BEAM CURRENT MONITOR SYSTEM OF THE EUROPEAN SPALLATION SOURCE

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Abstract

The Beam Current Monitor system of the ESS will be primarily used for beam current and charge measurements in absolute and differential modes. Moreover, it will provide a fast input to the Beam Interlock System, initiating a trigger to shut the beam off upon high beam loss detection. As the BCM system will be needed at an early stage for Linac commissioning, it needs to work successfully under non-optimal conditions, ex. short pulse and low current beams. It is planned to install in total 20 AC Current Transformers and one Fast Current Transformer along the Linac. The FCT will have a larger bandwidth and it will be used to measure the performance of the fast chopper of the Medium Energy Beam Transport with a rise time of 10 ns. A prototype based on a commercial ACCT and EPICS-integrated MTCA.4 electronics has been set up and successfully tested with an emulated beam. The ACCT signal has been FPGA processed to compensate for the offset and droop as well as filtering and synchronization to an external trigger. This paper gives an overview of the design and test results of the prototype ACCT system with an outlook to future modifications before installation in the ESS Linac.

INTRODUCTION

The Beam Current Monitor (BCM) system of the ESS Linac will be based on AC Current Transformers (ACCTs). Table 1 gives a summary of the beam and ACCT specifications. It is planned to install in total 20 ACCTs along the ~600 m Linac with a higher concentration of the sensors in the low-energy part. This is mainly to address issues regarding fast detection of high beam losses and initiating a trigger to stop beam operation in areas where Beam Loss Monitors (BLMs) cannot be successfully used.

It is also foreseen to include one Fast Current Transformers (FCT) in the BCM system. The FCT will have a significantly larger bandwidth compared to the ACCTs and it will be mainly used to measure the performance of the Medium Energy Beam Transport (MEBT) chopper with a rise time of 10 ns approximately.

The BCM system can be used to measure the pulsed beam current as well as the per-pulse and cumulative beam charge. The readout data can be presented to the end-user in numerical and graphical formats.

The ESS Machine Protection System (MPS) requirements mandate that a differential beam current shall be measured at several locations along the Linac. In this case, the readout current from two ACCTs need to be compared with each other and in case the difference exceeds a certain threshold, a request to stop beam operation will be sent to the Beam Interlock System (BIS) with a total response time of 10 µs from detection to having inhibited beam operation.

The ACCT electronics will be installed in the klystron gallery, which will extend in parallel to the Linac tunnel over most of the Linac length. In order to achieve a good signal-to-noise ratio for the ACCT output, care should be taken to use short and well-shielded cables for signal transmission to the ACCT front-end electronics in addition to a good grounding system with a low voltage difference between the tunnel and klystron gallery grounds. Moreover, some electronics developments are currently being done for differential signal transmission to the ACCT crate where the signals are digitized and FPGA processed.

MTCA.4 standard has been chosen at ESS as a prototyping platform for systems requiring high-performance electronics including the ACCT. A decision on the final electronics platform is expected in Sep. 2014. A demo MTCA.4 system has been used for digitizing the ACCT signal, FPGA processing and integration into the ESS EPICS control system. The ACCT data is communicated to the user through EPICS Input/Output-Controller (IOC) and Channel Access (CA).

It is planned to commission the Low Energy Beam Transport (LEBT) ACCT in the second half of 2015.

This article gives an overview of the current status of the ACCT project with the focus being mainly on the electronics with an outlook to future improvements.

Table 1: ESS Beam and ACCT Specifications

Max beam energy	2	GeV
Pulse repetition rate (nominal)	14	Hz
Pulse duration (nominal)	2.86	ms
Beam current (nominal)	62.5	mA
Beam current (min)	6.25	mA
Bunch frequency	352	MHz
BCM quantity	21	
ACCT accuracy (nominal beam)	+/-1	%
ACCT resolution (nominal beam)	1	%
ACCT response time (incl. elect.)	1 – 2	µs
Beam pipe diameter	60, 100	mm

