UPGRADE OF THE FAST BEAM INTENSITY MEASUREMENT SYSTEM FOR THE CERN PS COMPLEX

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Abstract

The CERN Proton Synchrotron complex (CPS) has been operational for over 50 years. During this time the Fast Beam Current Transformers (FBCTs) have only been repaired when they ceased to function, or individually modified to cope with new requests. This strategy resulted in a large variation of designs, making their maintenance difficult and limiting the precision with which comparisons could be made between transformers for the measurement of beam intensity transmission. During the first long shutdown of the CERN LHC and its injectors (LS1) these systems have undergone a major consolidation, with detectors and acquisition electronics upgraded to provide a uniform measurement system throughout the PS complex. This paper discusses the solutions used and analyses the first beam measurement results.

INTRODUCTION

The CERN PS complex is a chain of accelerators producing accelerated beams for the Super Proton Synchrotron (SPS), and subsequently for the Large Hadron Collider (LHC). In addition it delivers a wide range of particle beams to the secondary experimental areas.

The complex (Fig. 2) is comprised of the proton and the heavy ion linear accelerators ($LINAC_{II}$, $LINAC_{III}$), the Proton Synchrotron Booster (PSB) and the Proton Synchrotron (PS). Transfer lines transport the beams from the CPS accelerators to the appropriate targets (e.g. the On-Line Isotope Mass Separator ISOLDE), to the experimental areas (e.g. the Antiproton Decelerator AD), and for further acceleration to the SPS.

The transfer of particle beams nearly always involves some beam loss which has to be minimised. The beam transfer efficiency is calculated from the measured beam intensities at various locations in the accelerator complex. The beam intensity measurement in the CPS transfer lines is provided by the FBCTs, as shown in Fig. 2.

The FBCTs were installed during the construction of the accelerator chain and they were only repaired or modified when they ceased to function, or to cope with new requests. This resulted in a large variety of FBCTs designs, acquisition techniques and calibration methods. This state of affairs limited the accuracy of the transfer efficiency estimate to no better than 5%.

In 2010 the CPS FBCTs were equipped with new acquisition systems. The originally used analogue integrators were replaced by digital signal processing [1]. This improved the calculation accuracy of the transfer efficiency to $\approx 2\%$. A further improvement could be only achieved by upgrading the FBCTs and their calibration methods.

During LS1, a major upgrade of the FBCTs for the PS complex was therefore performed. Twelve out of 21 old FBCTs measuring the bunched beams at the PSB extraction were replaced (the red boxes in Fig 2), with the remaining FBCTs foreseen to be upgraded during LS2 in 2018.

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MECHANICAL CONSTRUCTION

The FBCT Toroid

The major issue associated with the design of the new FBCT for the PS complex was the choice of the measurement toroid. From past experience, it was known that the currently used toroids provided a beam position dependent signal which adversely affected the absolute accuracy of the intensity measurement. A collaboration was set up with Bergoz Instrumentation to design a toroid mitigating this problem. An iterative design process resulted in the fabrication of a new type of large-aperture toroid (210 mm) having an imperceptible beam position dependence. To achieve this the toroid's measurement bandwidth had to be lowered from the usual GHz range to 120 MHz. This 120 MHz bandwidth is sufficient to provide the bunch to bunch transfer line beam intensity measurements (droop $\approx$0.25%/μs) for the beams with bunch spacing greater than 100 ns. Using this toroid to measure the beams with bunch spacing of 25 ns (the LHC beams) requires further signal treatment

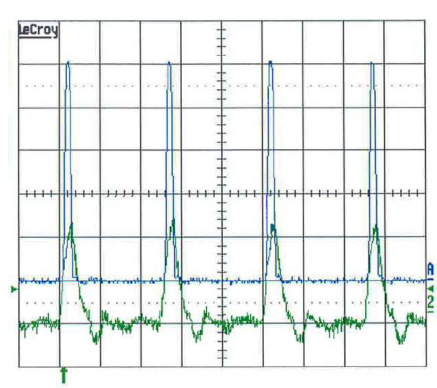

Figure 1: The impulse response of the 1:40 FBCT toroid. The blue trace shows the input signal fed through an antenna. The green trace shows the toroid output signal. The time scale is 10 ns/div.

