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MACHINE PROTECTION FEATURES OF THE ESS BEAM CURRENT MONITOR SYSTEM

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Abstract

The BCM system of the European Spallation Source includes several machine protection features to ensure that the actual beam parameters will be consistent with the selected beam and destination modes. Differential current measurements with several ACCT pairs are foreseen to detect beam losses particularly in the low-energy linac where Beam Loss Monitors cannot be used. The ACCTs will also be used to check that no beam will be present in the sections downstream of a temporary beam dump. These measurements will then be used to stop the beam shortly after an abnormal condition has been detected by the BCM system. This will require some customized interfaces with the Timing System and the Machine Protection System as well as an optical interface for differential current measurement over large distances. Automatic setting of the machine protection thresholds and masking/unmasking of the interlocks based on the beam and destination modes are among the technical complexities. This paper gives an overview of the design including the most recent updates and discusses in more details the machine protection features of the BCM system.

INTRODUCTION

The purpose of ESS machine protection is to support the high operational availability requirements by preventing equipment damage. ESS is largely relying on custom made and specialized equipment for its operation. Damage to this equipment could cause long shutdown periods, inducing high financial losses and interfere with international scientific research programs relying on ESS operation. Implementing a fit-for-purpose machine protection concept is required to mitigate these risks and achieve the required availability [1].

The ESS Machine Protection objectives are [2]:

- Machine protection shall, in that order, prevent and mitigate damage to the machine, be it beam-induced or from any other source, in any operating condition and lifecycle phase, in accordance with beam and facility related availability requirements.
- Machine protection shall protect the machine from unnecessary beam-induced activation having a potential to cause long-term damage to the machine or increase maintenance times, in any operating condition and lifecycle phase, in accordance with beam and facility related availability requirements.

Experiences in similar facilities and in particular SNS show that Beam Current Monitor (BCM) systems can indeed provide machine protection and also detect missing pulses or truncated beams [3, 4]. The aim in the SNS case is to stop the beam within 5 us hence protect the Super Conducting (SC) linac when all beam is lost.

The ESS BCM system will be part of the Protection Functions (PFs) below:

- Stop beam operation if the BCM system detects that the requested proton beam mode is exceeded (note: proton beam mode defines the maximum beam current, pulse length, and pulse repetition rate).
- Stop beam operation if the differential proton beam current measurement between two AC Current Transformers (ACCTs) is above acceptable limits.

BCM SYSTEM DESIGN OVERVIEW

The ESS BCM system relies mainly on ACCTs. These non-interceptive devices are planned to continuously measure the beam current at 18 points along the ~600-meter-long ESS linac with a bandwidth of 3 Hz - 1 MHz (max) and resolution of 1% full-scale. Within these limits, several beam parameters including pulse current, pulse length, charge and repetition rate will be measured for both diagnostics and machine protection purposes. The machine protection functions will be provided by comparing the actual beam parameters to the expected ones for consistency checks, measuring an unexpected beam in the gap between two pulses and measuring beam losses with several differential ACCT pairs. These measurements will then be used to initiate a beam stop request within 2-3 us upon detecting a fault.

9 ACCT sensors are foreseen in total in the ESS Normal Conducting (NC) linac that extends over a length of 50 m. Another 9 ACCTs are foreseen in all the downstream sections including the SC linac, Accelerator-to-Target (A2T) and the Dump-line. The higher concentration of the ACCTs in the NC linac in addition to a larger analogue bandwidth (due to shorter sensor cables) are particularly important at low beam energies where Beam Loss Monitors (BLMs) will not be used and damage potential due a beam loss can also be bigger. One more ACCT will be used to measure the current pulse of the High Voltage Power Supply (HVPS) that supplies the Ion Source. It is planned to use this ACCT for the Ion Source operation (proved to be useful during some early Ion Source tests in Catania – Italy [5]) and for verifying that a beam stop was

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successful by monitoring the supplied current to the Ion Source.

