ISBN: 978-3-95450-204-2 ISSN: 2673-5350 doi:10.18429/JACoW-IBIC2019-MOPP023

IONISATION CHAMBER BASED BEAM LOSS MONITORING SYSTEM FOR THE ESS LINAC

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Abstract

The European Spallation Source, currently under construction in Lund, Sweden, will be a neutron source based on partly superconducting linac, accelerating protons to 2 GeV with a peak current of 62.5 mA, ultimately delivering a 5 MW beam to a rotating tungsten target. One of the most critical elements for the protection of an accelerator is its Beam Loss Monitoring (BLM) system. The system is designed to protect the machine from beam-induced damage and unnecessary activation of the components. This contribution focuses on one of the BLM systems to be deployed at the ESS linac, namely the Ionisation Chamber based BLM (ICBLM). Several test campaigns have been performed at various facilities. Results of these tests will be presented here together with an overview of the ESS ICBLM system.

INTRODUCTION

The European Spallation Source (ESS) is a material science facility, which is currently being built in Lund, Sweden and will provide neutron beams for neutron-based research [1]. The neutron production will be based on bombardment of a tungsten target with a proton beam of 5 MW average power. A linear accelerator (linac) will accelerate protons up to 2 GeV and transport them towards the target through a sequence of a normal conducting (NC) and superconducting (SC) accelerating structures (Fig. 1).

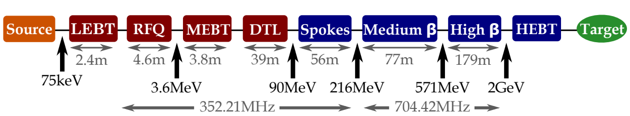

Figure 1: The ESS linac layout [1]. Red colour represents the NC and blue the SC parts of the linac.

A certain set of beam instrumentation is required for successful commissioning, tuning and operation of a linac. As part of this set, the Beam Loss Monitoring (BLM) system is designed to detect beam instabilities potentially harmful to the linac components and inhibit bean production before damage occurs. Additionally, the system provides information about the secondary particle rates close to the beam line during all machine modes of operation in order to enable tuning and keep the machine activation low enough for hands-on maintenance.

Two types of BLM systems differing in detector technology have been conceived at ESS. The Ionisation Chamber-based BLM (ICBLM) system employs 266 ionisation chambers located almost exclusively throughout the SC parts of the linac. Conversely, the neutron sensitive BLM (nBLM) system consists of 82 neutron detectors primarily covering the lower energy part of the ESS linac [2].

This contribution aims to report an overview of the ICBLM system design. In addition to this, results of detector tests performed at various facilities will be discuses.

DETECTOR DESIGN

The ICBLM system is based on parallel plate gas ionisation chambers. The detectors were originally designed by CERN for the LHC BLM system and fabricated by Institute for High Energy Physics (IHEP), Protvino, Russia between 2006 and 2008. The LHC type chambers were selected as the ICBLM detectors due to their fast response, stable gain and large dynamic range of 10^8 (pA–mA). In addition to this, they require little maintenance. Hence, in 2014 a new production line was set up for ESS, CERN and GSI needs [3]. However, certain modifications to the original detector design have been carried out for this production by ESS and IHEP. The modifications were required due to the issues with availability of certain components. Following the production and testing by IHEP, 285 chambers were received at ESS in July 2017.

The detectors are filled with N_2 gas at 1.1 bar, which is sealed in a 2 mm-thick stainless steel cylindrical container with inner length of 480 mm (Fig. 2). The active volume of the detector consists of 61 parallel electrodes, where the gap between the electrodes serves to reduce the charge drift path and recombination probability, which results in desired linear response of the detector. The thickness of aluminium electrode is changed to 0.54 mm compared to 0.5 mm found in the LHC type. Moreover, the gap size is alternating between 5.75 mm and 5.71 mm as opposed to constant value of 5.75 mm in case of LHC type detectors. The latter represents the most significant difference in design compared to the original LHC detectors.

Figure 2: ESS ICBLM detector with (bottom) and without (top) metal casing.

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Each signal electrode is surrounded by two bias electrodes maintained at 1.5 kV during detector operation. The assembly is attached to the stainless-steel cylinder via two high resistivity ceramic (Al_2O_3) plates, while the electrodes are connected through two ceramic feedthroughs.

In order to stabilise the high voltage (HV), a low pass filter (R = 10 MΩ, C = 0.47 µF) is mounted on the HV input of the detector assembly.

DETECTOR LAYOUT AND MOUNTING

As the primary loss monitors in the SC parts of the ESS linac, most of the ICBLM detectors will be in these parts with exception of 5 detectors in the DTL (one detector per intertank region). In general there are 3–4 detectors per lattice cell planned in the SC linac, namely 4 where there is a cryomodule and 3 in the transport sections. Thus, 3 detectors will surround each of the quadrupole magnet pairs sitting in so called Linac Warm Units (LWUs) between the cryomodules while 1 detector will be placed per each cryomodule.

