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BCM SYSTEM OPTIMIZATION FOR ESS BEAM COMMISSIONING THROUGH THE DTL TANK 4

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Abstract

The ESS BCM system is not only used for beam measurement but it also plays an important role for machine protection particularly in the normal-conducting part of the linac. During the previous beam commissionings to the MEBT and DTL1 FCs and before the cavities were fully conditioned, RF breakdowns and other types of discharges in the cavities had a major impact on beam availability due to the Fast machine protection functions of the BCM. Following an investigation on the root cause of the beam trips, the configuration of the machine protection functions was modified to improve beam availability in the more recent beam commissioning to the DTL4 FC. In addition to this, some optimizations were made in the BCM system to improve beam measurement, and a few more functions were added based on new requirements. This paper reports on these improvements and the results obtained during the beam commissioning through the DTL4.

INTRODUCTION

The ESS Beam Current Monitor (BCM) system includes in total nineteen AC Current Transformers (ACCTs) and one Fast Current Transformer (FCT) which are all from Bergoz. Ten of these ACCTs are installed in the normal conducting part of the linac that extends from the Ion Source (ISrc) to the Drift Tube Linac (DTL) tank 5. These sensors overall allow beam measurement at the interface between a section and the following one, and after the temporary beam dumps in the Low Energy Beam Transport (LEBT) and Medium Energy Beam Transport (MEBT) sections. The other nine ACCTs will be installed in the Linac Warm Units (LWUs) in between the cryomodules in the Medium Beta Linac (MBL), High Beta Linac (HBL), High Energy Beam Transport (HEBT) and in the Accelerator To Target (A2T) and Dump Line (DmpL) sections.

The analogue signal form each ACCT is buffered and amplified by a wall-mount Front End (FE) module from Bergoz, and then filtered and further processed in a custom designed Back End (BE) unit in the BCM rack. The signal is then converted to digital and FPGA processed by a Struck SIS8300-KU board in a mTCA crate. The digital signal processing includes baseline restoration, droop compensation, digital filtering, post mortem data buffering as well as a complete suite of machine protection functions that are tailored to meet the ESS beam and machine requirements. Part of these functions are used to measure the amplitude, width and repetition frequency of the beam pulse and send a beam abort request to the Fast Beam Interlock System (FBIS) within 1 µs if the measured values exceed their thresholds. The BCM firmware configures the machine protection functions including the levels and activation/deactivation of the thresholds based on a beam mode and a beam destination ID that are distributed over the ESS network before starting with beam. Time windows for the expected beam pulses from the ISrc and LEBT/MEBT choppers are generated by the BCM firmware using some events which are distributed by the ESS Timing System (TS) over an optical fibre network at well-defined times before the arrival of each pulse. These time windows are then used for measuring the beam properties including average beam current over a region of interest and pulse length/charge. The BCM firmware also checks the exact timing of the TS events for any inconsistency with the selected beam mode due to possible bugs in the timing tables, human errors etc. This feature has proven to be very useful to avoid potential damages due to ex. a wrong trigger length/frequency resulting in excessive beam power on a temporary beam dump. Other protection functions include differential beam interlocks with several BCM pairs, errant beam detection and BCM internal checks [1].

Each ACCT includes a calibration winding that is used not only to calibrate the sensor but also to test and verify the system with a test pulse from a waveform generator before starting with beam. A Wetest script is used to sweep the pulse amplitude, width and frequency in multiple steps from a minimum to a maximum, and in each step the full signal chain from the sensor up to the EPICS Process Variables (PVs) including all the protection functions are automatically tested and verified.