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ACCT DESIGN OVERVIEW

A few options are currently being studied for the final ACCT implementation. A Bergoz ACCT has so far been used for prototyping purposes with promising results. This system consists of an ACCT toroid and its associated front-end electronics module (i.e. ACCT-E), a DC power supply as well as a cable for the interconnection of the sensor to the ACCT-E. Fig. 1 presents a potential solution for the final ACCT implementation in the Linac. Based on this design, a cable with the length being shorter than 20 m will be used to connect the ACCT sensor to the ACCT-E module. Longer cables may result in a long settling time or a ringing during the rise/fall times of the pulse in addition to a higher noise level. In the final setup, it is planned to pass these cables through the RF stubs alongside the waveguides or through dedicated cable chutes to the klystron gallery. It is foreseen to install the front-end module near the end of the stub/chute in the klystron gallery. This, on one hand will meet the requirement on the cable length, and on the other hand will keep the electronics away from the harmful radiation from the tunnel. A differential driver module with high input impedance can be used to convert the front-end output signal to differential with the advantage of common-mode noise rejection, thus minimizing errors due to ground voltage fluctuations and external disturbances from nearby power and electromagnetic sources. The differential driver will also perform signal amplification, low-pass filtering and impedance matching to the differential line. The differential driver will consist of some active electronics and it can be supplied by the same power supply as the ACCT-E module. The output signal of the differential driver will then be sent over a shielded cable to the ACCT crate sitting in the klystron gallery at a distance that is expected to be no more than a few tens of meters to the differential driver.

MTCA.4 standard has been used for ACCT electronics prototyping. Based on this approach, the ACCT crate will include an analogue Rear Transition Module (RTM) where the ACCT signal can be received in differential format, level translated and filtered before being converted to digital. The RTM will have 10 input channels; therefore it can receive signals from up to 10 ACCTs which can be grouped as several pairs.

The differential driver and the ACCT RTM are currently under development in a collaboration with DESY-Hamburg. The RTM will also include an RS-422 interface which can be potentially used for the future connection to the BIS.

The RTM output is fed into an Advanced Mezzanine Card (AMC) where the ACCT signals are digitized by fast ADCs and FPGA processed. The FPGA processing includes algorithms for droop compensation, baseline level correction, filtering and synchronization to the pulse repetition rate. A timing receiver card, which is hosted by the same crate, generates a trigger for pulse synchronization and conveys the beam/machine mode information to the AMC. This information will be used by the FPGA for any mode-dependant configuration such as setting the threshold levels.

A CPU unit, which is hosted by the same crate, communicates the ACCT data to the end-user through EPICS IOC and CA. This data will also be time-stamped and stored by an Archiver unit for data-on-demand and post-mortem analysis.

The MPS group requires that a differential current be measured at 6 locations along the Linac [1]. The distance between the two ACCTs that are used for the differential measurement varies from 5 m approximately to more than 200 m depending on their location. For the larger separations, the two ACCT signals cannot be directly fed into one digitizer card. In these cases, it is planned to use an optical fiber link for data communication from one FPGA card to another. The receiving FPGA can then calculate the current difference and initiate a beam_abort request if the difference exceeds a threshold.

The current prototype follows the same design concept, but the differential driver, the ACCT RTM and the optical link are not available yet.

Data acquisition electronics for the FCT is still under study. As a very limited quantity will be required, a fast and reliable solution would be to acquire the FCT signal using a modular oscilloscope card integrated into the ESS EPICS control system. Although this solution will provide a more limited functionality compared to the existing one, it is believed to be sufficient for the purpose.

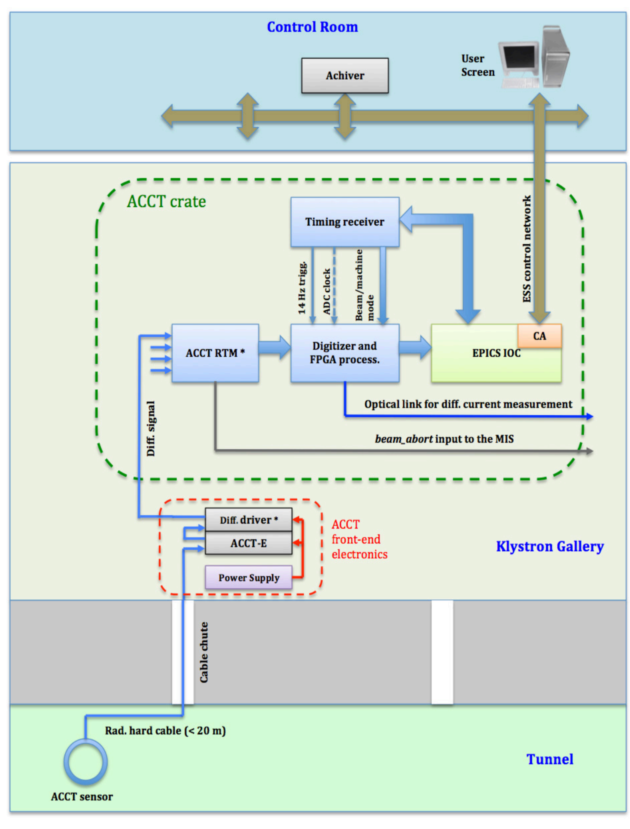

Figure 1: Simplified block diagram of a potential solution for the final ACCT implementation.