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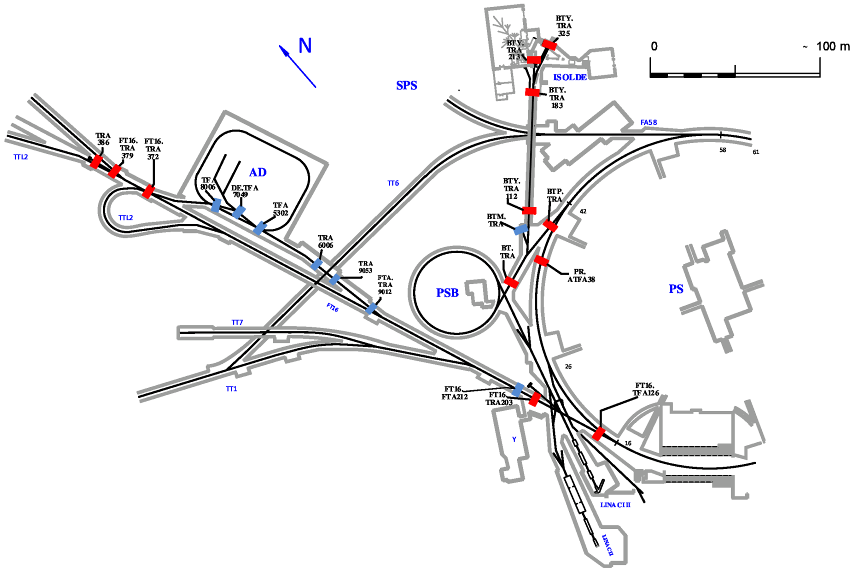

Figure 2: The FBCTs in the CERN PS complex. Twelve FBCTs have been upgraded during the LS1 (shown as the red boxes), the remaining FBCTs will be upgraded during the LS2 (shown as the blue boxes).

in the digital domain as the toroid's output signal transient extends beyond 25 ns (Fig. 1).

The FBCT Housing

The complete FBCT assembly is shown in Fig. 3. The toroid (orange) and the calibration turn (dark blue) are housed in two magnetic shieldings. Each shielding is made of two 1 mm thick μMetal sheets rolled and forged to form a shell. To restore the shielding efficiency, the μMetal was thermally treated for 1 hour at 1080 °C and naturally cooled. Both shieldings are separated by fibre glass spacers (green) to maintain their respective positions. The spacers also improve the mechanical stability of the assembly.

The shielding and the toroid assembly are inserted into the outer shell (brown) which serves as a mechanical housing. The shell is fabricated from the pure iron, commercially known as Armco. The shell provides a well-defined, low-impedance path for the beam induced wall image current. An excellent electrical contact between the body parts and the vacuum chamber is achieved by plating the Armco with a 25 μm layer of silver. The Armco's high magnetic saturation (2.15 T) and permeability (μ_r = 300-500) provide an additional layer of magnetic protection. The initial permeability can be further increased by thermal treatment (μ_r = 3500 - 6000). Hence the FBCT housing was thermally treated for 1 hour at 870 °C and cooled down in a furnace at 100°C per hour.

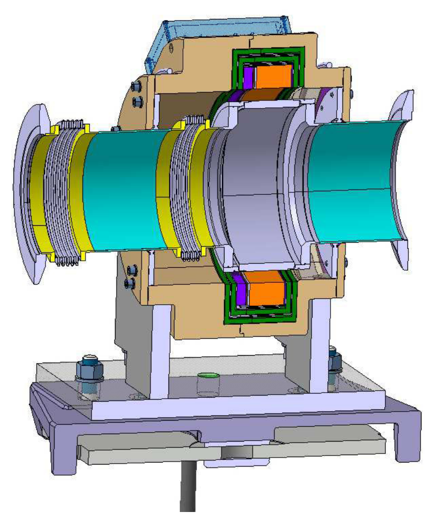

Figure 3: The CATIA model of the FBCT. The toroid is shown in the orange colour.

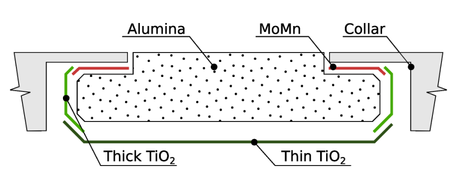

Figure 4: The cross-section of the ceramics showing the deposited layers.

