to 1248×10^{10} charges (0.1 to 2 μC).

Due to the tolerance of resistors and capacitors (1 %) and ADC_{HV} non-linearity (2 %), the calibration method has a type-B uncertainty (through error propagation [2]) of approximately 2.7 % (Fig. 3).

In order to reduce the error, some modifications have been done: The resistors have been replaced by 0.1 % ones, the ADC_{HV} voltage offset is removed and its acquisition is averaged by firmware to reduce the measurement noise. A calibration uncertainty of ~ 1.2 % in the range of 10 to 200 V has been obtained (Fig. 3).

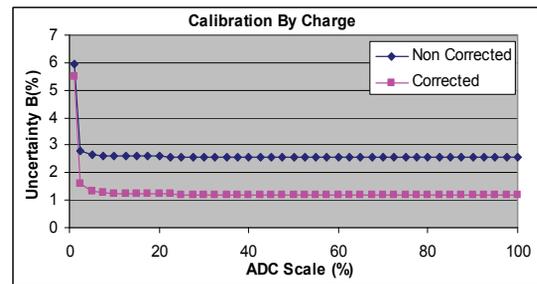


Figure 3: Relative type-B uncertainty of the generated charge plotted with respect to ADC_{HV} dynamic range.

Calibration Error in Calibration by Current

In case of the current calibrator, a constant current of 2 mA to 2 A can be sent to the calibration turn. Equivalent number of charges can be determined as:

$$Np = \frac{I \cdot t}{e}, \quad (\text{Eq. 3})$$

where I is the amplitude of the current sent to the transformer, t the duration of the pulse and e the elementary charge.

In current calibration mode, the errors are generated by the ADC (ADC₁), the shunt resistor used to measure the current, and the clock jitter. The latter can be ignored due to the low ADC clock jitter (20 ppm).

As in calibration by charge, the calibration by current electronics has been updated replacing the resistors by high precision ones (0.1 %). FPGA firmware was also updated to remove the generated current offset, and thus improving the uncertainty and the usable dynamic range of the ADC₁ (Fig. 4).

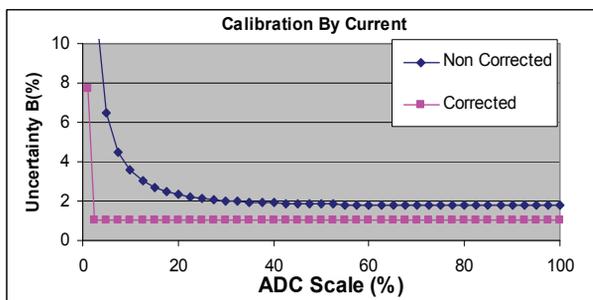


Figure 4: Relative type-B uncertainty of the generated current pulse plotted with respect to ADC₁ dynamic range.

Acquisition Error

The on-board calibrator permits to compensate gain and attenuation variations in the transmission lines. At the same time, the integration and acquisition algorithm compensates for any DC offset and minimises the white noise. The major error sources are the ADC non-linearity and quantisation error. For this, the acquisition error is estimated to be between 0.3 to 0.7 % in the working region (10 to 100 %) as is shown in Fig. 5.

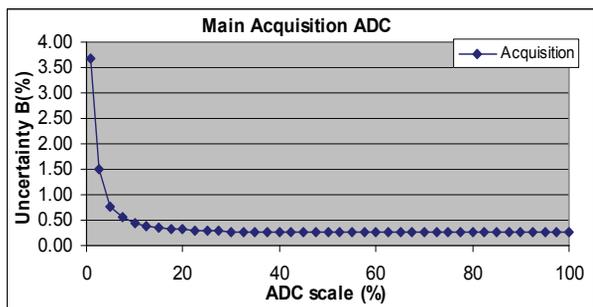


Figure 5 : Relative type-B uncertainty of the acquisition.

Calculation Error

Like in other digital measurement devices, the precision of the calculations is limited by the number of bits and format of the variables used during the numerical operations. In case of the TRIC, the order of operations, size of variables and units have been chosen to keep the resolution below 2×10^6 charges.

TRIC Cross Calibration

Combining the calibration and measurement errors, the uncertainty obtained ranges from 1.2 to 1.5 %. In order to go below this error, it has been decided to calibrate the TRIC calibrators.

Due to the lack of instrumentation with high dynamic range and measurement error below 1 %, it is hard to calibrate below the obtained error. For this purpose it was decided to cross calibrate using one TRIC calibrator (TRIC_{ref}) to calibrate all the others.

The cross calibration procedure starts by sending a series of calibration pulses from TRIC_{ref} to the analogue inputs of the other cards. The measurement results are then averaged in each channel and later on averaged with all the other TRICs (Eq. 4). The result of the averaging is the number of charges sent by TRIC_{ref} but with a lower uncertainty (Eq. 5). This value is used to calibrate the other TRICs.

$$\overline{Np}_{ref} = \frac{\sum_1^n (\overline{Ch1} + \overline{Ch2})}{2 \cdot n} \quad (\text{Eq. 4}) \quad Error_{ref} = \frac{Error_{TRIC}}{\sqrt{2 \cdot n}} \quad (\text{Eq. 5})$$

These results are stored in a database where each TRIC has its calibration constant together with its serial number. This information is later on used by the TRICs to minimize the measurement error.

CONCLUSIONS

With the new modifications done in hardware, firmware, software and cross calibration, the TRIC is achieving a relative calibration pulse uncertainty below 1 % in both calibration methods. Together with the expert GUI, this system is much easier to maintain than the original electronics.

TRIC has become the new standard for beam intensity measurement in the PSB and CPS transfer lines, with 14 units currently installed between PSB and PS, and more than thirty units expected to be installed for LINAC3, LINAC4, AD and LEIR.

REFERENCES

- [1] Kasprovicz, G. "Beam intensity measurement system for proton synchrotron booster", Proc. SPIE 6347, 63470F, 2006.
- [2] Belohrad, D. "The Fast Intensity Measurements for the LHC", doctoral thesis, CERN, Genève, Switzerland 2010