BEAM COMMISSIONINGS THROUGH THE LEBT, MEBT AND DTL TANK 1

With the start of the beam commissioning through the LEBT (Sep. 2018) and MEBT (Nov. 2021) [2], a large number of beam trips were initiated by the BCM system and in particular the errant beam interlock. An investigation then showed that part of the trips was due to Electro Magnetic Interference (EMI) issues caused by the safety relay (i.e. ground relay), High Voltage Power Supply (HVPS) and the high power contactors of the ISrc. The issue was then resolved by improving the groundings of both the ISrc cage and the electronics racks, reinforcing the shielding and grounding of the ISrc/LEBT BCM FEs, additional EMI filters, surge protectors, analogue filters on the HVPS current/voltage readouts and digital processing in the BCM FPGA. The tests also showed that a broken insulator around a LEBT repeller ring resulted in some sparks and these occasionally caused some large spikes on the LEBT BCM readout thus adding to the beam trips. The

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repeller was then repaired through a LEBT intervention and that fixed the issue with the sparks, but an uncareful reassembly of the LEBT components then resulted in some broken connectors as well as a short circuit through the LEBT BCM sensor by a thermocouple cable, and these rendered this BCM temporarily non-operational. The broken connectors were then replaced and the short-circuit was removed through another LEBT intervention. With the start of the beam commissioning through the DTL tank 1 (June 2022), a large number of spikes showed up on the DTL1 BCM readout and these had a major impact on beam availability. In order to better analyse the beam trips, a Post Mortem (PM) function was then added to the BCM firmware. This includes a configurable ring buffer that keeps the most recent BCM data with a sample rate of 88 MSPS from all the channels, and freezes the buffer contents as soon as the Beam Permit is changed to NOK. For the spike analysis, the buffer size was set to 1.1 GB that is equivalent to 1 s of BCM data (i.e. 400 ms before plus 600 ms after a beam trip). The PM data analysis then showed a correlation between the spikes and the DTL RF/vacuum levels, but the root causes of the spikes were understood and the issue was resolved only after the start of the following beam commissioning through the DTL tank 4.

BEAM COMMISSIONING THROUGH THE DTL TANK 4

In April 2023 with the start of the DTL tanks 1-4 RF conditioning activities, spikes were frequently observed with the DTL BCMs and in particular tank 2, but fewer spikes were observed in the tank 1 compared to the previous beam run in June 2022. A thorough investigation on the root cause of the spikes then showed the followings:

1. The inner surface of the DTL tanks emits electrons when it is subject to the RF pulse. These electrons travel a short distance after they exit from both the beam entrance and the beam exit ports of the tanks. Part of the electrons reach the BCM sensors which are installed in between each two tanks and that results in a small spike of max 0.2 mA on the BCM readout.
2. Two small spikes of typically -0.3 mA are observed on the Radio Frequency Quadrupole (RFQ) BCM readout at the rising and falling edges of the RF pulse due to multipacting.
3. The rising edge of the ISrc beam pulse results in a small spike of +0.6 mA approximately on the LEBT BCM readout.
4. RF breakdowns and other types of discharges in the cavities result in large spikes on the DTL BCM readouts. These spikes can easily hit the machine protection thresholds and cause beam trips by the BCM and the RF Local Protection System (LPS).
5. RF and vacuum breakdowns in the MEBT buncher 3 cavity can cause spikes with an amplitude of a few tens of mA on the MEBT BCM 2. The spikes start showing up when the buncher 3 voltage goes above ~130 kV.
6. An RF breakdown in a DTL tank induces a current in the BCM calibration windings. In the ISrc to DTL tank 2 sections, calibration windings of seven BCM sensors are connected in series, and the induced current can cause beam trips by the LEBT, RFQ and MEBT BCMs as well even if the protection functions of the DTL BCMs are disabled.

The investigation confirmed that most of the spikes listed above are directly linked to RF and vacuum, and they become less frequent with cavity conditioning. The spikes of type 1-3 are overall very small and do not cause an issue. Figure 1 shows a beam pulse with an amplitude of 4.5 mA and width of 50 µs that is measured by all the BCMs from the LEBT to the DTL tank 4. The differences in the pulse amplitude (beam loss), the small spikes on the RFQ BCM readout (multipacting) and the baseline variations due to the secondary particles from the DTL1-3 are visible in the plot.