The same concept for mechanical supports in all LWUs has been adopted. Here the supports will hold the detectors centred at the beam line at 45° from the vertical axis (Fig. 3). Similar concept is considered for the ICBLMs in DTL, with detector holder attached to the rail supporting both nBLM and ICBLMs. For the detectors placed at the cryomodule positions attachment to the cryomodule via metal band is under consideration.

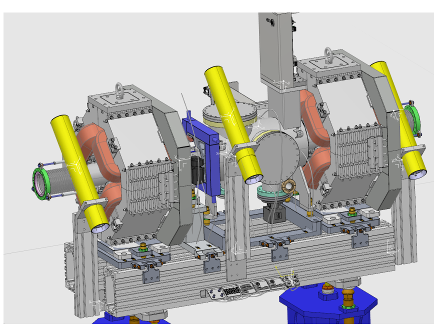

Figure 3: ICBLM detector placement in one of the LWUs.

SYSTEM ARCHITECTURE

Analogue signal from each detector located in the ESS tunnel are routed through a twinax cable to the Klystron Gallery, where racks with Back-End-Electronics (BEE) are located. Here the signal is first digitised and sampled at 1 MHz rate by a customised FMC from CAENels. The card is a 20-bit, 4-channel bipolar current input ADC with 1 MHz sampling rate based on FMC-Pico-1M4 [4] board. The modification was required in order to comply with both the requirement on the system dynamic range (10 nA–10 mA) and the 10 µs response time limit requirement of the system for machine protection purposes. The customised version offers ~300 kHz bandwidth, and operates at two measuring ranges of ±10 mA and ±500 µA.

Two pico FMCs are mounted on MTCA.4–based AMC board (IOxOS IFC1410 [5]) equipped with Xilinx Kintex Ultrascale FPGA used to process the signals in real time. The Pico FMCs have been successfully integrated to the IFC1410 platform with analogue performance meeting the system requirements.

The IFC1410 board handles up to 7 detector channels simultaneously and manages the communication to the Machine Protection System (MPS). Monitoring and control of the system (including data acquisition and slow control) is managed through an EPICS based software, running on the Single Board Computer (SBC) located in the MTCA crates.

The detectors are biased with 1.5 kV through a 1-channel ISEG High Voltage Power Supply (PS) unit [6]. The unit feeds a group of 5–7 detectors in parallel. In addition to the 1.5 kV DC HV, the ISEG PS provides a small voltage modulation to the ICBLM detectors. This results in modulation of the measured detector current, which is planned to be used to diagnose failures. Both modulation and DC voltage are driven point by point through EtherCAT IO modules interfacing the HV PS to the MTCA control system (see Fig. 4). The voltage set points are computed by the SBC synchronously to the machine cycle triggers provided by the timing system. Working modulation frequency an amplitude are on the order of few 0.1 Hz and few 10 V, respectively.

In order to increase system robustness and to avoid situations when a certain electronics failure results in the system being unable to react on dangerous beam conditions, the detectors are grouped in two groups with respect to electronics layout. They are formed by grouping odd or even detectors based on their position number along the linac. The general idea is to separate the two detector groups to the rack level by placing all signal and HV electronics needed for each of the groups in a separate rack. The idea is schematically presented in Fig. 4. In the end parts of the linac (from end of HEBT on) the separation runs down to the crate level in order to avoid the cable length exceeding 100 m substantially.

DATA PROCESSING

The main task of a BLM system is to detect beam instabilities that might cause damage to the linac equipment. When such conditions are detected, the system triggers a stop of beam production by dropping the BEAM_PERMIT signal which is continuously transmitted to the Beam Interlock System (BIS), the backbone of the MPS. Additionally the system provides information about the beam losses for monitoring purposes in order to avoid unnecessary activation of the linac equipment.

One of the challenges when measuring beam losses in a linac is related to the RF-induced background. This background is mainly due to the electron field emission from RF cavity walls resulting in bremsstrahlung photons created on the cavity or beam pipe materials [7]. In order to diminish the influence of this background on the ICBLM

