IMPLEMENTATION ISSUES AND FIRST RESULTS OF THE ESS BEAM CURRENT MONITOR SYSTEM

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Abstract

The BCM system of the European Spallation Source needs to measure several beam parameters including pulse profile, charge, current, pulse width and repetition frequency. Moreover, it will measure differential beam currents using several ACCT pairs along the linac. This is particularly important at low beam energies where BLMs cannot be used for measuring beam losses. Due to the ESS-specific requirements, the BCM software and firmware will be customized. Also, parts of the electronics may need to be customized to be consistent with the ESS standard electronics platform, hence facilitate maintenance and maximize synergy with other systems. Technical challenges include maintaining signal integrity and a fast response despite large variations in the sensor cable length and ambient temperature, as well as minimizing the effect of the ground voltage fluctuations. This paper gives a general overview of the design and focuses on a few technical issues that are particularly important for satisfying the performance requirements. Also, BCM test results in laboratory conditions as well as preliminary results with the ESS ion source will be presented.

INTRODUCTION

The Beam Current Monitor (BCM) system of the European Spallation Source (ESS) will be used for measuring several beam parameters including pulse profile, mean current over the pulse flat top, per-pulse and cumulative beam charge as well as the pulse rising/falling edges. The BCM system will be the first and arguably the most important Beam Instrumentation (BI) system that will be used for machine protection purposes in the warm linac. The machine protection functionality requires measuring several other beam parameters including differential current, errant beam, beam presence as well as pulse amplitude, width and frequency. A fast digital interface will then be used to transfer this information to the Beam Interlock System (BIS) and stop the beam if the BCM system detects a fault. The primary reason for the beam presence signal is to check and verify that no beam is present in the downstream sections of the linac after ex. a Faraday Cup (FC) is inserted into the beam. The pulse amplitude/frequency/width measurements will, on one hand, be used to verify that the actual beam parameters are consistent with the beam mode distributed through the Timing System (TS), and on the other hand for estimating the beam power hence damage potential.

The total number of BCMs in the ESS linac will be 20 where 18 will be of Bergoz AC Current Transformer (ACCT) type. The distribution of these ACCTs in general makes it possible to measure the beam at the entrance/exit of different sections as well as at the exit of temporary beam dumps. The other 2 BCMs are a Fast Current Transformer (FCT) and a Beam Position Monitor (BPM) that will be both used for measuring the pulse rise/fall time of ~10 ns downstream of the Medium Energy Beam Transport (MEBT) chopper.

The ACCT electronics includes an analog front-end (i.e. ACCT-E) that should be calibrated for each toroid based on the toroid cable length. In order to achieve the maximum ACCT bandwidth of 1 MHz, the toroid cable length needs to be limited to 20 m. This, however, will not be possible for several ACCTs at ESS and in particular those in the high energy linac where a long cable of ~80 m will be needed to connect the ACCT toroid to the ACCT-E in the Target Building. The long cable will then significantly reduce the analog bandwidth, and the resultant increase in the rise time should be compensated in firmware so that it does not cause false beam aborts.

Fast FPGA processing will be required for measuring the ESS beam parameters including those relevant to machine protection. This is done by a complex piece of firmware that is based on the BI and Machine Protection System (MPS) requirements, and tailored to the ESS beam and machine parameters. Also, some custom interfaces will be needed for the interconnection of the BCM electronics with external systems including the TS and the BIS, and for transferring differential BCM data over large distances.

As the Beam Loss Monitors (BLMs) cannot be used at low energies, the ESS MPS will mainly rely on the BCMs in the warm linac. In order to provide redundancy in these sections, the ACCT signal will be processed in parallel by two sets of readout electronics, whereas in the cold linac, the BLMs will serve as the primary system for measuring beam losses and the BCMs will provide some redundancy. The beam loss measurements by the BCMs will be done by measuring differential beam currents using several ACCT pairs. In areas where the two ACCTs of a differential pair are not both connected to the same processing board, an optical link will be needed for transferring data from the processing board of the upstream ACCT to the one of the downstream ACCT, and the differences in propagation delays should be precisely compensated in firmware.