The BCM electronics includes an ACCT front-end unit, readout electronics based on the uTCA standard as well as a customized ACCT Interface Unit (AIU). The AIU will, among other things, generate a precise current pulse for the ACCT calibration, and provides a hardware interface between the front-end unit and the uTCA electronics. 7 uTCA crates (plus 2 for redundancy) are in total foreseen for the ACCT readout electronics. The number of the ACCT sensors per crate is chosen to minimize the sensor cable lengths and it varies between 1 and 7 depending on the ACCT location.

The current design is based on a Struck SIS8300-KU Advanced Mezzanine Card (AMC) that will be used to digitize and process the ACCT signals at 88.0525 MHz (i.e. a quarter of the bunch frequency). The combination of the fast ADCs and FPGA processing is used for reducing both signal noise (through digital averaging without compromising the overall bandwidth) and the BCM processing time. A complex piece of firmware consisting of a core firmware (ongoing collaboration with DESY-Hamburg) and integration firmware (in-house development) is planned for the full monitoring and protection functions. The core firmware functionality includes low-level ACCT signal processing (such as ACCT droop compensation and baseline level correction), beam measurement functions and the machine protection logic. Automatic configuration of the machine protection thresholds based on an announced beam/destination mode, ACCT data transmission over an optical link based on the Xilinx Aurora 8B/10B Intellectual Property (IP) core and the interface to the Beam Interlock System (BIS) are among the functions of the integration firmware. Two versions of the BCM firmware with limited functionality were developed earlier through collaborations with DESY and Cosylab and successfully tested on a BCM test bench and during the early Ion Source tests in Catania-Italy.

Electronics sanity checks will be performed by the Intelligent Platform Management Interface (IPMI) in the uTCA crate and by remotely measuring the supply voltages and temperatures at multiple points inside the AIU. Also, correct cable connections to the readout electronics will be checked and verified automatically by measuring a small DC offset that is added to the ACCT signals in the AIU.

The BCM readout electronics will receive the intended beam and destination modes from the ESS global Timing System through a Micro Research Finland (MRF) event receiver module. This information will then be used to configure the electronics including machine protection thresholds and beam existence tables. The Timing System will also provide a 88.0525 MHz clock for the analogue-to-digital conversion, an external trigger that always arrives 100 us before the beam pulse as well an ACCT calibration announcement.

A customized interface is foreseen to connect the BCM electronics to the Beam Interlock System (BIS). This interface will include two discrete signals (i.e. Beam Permit and BCM Ready) as well as a fast serial datalink that will transfer the BCM configuration information for the sake of consistency checks in the BIS. Redundancy will be provided for the critical signals by sending the Beam Permit and BCM Ready signals once more through the serial datalink.

MACHINE PROTECTION BY THE BCMS

The current definition of the ESS beam modes sets an overall range of 0 Hz – 14 Hz on the pulse repetition rate, 0 ms – 2.86 ms on the pulse length and 0 mA – 62.5 mA on the beam current. From these 3 parameters, 1, 2 or all 3 are allowed to change within certain limits in a beam mode. The machine protection functions of the BCM system should therefore not cause an unwanted beam stop if the beam parameters change within their allowed ranges in a certain beam mode. This will be done partially by activating/deactivating some beam interlocks over precise time windows that are based on the external trigger, and partially by automatic setting of the machine protection thresholds based on the selected beam mode. It is foreseen to store these parameters on a server with controlled access through the control system (EPICS). The integration firmware will then read the complete set of the thresholds and store it on its local AMC memory. Upon changing to a new beam mode, the integration firmware will configure the core firmware by selecting/setting the thresholds corresponding to that specific beam mode. The foreseen PFs consist of the followings:

Protection Against Too-High Beam Currents

This function sets an upper threshold individually on each ACCT readout (see Fig. 1). The upper threshold will be activated continuously and it will normally be slightly above the maximum beam current that is allowed by the beam mode at a certain ACCT location. As a significant part of the beam current (expected to be as high as 30%) can be lost in the Radio Frequency Quadrupole (RFQ), different upper thresholds will be used for the ACCTs upstream and downstream of the RFQ.