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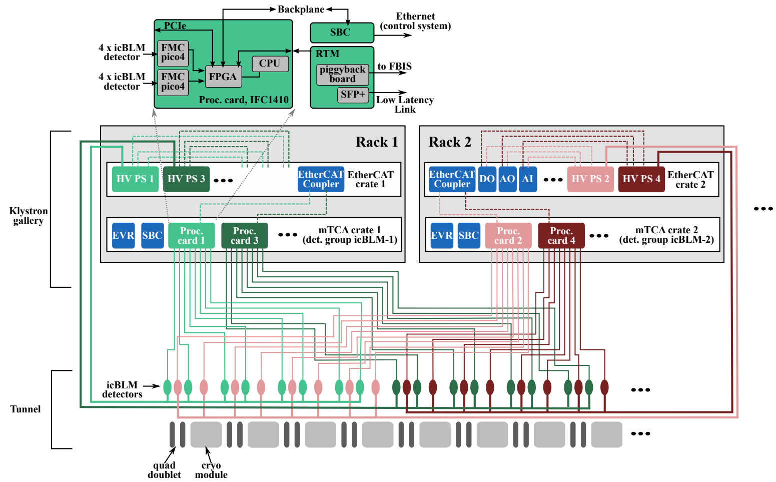

Figure 4: Schematic view of ICBLM detector and electronics layout.

measurements, automatic correction will be applied during the FPGA based real-time data processing as presented here.

The digitised raw signal from each detector will be continuously processed to provide beam loss-induced current measurements at 1 MHz rate. At the beginning of the processing chain the background correction will be applied. This is planned to be achieved by subtracting the Average Background Waveform (ABW) from the raw data on a point by point basis in a configurable time window that covers the period with RF pulse (RF_ON period) inside the machine cycle. The subtraction will be performed for every machine cycle with RF_ON period present.

In parallel, the ABW will be computed as average waveform of Background-Qualified Waveforms (BQWs), where point by point averaging is performed through exponential moving average. The BQWs are defined as waveforms sampled from the raw data in a time window inside the machine period coinciding with the time window for background correction. However, only pulse cycles without beam pulse (or with a short beam pulse) and with RF_ON present will be considered for the background waveform calculation. The presence of these diagnostics pulses is expected to be signified by the Machine Timing System well in advance.

After background correction, the induced current measurements will be streamed at 1 MHz to the input of Protection Function Algorithm responsible for continuous assessment if conditions to inhibit beam production have been met. Here the data will first be passed through configurable filters and then compared to the channel-dependent thresholds. The final result is a BEAM_PERMIT signal that will be aggregated over all functioning channels on each AMC. The signal will be continuously transmitted to the BIS that will further handles inhibiting of beam production in case of its absence.

The induced current measurement together with other processed data will additionally be used to compute several statistics called Periodic Data, typically extracted on every machine cycle (14 Hz) for monitoring purposes. An example of such monitoring variable is induced current averaged over full machine cycle. In addition to the Periodic Data, certain types of data originating from various stages of processing will be buffered and available for retrieval on demand (Data On Demand). This among other includes raw detector signal (1 MHz) and BQWs (for each background qualified pulse).

Modulation detection in the measured current, to be used for diagnosing failures in the system, is planned to be performed on the firmware level. The modulation detection algorithm is foreseen to be based on Fast Fourier Transform of the decimated input signal.

Apart from the system-specific processing like background subtraction in case of ICBLM or Neutron Detection Algorithm in case of nBLM, the ICBLM and nBLM FPGA firmware follows the same idea.

The firmware and software implementation are currently in progress with first prototype expected in the following months.

DETECTOR TESTS

The detectors have undergone several tests before arrival to ESS and are now under the reception and calibration tests at various facilities, namely HiRadMat at CERN, Lund University and FREIA at Uppsala University.

In IHEP, Protvino, high voltage QA tests were performed with each detector at various stages of assembly process:

- after complete assembly and before closing it by welding,
- after cleaning, pumping, baking, filling with the working gas and closing the pinch off and
- after the electrical box and filters were assembled.

All ESS detectors can withstand 2000 V without breakdown and exhibit leakage current of 1–10 pA. In addition to this, a few LHC and ESS type detectors were tested at Panda irradiation facility in Protvino. The results show no observable difference in signal between the LHC and ESS detector types.

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Figure 5: ESS and LHC type chambers installed at HiRadMat.

After the production in Russia the detectors were received at CERN, where each of the detectors was individually tested by CERN and ESS team at CERN gamma irradiation facility (GIF++). The tests consisted of leakage current and radioactive source induced signal measurements [3]. All ESS detectors passed the tests and were shipped to Lund.