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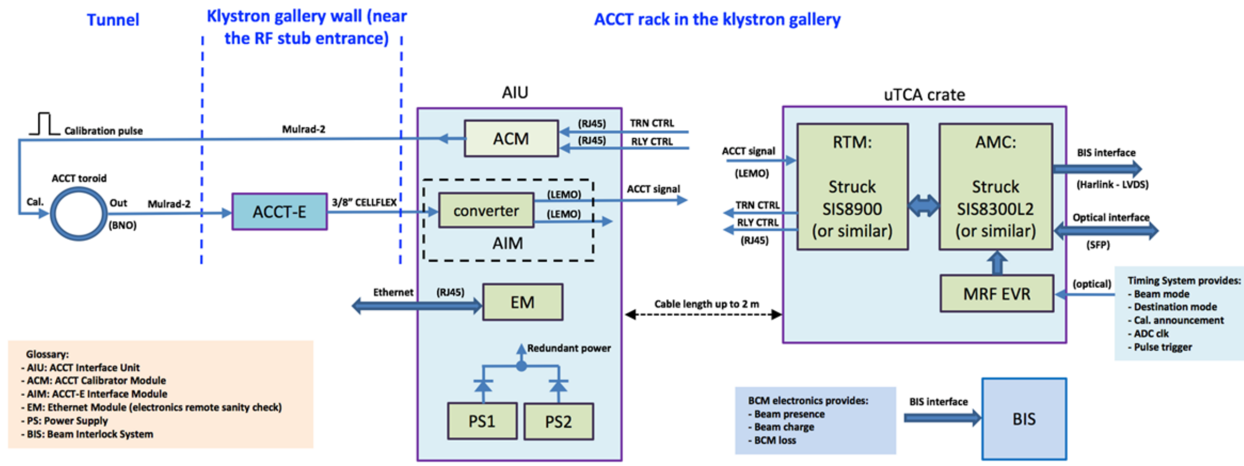

Figure 1: Draft and simplified ACCT layout showing the interconnection of the toroid to the AIU and the crate.

DESIGN OVERVIEW

Figure 1 shows the simplest case of the interconnection between the ACCT toroid, electronics, TS and the BIS. This is planned for the Medium Beta (MB), High Beta (HB) and the upstream High Energy Beam Transport (HEBT) ACCTs where only one toroid will be connected to an ACCT Interface Unit (AIU), and a second crate will not be provided for redundancy. In the other sections, up to 7 toroids will be connected to one AIU/crate and the calibration windings of all these toroids will be connected in series. The toroid output current is transferred by a twin-axial Mulrad-2 (Siltem) cable to the ACCT-E. The ACCT-E converts the current into a voltage of +/-10 V full-scale. A 3/8" CELLFLEX cable (coaxial) is planned to transfer the ACCT-E output signal to the AIU that will be installed in the same rack as the ACCT uTCA electronics. The AIU includes several customized modules being: an ACCT-E Interface Module (AIM), an ACCT Calibration Module (ACM), an Ethernet Module (EM) as well as a redundant power module. The AIM matches the output voltage and impedance of up to 10 ACCT-Es to those of the Rear Transition Module (RTM) inputs. The AIM has two identical outputs (buffered) for each ACCT signal. The second output will then be used for the redundant electronics set where needed. The ACM generates pulses of fixed amplitude for ACCT calibration as well as for electronics sanity check. The EM also provides some level of sanity check by measuring supply voltages and temperatures at several points within the AIU and sends the data to the control system through Ethernet. The AIM output signal is transferred by a short cable to the RTM where it is converted from single-ended to differential and fed to the Advances Mezzanine Card (AMC) through the 'zone-3' connector. The ACCT signals are then digitized by 16-bit ADCs and FPGA processed on the AMC. A Micro Research Finland (MRF) EVent Receiver (EVR) provides the AMC with the ADC clock, pulse trigger, calibration announcement as well as beam and destination mode information from the ESS TS. The ADC sample rate is set to 88.0525 MHz that is equal to ¼ of the RF frequency in the warm linac. The combination of fast ADCs (note that the ACCT-E analog bandwidth is limited to 1 MHz) and FPGA processing is used for reducing both noise and processing latency. Noise reduction is done by a moving average filter in the ACCT firmware. The filter is followed by an 8-1 decimator that results in a sample rate of 11 MSPS. This significantly reduces the amount of ACCT data but still uses the extra ADC samples for noise reduction before they are discarded. Synchronization to the beam pulse is done by an external trigger from the EVR. This trigger should have the same frequency and width as the real beam pulse, and it should be received by the ACCT electronics at a well-defined time before the beam pulse arrives. The ACCT electronics is integrated into EPICS and the measured pulse data is sent to the network after the pulse. Tests with an ACCT setup including uTCA electronics, ACCT firmware/software, operator interface and a prototype AIU are currently going on at ESS.

TECHNICAL ISSUES AND FORESEEN SOLUTIONS

ACCT Signals Drifts

Figure 2 shows the results of a two-day stability test with an overall cable length of 85 m (25 m of Mulrad-2, plus 60 m of low-quality coaxial cable) from the toroid to the RTM. This shows a clear correlation between temperature variations and the ACCT signal drifts. The sharp variation of the ACCT signal at the start of the acquisition is due to the initial cable warm up (the coaxial cable was taken from a cold storage room). Although these drifts are at least by a factor of 3 smaller than the required ACCT accuracy of +/-1%, it is foreseen to significantly reduce them using the very stable calibration pulse from the ACM. Slow drifts can then be precisely measured and compensated using an algorithm in software. Figure 3 shows that the ACM output current changes by only 0.07% when the temperature is increased from 23 to 75 deg. C. Other ACM design considerations include short rise time, constant current over the pulse flat top, being insensitive to cable length variations, external control through a digital port on the RTM and mechanical relay for disconnecting the ACM from the calibration winding(s) when not operated in calibration mode. Timing of the ACCT calibration (in a dedicated mode without beam, or in between two consecutive pulses) is currently under discussion.