The Vacuum Chamber

The FBCT body is installed over the vacuum chamber. The design of the vacuum chamber differs for the various installation locations, but the ceramics-bellow assembly inside the cavity of the FBCT is always present (Fig 3). This ceramic insert forces the wall image current to flow through the Armco body making the magnetic field of the particle beam to be visible to the toroid. The bellow internal to the housing relaxes the transversal forces applied to the ceramic,

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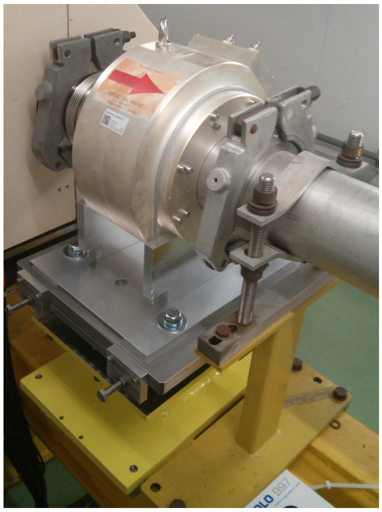

Figure 5: The upgraded FBCT BTY.TRA183.

while the presence of the bellow outside the FBCT cavity depends of the surrounding equipment in the PS complex.

The ceramic insert is composed of two copper collars and a 98% pure alumina ring (Al_2O_3, Fig. 4). The ceramic's extremities were factory covered by a Molybdenum-Manganese coating, which was sintered onto the Alumina surface. This provided a metal contact layer for the brazing of the collars, which were fabricated from OFE copper. Kovar could not be used, as simulations performed using the Maxwell code showed that the magnetic properties of Kovar could induce a significant magnetic coupling with magnetic fields external to the toroid.

To ensure that there was no electrostatic charge build-up on the ceramics, a titanium (Ti) coating with a resistance of 20-25 Ω end-to-end was deposited on the inside surface. The resistance value chosen was a compromise between reducing the ringing of the FBCT signal and not causing too much attenuation.

Due to technological limitations the assembly had to be constructed in three steps. First a thick Ti layer was deposited on the sides of the ceramic (resistivity of ≈2 Ω). The collars were then brazed in a second step, and the final resistivity was achieved by depositing a thin Ti layer of ≈20 Ω. Further oxidation of the deposited layer in air then causes an increase of the total stable layer resistance to the final 20-25 Ω.

One of the FBCTs, assembled and installed in the CPS, is shown in Fig. 5 (corresponding to BTY.TRA183 shown in Fig. 2).

ANALOGUE-FRONT END AND ACQUISITION SYSTEM

To maximise the signal to noise ratio (SNR) of the FBCT signal, there is an analogue front-end installed in the vicinity of each FBCT[1]. This consists of a 6 dB resistive splitter and an amplifier. One of the splitter outputs is fed directly into the acquisition system and provides a low-gain measurement. The other is amplified (G = 30 dB) to provide high-gain measurements. The bandwidth of this channel is limited to 18 MHz due to the operational amplifiers used. The amplifier and the splitter are implemented on a single PCB using commercially available components with current feedback amplifiers (THS3001) used to achieve the required amplification.

The analogue signals are transported to the acquisition systems outside the accelerator tunnels, using 7/8" foam-filled non-corrugated coaxial cables The cable type chosen ensures a minimum signal loss over the cable length, which for some FBCTs exceeds 400 m.

The FBCT acquisition system uses the 6U VME form-factor Transformer Integrator Card (TRIC) [1] to sample the analogue signals, compare them to the calibration signals, and compute the total beam charge. The TRIC is equipped with two 100 MSPS ADCs providing two independent acquisition channels. These are connected to the high and low gain signals coming from the front-end electronics through additional 3 MHz low-pass filters. The filters extend the width of the raw signals (σ = 1 - 5 ns) so they can be sampled using a 100 MHz sampling system, and still allow bunch to bunch measurements for the beams spaced by 100 ns or more.

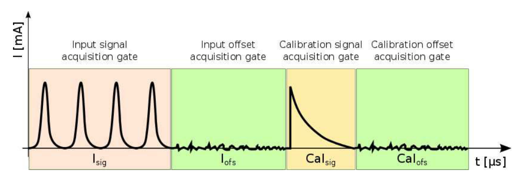

Figure 6: The TRIC sampling windows.

The total beam charge is calculated in the TRIC using measurements from four independent acquisition windows as shown in Fig. 6. The simple sum of all the samples within each window is used to estimate the integral in the measured intervals. The four intervals correspond to the beam signal, its offset without beam, the calibration signal and its associated offset. The measured offsets are subtracted from the measured beam and calibration signals to improve the immunity from low-frequency signal fluctuations and FBCT droop. The total measured charge is calculated using following equation:

$$N_q = \frac{I_{sig} - I_{ofs}}{Cal_{sig} - Cal_{ofs}} \cdot Cal_q, \qquad (1)$$

where the $I_{[sig,ofs]}$ and the $Cal_{[sig,ofs]}$ are the integrals of the respective intervals shown in Fig. 6, and Cal_q corresponds to the charge generated by a calibrator.