After transportation to ESS, the reception tests with few chambers were performed at Lund University, where induced detector current was measured with a Keithley 6485 picoammeter [8] under gamma irradiation. The measured induced current was observed to be ~12 pA for all detectors under test, while their leakage currents were found to be below 1 pA. Due to the modifications in the design compared to the original LHC type detectors, the ESS chambers are currently under additional investigation, in order to assess their performance. The calibration curve measurements and performance comparison with ESS and original LHC type of detectors have been performed in mixed particle fields at HiRadMat facility at CERN, where the conditions are expected to be close to those anticipated in high energy parts of the ESS linac during its operation. Here detectors were installed on top of the SPS proton beam dump (Fig. 5). Preliminary results indicate differences between ESS and LHC

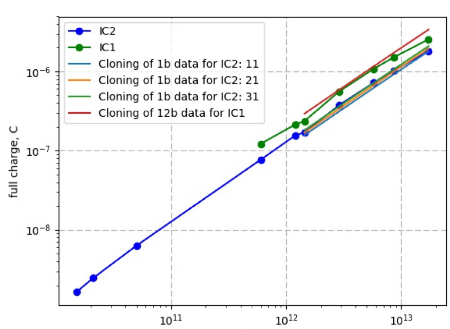

Figure 6: Preliminary calibration curves for ESS (IC2) and LHC (IC1) type chambers measured at HiRadMat. The curve represents total charge measured per proton extraction pulse as a function of number protons per pulse. The word cloning refers to simulation results.

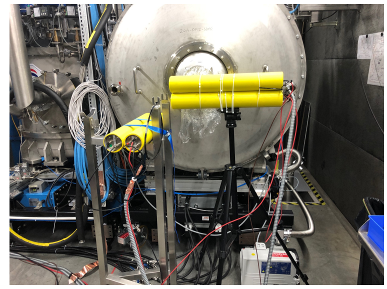

Figure 7: ESS BLM chambers installed at FREIA.

type detectors in signal close to saturation of the chambers (Fig. 6). Further tests at HiRadMat together with analysis and simulation are foreseen for 2020, when the facility is back in operation again.

In order to evaluate the expected RF induced photon background, the ESS chambers have been installed at FREIA test facility in Uppsala, where performance of the 352.21 MHz ESS Spoke cavity prototype is being studied. Here, the detectors are placed in two different configurations close to the cavity (Fig. 7). The induced current is measured with the final Pico FMC digitiser mounted on DAMC [9] carrier board. This test campaign is ongoing and in addition to background assessment, it aims to measure the BLM performance with different cable types and routing with or without cable conduit for electrical shielding.

SUMMARY AND OUTLOOK

Ionisation chamber based BLM system has been developed as the primary loss monitor in the SC parts of the ESS linac. The system provides information about beam losses by measuring the current induced in the detectors. The influence of RF induced photon background on the measured current is accounted for through FPGA based data processing in real time.

Several tests have been performed with the detectors. Extensive QA measurements with each detector were performed during and after the assembly. The tests focused on calibration curve measurements and understanding the influence of RF induced background on detector performance are ongoing.

Following the ESS linac schedule, the system is planned to be deployed in stages throughout 2020 and 2021. First few detector channels, located in the NC linac, are foreseen to be commissioned in 2020 while commissioning of the rest of the system is planned to start in late 2021.

ACKNOWLEDGEMENTS

The authors would like to thank C. Zamantzas, T. Medvedeva, the HiRadMat team, L. Hermansson, R. Ruber, the FREIA team, IHEP and Lund University team for their help with the detector tests. This work was partially supported by the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 730871.

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REFERENCES

[1] R. Garoby *et al.*, "The European Spallation Source Design", *Phys. Scr.*, vol. 93, no. 1, p. 014001, Dec. 2017.

[2] I. Dolenc Kittelmann *et al.*, "Neutron sensitive Beam Loss Monitoring system for the ESS linac", presented at IBIC2019, Malmö, Sweden, Sept. 2019. paper MOPP022.

[3] V. Grishin, B. Dehning, A. V. Koshelev, A. Larionov, V. S. Seleznev, and M. Sleptsov, "Ionization Chambers as Beam Loss Monitors for ESS Linear Accelerator", in *Proc. 6th Int. Beam Instrumentation Conf. (IBIC'17)*, Grand Rapids, MI, USA, Aug. 2017, pp. 454–457. doi:10.18429/JACoW-IBIC2017-WEPWC03

[4] FMC-Pico-1M4, https://www.caenels.com/products/fmc-pico-1m4/

[5] IOxOS IFC1410, https://www.ioxos.ch/produit/ifc_1410/

[6] DPr 40 305 24 5_CAB High Precision HV-PS, DPS series, https://iseg-hv.com/en/products/detail/DPS.

[7] J. Norem, L. Ducas, S. Geer, A. Moretti, M. Popovic, and N. Solomey, "The Radiation Environment in and near High Gradient RF Cavities", in *Proc. 19th Particle Accelerator Conf. (PAC'01)*, Chicago, IL, USA, Jun. 2001, paper MPPH030, pp. 837–839.

[8] Keithley 6485 picoammeter, https://www.tek.com/datasheet/series-6400-picoammeters/model-6485-picoammeter.

[9] DAMC-FMC25, https://www.caenels.com/products/damc-fmc25/