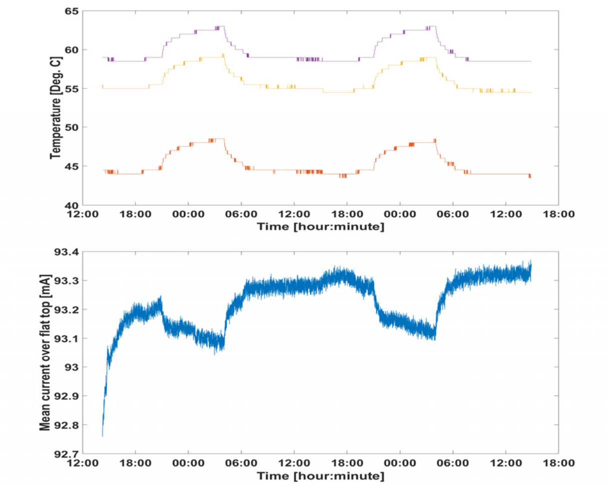

Figure 2: two-day stability test results. Top: measured temperature with 3 sensors in the crate, bottom: history of the measured average current over the pulse flat top.

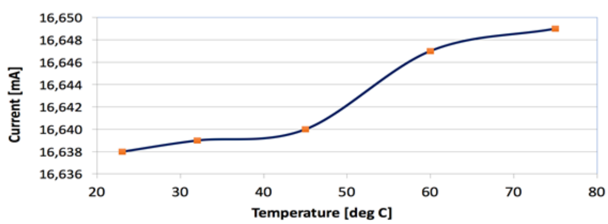

Figure 3: measured ACM drifts with temperature.

Single-ended vs Differential Signal from the ACCT-E

The current design uses a single-ended signal from the ACCT-E output to the RTM input. Although this simplifies the design, it may degrade the signal integrity in the final installation due to potential noise and disturbances that can be picked up by the coaxial cable over its length of few tens of meters. It is therefore foreseen to change to differential signal transmission at a later stage if that proves to improve the performance. A differential driver module will then be needed for the ACCT-E output. This signal can be received at the other end of the cable either by an off-the-shelf FPGA Mezzanine Card (FMC) with differential inputs, or with a custom-designed RTM.

Grounding

Providing a solid and stable ground is essential to any electronics design and in particular those dealing with small and sensitive signals. Ground loops and ground voltage fluctuations can significantly add to noise level, hence degrade the measurement resolution. Providing an appropriate ground connection for the ACCT toroids, cables and the electronics is a non-trivial task that on one hand requires some knowledge about the final setup and type of disturbances, and on the other hand may impact the design including the customized modules, connectors, chassis and patch panels. The aim is to proceed with a grounding scheme that is believed to give the required performance, but still make the design flexible so that it will be possible to switch to other grounding schemes if needed. Also, ferrite beads will be used on the toroid cables to reduce the effect of the Electro-Magnetic Interference (EMI) [1].

ACCT INSTALLATIONS ON THE ION SOURCE AND THE LEBT

An ACCT toroid was installed in Nov. 2016 on the High Voltage Power Supply (HVPS) of the ESS ion source that has been built by INFN-Catania. Since then, the toroid has been successfully used in Catania to measure the current pulse of the HVPS (see Fig. 4). A second toroid was delivered to INFN-Catania in April 2017 to measure the beam pulse at the exit of the Low Energy Beam Transport (LEBT). The recent delivery also includes uTCA electronics and a demo ACCT firmware [2] that, among other things, compensates for the droop and restores the baseline level of the ACCT signal. It is planned to replace the demo firmware at a later stage with a new firmware thus providing extra machine protection and current monitoring functionalities.

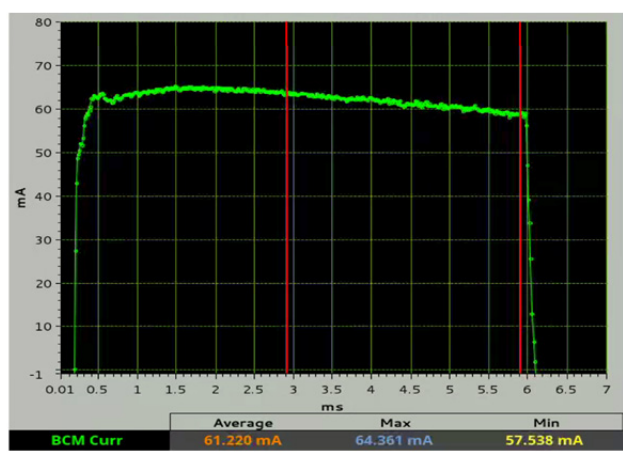

Figure 4: ACCT-measured pulse of the HVPS of the ESS ion source, courtesy of Lorenzo Neri (INFN-Catania) and Oystein Midttun (ESS).

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