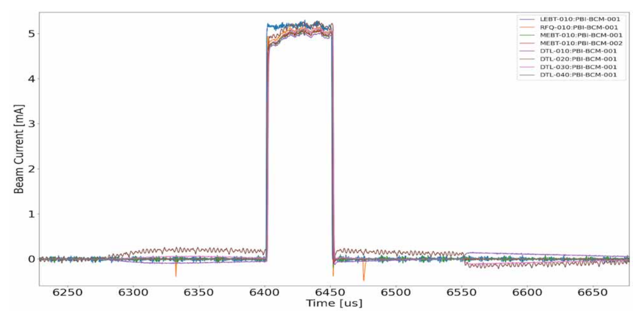

Figure 1: A low current beam pulse that is measured by eight BCMs from the LEBT to the DTL tank 4.

In order to improve the beam availability due to the spike types 4-5, following an assessment by a Beam Damage Team (BDT), the interlocks on the beam amplitude and errant beams in the DTL section were replaced by Medium-speed differential thresholds on beam losses. This however did not compromise the errant beam interlock function because any errant beam would still be detected by the Fast thresholds of another four BCMs located upstream of the DTL BCMs.

Figure 2 shows the BCM PM data including a large spike (i.e. RF breakdown) on the DTL2 BCM readout causing signal saturation with this channel as well as some ringing on the other channels (item 6 in the spikes summary).

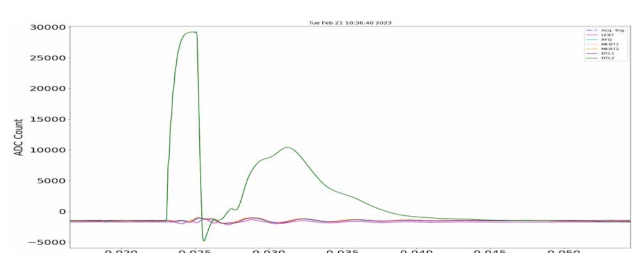

Figure 2: A large spike on the DTL2 BCM readout causing some ringing on the other BCM channels.

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Given that the BCM signal drifts with temperature are extremely small, this issue was easily resolved by disconnecting the BCM calibration cables after the system was calibrated and the in-situ tests were completed before starting with beam.

The combination of the above-mentioned action items fully resolved the beam availability issue with the BCM.

DIFF BCM INTERLOCKS

Differential BCM interlocks are mainly used to measure beam losses between a BCM pair and stop the beam if the losses exceed a threshold. The BCM firmware allows using three types of differential interlocks, being: Fast, Medium-speed and Slow for each pair. The Fast and Medium-speed thresholds are set on the differential current and they can include a configurable moving average filter as well. The Slow threshold is however set on the cumulative charge per cycle and it gets reset shortly before the arrival of the next pulse.

Figure 3 shows the absolute and differential beam currents from a differential pair with the RFQ BCM and MEBT BCM 1. The difference in the pulse lengths (20 µs vs. 5 µs) is due to the MEBT chopper, and the 0.1 mA step before the MEBT BCM 1 pulse is the scattered beam from the MEBT chopper dump. For the beam commissioning to the DTL tank 4, the Fast and Slow differential interlocks were disabled, but the Medium-speed one was enabled with several BCM pairs. The width of the moving averager was set to 55 µs (LEBT-RFQ BCM pair) and 6 µs (three pairs between the consecutive DTL tanks from 1 to 4) to make the differential interlocks less sensitive to the spikes from the RF breakdowns, but sensitive enough to beam losses that have the potential to cause a damage. This proved to be an effective method to avoid unwanted beam trips particularly at the start of the beam commissioning and before the cavities were fully conditioned.