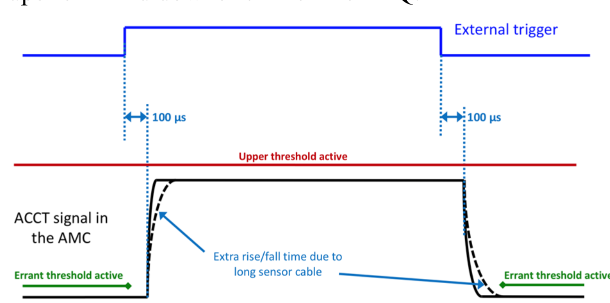

Figure 1: activation time windows of the BCM machine protection thresholds.

Protection Against Errant Beams

This threshold (see Fig. 1) is foreseen to detect unwanted beams in the no-pulse periods (i.e. the gap between two consecutive pulses). The threshold is normally set to be slightly above the noise level and it is

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activated from shortly after the pulse ends until shortly before the next pulse starts. As the measured pulse rise/fall time is dependent on the sensor cable length, the activation time window of the errant threshold should be individually set for each ACCT. Also, the activation time windows of the errant threshold before and after the Medium Energy Beam Transport (MEBT) chopper should be generated separately because the MEBT chopper cuts 20 us from the beginning of the pulse.

Protection Against Inconsistent Pulse Rate

This interlock will be implemented by measuring the repetition rate of the external trigger (equal to that of the beam pulse) and checking its consistency with the selected beam mode.

Protection Against Inconsistent Pulse Length

This interlock will be implemented by measuring the pulse length. This will then be compared to the maximum pulse length that is defined by the beam mode and a beam stop request will be generated if the two values are not consistent.

Differential Current Interlock

The ESS machine protection requirements include several differential pairs with an ACCT distance ranging from a few meters to more than 300 m. In the differential pairs where the two ACCTs are not connected to the same crate, a low-latency optical link will be used for sending the ACCT data from one crate to another. The BCM electronics in the receiving crate will then calculate the current difference and generate a beam stop request if the differential current exceeds certain thresholds. The differential interlock consists of a fast (integration time of ~1 us), medium (integration time of ~100 us) and a slow (i.e. integration over the whole pulse width) algorithm to be able to detect large and sudden as well as small and persisting losses. A fine delay mechanism will be used to compensate the propagation delays of the differential pulses, hence avoid unwanted beam stops particularly during the pulse transient times. Also, the differential interlocks will be deactivated during short intervals around the pulse rise/fall times in the differential pairs where the two pulses have different widths and/or different rise/fall times.

Protection of the Insertable Devices

The ESS Insertable Devices IDs) include among others Emittance Measurement Units (EMUs), Faraday Cups (FCs) and Wire Scanners (WSs). While the EMUs and the FCs will result in 100% beam loss, the WSs are expected to cause only 2-3% beam loss as maximum. The IDs will have their own local protection. After an evaluation has been done, a decision will be made on how to use the BCM system to provide some extra protection ex. by ensuring that the beam power does not exceed the ID damage limit (protection in absolute mode), and by setting an upper limit on the beam loss across the WS (protection in differential mode).

SUMMARY AND OUTLOOK

The BCM system will contribute to the ESS machine protection by implementing several protection functions including check and verification of the beam parameters consistency with the announced beam mode, errant beam detection as well as differential current interlocks with several ACCT pairs. A non-complete version of these interlocks has already been implemented and successfully tested on a BCM test bench. A more comprehensive set of the interlocks for the final installation is foreseen in the next step through internal and external collaborations.

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