As the PS complex provides beams differing in number of bunches, amplitudes and intensities, all the TRIC window gates have to be set-up separately for each beam.

[1] Except for the ISOLDE FBCTs due to too high ambient radiation damaging the electronics.

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CALIBRATION

The absolute accuracy of the measurement is primarily determined by the absolute accuracy of the calibrator and the coupling of the FBCT calibration turn to the FBCT measurement winding.

The FBCT calibrator forms an integral part of the TRIC. To calibrate the FBCTs, the TRIC charges a capacitor to a known voltage and then discharges it into the FBCT calibration winding to provide a reference calibration signal Cal_{sig}.

This calibration method was preferred over a pulsed current source generator due to its simplicity. The absolute accuracy of the calibrator is mainly determined by the quality of the capacitor used and the precise knowledge of its capacitance and the applied voltage.

The FBCT calibration turn is formed using 8 parallel single-turn windings distributed equidistantly over the toroid circumference. The windings are connected together using a set of resistors so that the entire structure looks like a single 50 Ω terminated calibration turn when measured at the SMA connector. The structure is manufactured on a single PCB and is installed on the side of the toroid (Fig. 7) to minimise the mechanical forces applied to the resistors.

Figure 7: The installed calibration winding.

In order to further improve the accuracy of the transfer efficiency measurements, the TRICs in the PS complex were cross-calibrated. This was done in the laboratory during the reception testing of the TRICs. One master TRIC was used to generate a calibration signal, which was consecutively injected into all the tested TRICs as a measured signal. The tested TRICs used their on-board calibrators to estimate the injected calibration signal intensity as if it was the beam signal. If the calibrators of all the TRICs were the same, there would be no difference seen in the calculated intensities. However, due to the accuracy of the calibrators, the measurement results differ. Sixteen fabricated TRICs showed a difference ranging from -3.07% to 1.2% (σ=1.14%) with respect to the mean value calculated over the entire batch.

The calculated differences were used to correct the calibration factors by multiplying Cal_q in Eq. (1) by a correction factor, so that the measurements of the injected calibration signals for all TRICs were equal.

The authors acknowledge that the presented cross-calibration method requires improvements, since it requires the testing of all cards at once. This is difficult when the TRICs are already installed in the CPS. A study is currently ongoing to see how a DC current source could be used to independently cross-calibrate the TRICs.

SOFTWARE DESIGN

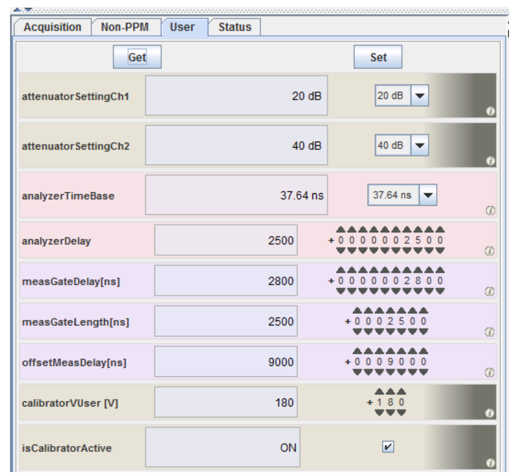

Figure 8: Screen-shot from expert application provided to control settings specific to one selected cycle.

The control system at CERN uses the concept of "devices" whereby the name of any given BCT device is derived from the specific beam-line, its type and position. As an example of this convention BTY.BCT183 measures the total intensity in number of charges in the BTY transfer-line from the PSB to ISOLDE (Fig. 2). The real-time software maps a physical BCT detector to one controls device through one TRIC module. This simplifies the integration in the control system. Two real-time (RT) actions are used for the acquisition:

1. "Prepare" which sets up the TRIC modules with the next acquisition and calibration parameters. The timing event is chosen such that the execution of the RT action finishes safely before the external fast trigger to launch the acquisition arrives. Typical execution times per controls device is of the order of a 1 ms. The operational settings are split into two categories:
   (a) Cycle specific settings, examples of which can be seen in Fig. 8, and typically involve the attenuation for each of the two channels and the measurement gate delay and duration.
   (b) Cycle independent settings, such as those for the calibrator.
2. "Acquire" which checks that the acquisition has completed and then reads the values from the different acquisition modes. The data is normalised using the acquired offset and gain values. The internal analyser

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(Fig. 10) is used for verifying that the settings are correct, i.e. that the gates are correctly set-up with respect to the beam and that the ADC is not saturated.