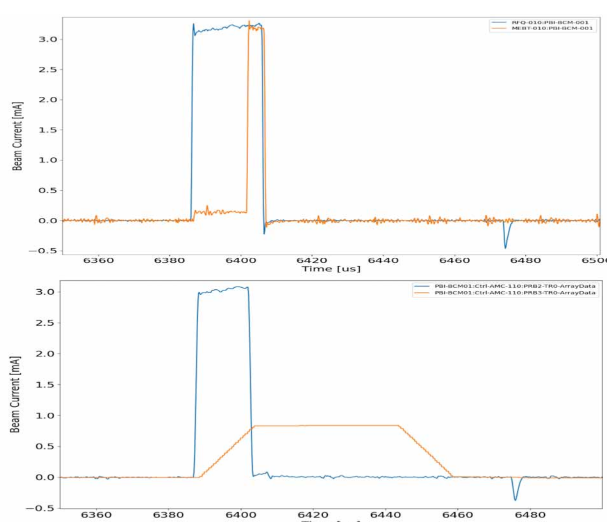

Figure 3a: RFQ BCM (blue) and MEBT BCM 1 (orange) readouts. Figure 3b: Fast (blue) and Medium-speed (orange) differential currents for the above pair; the amplitude of the Medium-speed signal is 70% lower than the Fast one due to the moving averager.

OTHER IMPROVEMENTS

Fast BCM

The Fast BCM (i.e. FCT) is installed towards the MEBT end and it is mainly used for verifying the 10 ns rising/falling edges of the beam pulse from the MEBT chopper. The analogue signal from the FCT is measured by a fast oscilloscope with a sample rate of up to 20 GSPS and an overall measurement bandwidth of 700 MHz. Figure 4 shows a screenshot of the FCT signal. The falling edge of the beam pulse and the beam bunches and their frequency spectrum up to the second harmonic (i.e. 2*352 MHz) can be seen in the screenshot.

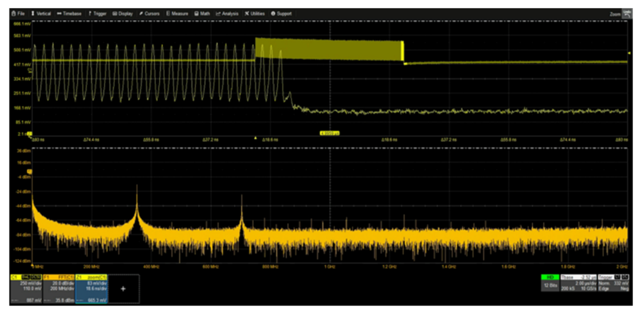

Figure 4: The falling edge of the beam pulse from the MEBT chopper as measured by the Fast BCM.

One Hour Average Beam Current Measurement with sub-µA Accuracy

During the beam commissioning to the DTL, a temporary shield wall was used to isolate the DTL tank 4 from the downstream sections. This allowed to run the beam to the DTL4 FC and in parallel continue with the installation work in the superconducting part of the linac. Under these conditions, personnel safety regulations set a limit of 1 µA average beam current over a rolling period of one hour to ensure the workers would not receive a radiation dose rate higher than 3 µS/h. The limit was imposed in the first hand by only allowing certain beam modes, but the BCM system was also used to ensure the actual beam current would not exceed the 1 µA limit. Given that the required accuracy needed to be by ~4 orders of magnitude better than that the regular BCM accuracy (i.e. +/- 0.8 mA), this measurement could only be successfully done after the following issues were resolved:

- Any DC offset due to measurement errors needed to be precisely removed from the BCM readout. This particularly applies to the baseline restoration function.
- The LEBT/MEBT choppers with a reduced electrode voltage result in some leakage beam which can potentially get accelerated by the RF in the following sections and contribute to the radiation dose. The regular BCM channels however may not always measure leakage beams because of the chosen triggers for the baseline restoration function. In order to fix this issue, a copy of the MEBT BCM 2 signal was used for the sub-µA beam measurement but its trigger was

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configured differently so that it would not be blind to potential leakage beams.

- An earlier study shows that below 85% of the nominal RFQ voltage, the beam will be lost either in the RFQ or in the downstream sections [3]. Then, this particular BCM channel was configured to only measure the beam within the time window of the RF pulse, and this significantly improved the measurement accuracy comparted to a continuous measurement.

Figure 5 shows a 20-hour history of the charge per pulse as well as the 1-hour average beam current including any leakage beams within the RF pulse window. The peak value is 0.27 µA which is equivalent to 27% of the "budget". The tests showed that the BCM can indeed measure the average beam current with an accuracy significantly better than 1 µA provided that the triggers are all correct.