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CONTROL SYSTEM ARCHITECTURE

EPICS is the control system of choice for ESS. For the ACCT prototype, a demo Control System Studio OPerator Interface (CSS OPI), some EPICS modules and an EPICS IOC have been developed. An ACCT EPICS module interfaces to the digitizer card and is responsible for data extraction and configuration of the card. A Micro Research Finland (MRF) EPICS module is used to interface to the MRF timing receiver. These two modules are used in the EPICS IOC that allows controlling both the digitizer and the timing receiver cards. Upon proper configuration of these two cards, the user is able to collect the ACCT data using CSS OPI demonstration screens.

In production environment, the ACCT data will be handled using the tools provided by the ESS Integrated Control System (ICS) division. Tools such as data archiving, alarm handling, configuration deployment, scripting and application execution environment are collectively called ESS Control System Services. These services shall be able to talk to all EPICS integrated devices in the machine.

Operator/engineering screens and applications that in turn rely on the data provided by the devices or services reside on top of the control system service layer.

TEST RESULTS

The ACCT prototype was tested under laboratory conditions. An MTCA.4 crate from Schroff with a CPU and MicroTCA Carrier Hub (MCH) from N.A.T. was used. The Bergoz ACCT signal was fed into a Struck SIS8900 RTM and FPGA processed in a SIS8300 digitizer. The ADC clock and the external trigger were set to 88 MHz and 14 Hz respectively. Both of these signals were received via the crate backplane from a MRF timing receiver. The beam was emulated by a 2.86 ms pulsed current passing through the ACCT coil.

In Fig. 2, the red waveform shows the ACCT signal before being FPGA processed. The signal has a DC offset of about -0.6 mA and a droop of approximately 5% of the pulse amplitude. The noise level is approximately 1% of the pulse amplitude. The blue waveform shows the signal after being processed in the FPGA. The DC offset and droop are compensated and the noise amplitude is decreased to 0.15% approximately.

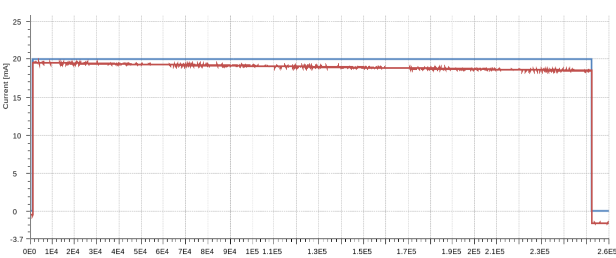

Figure 2: Current pulse from the ACCT before and after FPGA processing.

The SIS8300 digitizer has recently been replaced with a Struck SIS8300-L with a larger FPGA of the Virtex-6 family. This was mainly done to resolve an issue with the size of the SIS8300 FPGA (Virtex-5), which proved not to be sufficient for the complete ACCT signal processing beside the original firmware, especially when the card is being used for several ACCTs.

Preliminary tests for differential current measurements with the ACCT and a waveform generator emulating a second ACCT signal shows that an electronics response time of ~1 μs will be achievable. This response time includes the measurement of the 2 ACCT output signals, level comparison and changing the BIS input (i.e. output signal of the ACCT electronics) from 1 to 0 state in case the calculated difference exceeds the pre-defined threshold. Changing the state from 1 to 0 is equal to requesting an immediate stop of beam operation.

ACCT tests in the presence of an external magnetic field generated by a Helmholtz coil have shown that the error from a sinusoidal 1 Gauss external field is 0.7 mA for transverse and 5.3 mA for axial fields [2]. These tests have proven that adequate ACCT shielding will be needed for the future Linac.

SUMMARY AND OUTLOOK

A BCM prototype based on a Bergoz ACCT sensor and MTCA.4 electronics has been set up and successfully tested at ESS. The FPGA of the digitizer card has been programmed to compensate for the ACCT droop, noise and offset thus reconstructing the original shape of the beam pulse with an overall error of < 1%. The ACCT will be interfaced with the future ESS Beam Interlock System to shut the beam off under fault conditions such as a large beam loss, an incorrect pulse width/rate or an unexpected pulse. The system is currently being improved in the following areas: modification of the FPGA code to improve its performance, an RS-422 digital interface to the Beam Interlock System, development of a differential driver/receiver for ACCT signal transmission to the data acquisition crate, an optical link for differential beam current measurement over large distances and an appropriate ACCT shielding against external magnetic fields. It is planned to use a new version of the system in the second half of 2015 for LEBT commissioning.

REFERENCES

[1] R. Schmidt et. al, "ESS Machine Protection Architecture of the ESS Beam Interlock System", ESS internal report.

[2] H. Hassanzadegan et. al., THPME160, proc. IPAC2014.