FIRST MEASUREMENT RESULTS

The upgrade of the CPS FBCTs started in August 2013 with the last FBCT installed in April 2014. They were then tested without beam using measurements of noise in the machine. This permitted the complete acquisition chain to be verified, as the input signal, including the calibration pulse, could be displayed. Such a measurement for the low-gain signal inputs is shown in Fig. 9. The histogram depicts the data published to the CERN control system and to the logging databases.

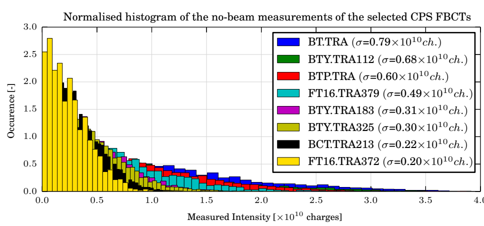

Figure 9: The normalised histogram of the low-gain channel noise measurements of the selected FBCTs installed in the PS complex.

The first beam measurements were taken in mid-2014, when the PSB re-started. The integrating gates had to be correctly set up for all the FBCTs and all different beam types, as shown e.g. in Fig. 10 for the BTY.TRA325. The picture shows a beam well fitted into the signal measurement gate, followed by the signal offset measurement gate, the calibration pulse gate and the corresponding calibration offset gate.

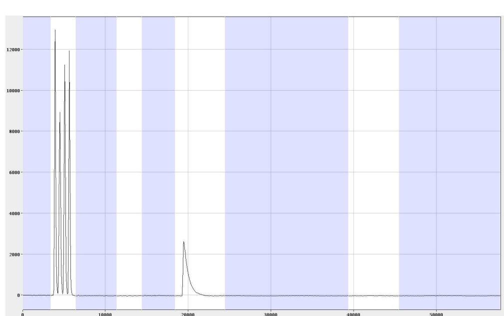

Figure 10: The correctly set up FBCT measurement for the ISOLDE BTY.TRA325. The four measurement gates (white background) identify the regions where the beam signal, its offset, calibration signal and the calibration offset are measured. The picture shows the measurement of the 4 bunches extracted from the PSB to the ISOLDE (Fig. 2). Even when using 3 MHz low-pass filter the four individual bunches can be clearly identified.

During the commissioning, it was found that some of the FBCTs diverge from the optimal behaviour shown in Fig. 10. Such an example, the measurement of BTY.TRA213, is depicted in Fig. 11. The figure shows a low-frequency fluctuation of the baseline, resulting in a deterioration of the absolute accuracy. This issue is currently being investigated, but is believed to originate from an electro-magnetic coupling of the FBCT to the dipole magnet installed nearby (< 20cm).

The long-term drift shown in Fig. 11 cannot be suppressed using the offset subtraction due to the ratio of the drift period and the measurement gate lengths. However, as this is a systematic effect, it can be suppressed using additional signal treatment in the digital domain. An algorithm subtracting the low-frequency baseline drifts is currently being tested in the CERN LINAC$_4$ and if it works, it will added to the PS complex intensity measurements.

Figure 11: A low-frequency fluctuation of the base line in the BTY.TRA213.

SUMMARY

As the CERN injector complex re-starts after the long shutdown, the newly installed fast beam current transformers are currently being set-up for the different types of accelerated beams. First measurements indicate that the systems are fully functional, but additional tuning will, however, be required to achieve optimal measurement accuracy. This mainly concerns the FBCTs installed in the vicinity of magnets, as these magnets induce low-frequency baseline drifts that are not effectively suppressed by the currently used base-line restoration algorithm. The method for cross-calibration of the individual TRIC acquisition boards, to maintain a relative accuracy between transformers at the 1also has to be improved. Following the success of this consolidation, the remaining transformers are now foreseen to be upgraded during Long Shutdown 2 in 2018, which will result in a standardised installation of FBCTs throughout the injector complex.

REFERENCES

[1] A. Monera et al., "Upgrade of the CERN PSB/CPS Fast Intensity Measurements", DIPAC 2011, Hamburg, Germany

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