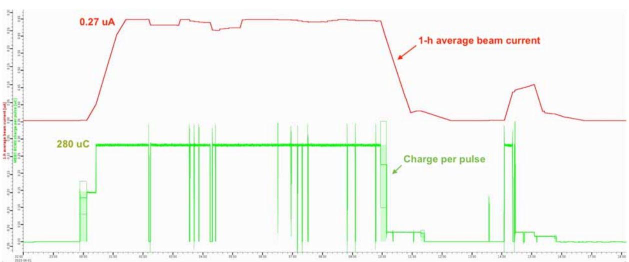

Figure 5: 20-hour history of the charge per pulse as measured by the MEBT BCM 2 (green) and the 1-hour average beam current with sub-µA measurement accuracy (red).

LVDS to RS-485 / Optical Converter

The existing BCM-FBIS interface uses four Low Voltage Differential Signalling (LVDS) channels, being three discrete and one customized serial data link. The discrete channels are used for the Beam Permit, BCM Ready and Beam Presence signals. The serial data is Manchester encoded and used for sending the same information as the discrete channels (for redundancy purposes) as well as some more information including beam mode/destination IDs, life-sign counter, beam exist flags etc. with an update rate of 100 kHz. Although this interface has so far worked without a major issue, concerns over its reliability with long cables in noisy environments triggered the development of some new electronics in collaboration with the Warsaw University of Technology (WUT) with the aim of making the interface more robust. The new electronics consist of a transmitter Printed Circuit Board (PCB) for data aggregation and LVDS conversion to RS-485/optical as well as a receiver PCB for optical signal conversion to RS-485. The transmitter comes in two form factors being: 1) mTCA Advanced Mezzanine Card (AMC) with two channels, and 2) Rack-mount unit with up to four channels. The two form factors are planned respectively for the BCM and the Beam Position Monitor (BPM) systems. Figure 6 shows the first prototype of the transmitter AMC that was successfully tested at ESS in April 2023 together with a receiver unit and the BCM/FBIS electronics.

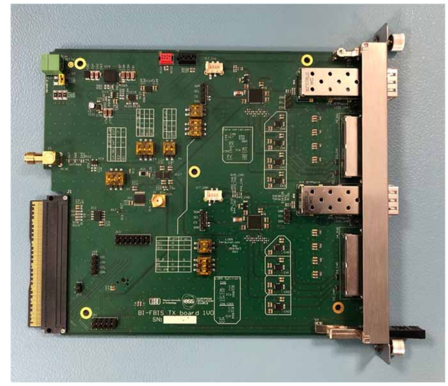

Figure 6: Photo of the new LVDS to RS-485/optical converter AMC (Courtesy of Pawel. K. Jatczak - WUT).

SUMMARY AND OUTLOOK

During the ESS beam commissioning through the DTL tank 4, nine BCM channels were successfully used for beam measurement, machine protection and timing synchronizations. At the start of the commissioning, the beam availability was impacted by a large number of beam trips due to spikes on the BCM readouts. An investigation then showed that the spikes were partly due to EMI and other types of external disturbances, and partly due to RF / vacuum breakdowns particularly in the DTL section. The issue was then resolved by addressing the EMI issues and reconfiguring part of the BCM protection functions to make them less sensitive to the spikes but sensitive enough to beam losses that pose a damage potential. During the same commissioning run, a Fast BCM, a Medium-speed differential interlock and a special BCM channel with sub-µA measurement accuracy were successfully tested and verified with beam as well. It is planned to continue with the BCM activities in 2023-2024 by installing in total ten new BCMs in the DTL tank 5 and the superconducting part of the linac as well as three BCMs in a new ISrc-LEBT Test Stand that is under construction. It is also planned to make the BCM-FBIS interface more robust by deploying a newly developed RS-485/optical interface module. The other parts of the system including the electronics, FPGA firmware, software and the operator interfaces have already become mature following a few rounds of improvements, hence no major changes are planned in the near future.

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