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Requirements and Technical Specifications - ESS icBLM System

	Name	Role/Title
Owner	Irena Dolen Kittelmann	Scientist / BLM system lead
Reviewer		
Approver		

Contents

1 Introduction

One of the proton beam instrumentation systems to be operated at the ESS linac is the Beam Loss Monitoring (BLM) system. An important function of this system is to detect high beam losses potentially harmful to the linac components and inhibit beam production before damage occurs. In addition to the protection functionality, the system provides information about the particle rates during all linac modes of operation in order to enable tuning and keep the machine activation low enough for hands-on maintenance.

The ESS BLM system employs 3 types of detectors resulting in 3 independent beam loss monitoring sub-systems:

- Ionisation Chamber based BLM (icBLM),
- Advanced BLM (cBLM),
- Neutron sensitive BLM (nBLM).

icBLM system is the main BLM system in the superconducting parts of the linac (SCL). However, photon background due to the RF cavities must be taken into account when using ionisation chambers in a linac. This background is mainly due to field emission from the electrons form the cavity walls, resulting in bremsstrahlung photons created on the cavities or the beam pipe materials[1]. In order to avoid this type of background, additional system (cBLM) may also be deployed in future in the SC parts of the linac in addition to the icBLM. This system is planned to be based on Cherenkov radiation detectors which offer inherent rejection of the RF cavity background.

Beam loss monitors are planned in the MEBT and DTL sections of the normal conducting parts of the linac (NCL) as well. Here the particle fields outside the tanks and beam pipe are expected to be dominated by the neutrons and photons. Thus, the nBLM system based on specially designed neutron sensitive Micromegas neutron detectors will be deployed as the primary BLM in these two sections.

The focus of this document is to state requirements and describe technical specifications for the icBLM system.

2 icBLM system

2.1 Level4 requirements

Table 1 gives a snapshot from the Level4 (L4) Proton Beam Instrumentation (PBI) requirements [2] relevant for the BLM systems, which were set in the past.

#	Type	Name	Description
1	Beam loss	XXX beam loss measurement	The beam loss shall be measured in the XXX section.
2	Beam loss	XXX beam loss measurement sensitivity	A beam current loss of 10 mW/m shall be detected.
3	General	XXX PBI damaging beam detection mitigation	Beam conditions that are potentially damaging to machine components shall be detected by the instrumentation and reported fast enough so that the conditions can be mitigated before damage occurs.
4	General	XXX PBI peak current range	Proton beam instrumentation in the XXX section shall function over a peak beam current range of 3 mA to 65 mA.
5	General	XXX PBI pulse length range.	Proton beam instrumentation in the XXX section shall function over a proton beam pulse length range of 5 µs to 2.980 ms.
6	General	XXX PBI pulse-by pulse measurement update rate	Unless specifically stated, all instrumentation shall be able to perform the measurements and report the relevant PV data at a repetition rate of 14 Hz.

Table 1: L4 PBI requirements [2] relevant for the BLM system. The 'XXX' refers to specific linac section and runs over all section from including MEBT on.

2.2 Requirements on the components

The following has been required for the BLM system components:

1. Any BLM system hardware component shall be compatible with the radiation environment specific to the component location.

2. All components of the system (detector, electronics, mechanical support, software, firmware, etc) shall be compliant with the standards set by ESS ERIC. In particular, the firmware

design and implementation shall follow the FPGA Development Standards available in [4].

3. The same Fast Beam Interlock System (FBIS) interface card shall be used for all BLM systems.

2.3 Response time of the system (requirement)

The time response of the system is defined as the time from the onset of the beam loss to the time when the decision about unacceptable conditions reaches the output connector on the BLM side leading to the Fast Beam Interlock System (FBIS) interface card.

Currently the Machine Protection System (MPS) requires the BLM system to react within 10 µs in the Superconducting (SC) and within a couple of µs in the Normal Conducting (NC) parts of the ESS linac [3], the former being applicable to the icBLM system. However, these numbers were set in the past based on a simplified calculation of time needed to melt a block of material under a perpendicular incidence and for the beam parameters before [5] and after [6] the linac redesign in 2014.

2.4 Mode of operation

The icBLM system is based on ionisation chambers as detectors. Thus, it operates in current mode, where the measured current produced by the ionisation chamber scales with the flux of incoming ionising radiation that traverses the detector active area. Note that the scaling in general depends on incoming particle type, energy and incidence angle.

2.5 Detector design

Parallel plate gas ionisation chambers were selected as detectors for the icBLM system. They were originally designed by CERN for the CERN LHC BLM system when over 4000 detectors were produced and tested in the period between 2006 and 2008 by the Institute for High Energy Physics (IHEP) in Portvino, Russia. In 2014 the production line was restarted (830 detectors) in order to replenish spares for the LHC BLM and make production series for the GSI as well as for the ESS icBLM system. Following this production, 285 ionisation chambers were received at ESS in July 2017.

These chambers were selected as the icBLM detectors due to their fast response, being the fasts among the candidates considered at the time. In addition to this, the chambers are built for 20 years operation (in LHC conditions), have large dynamic range (10^8) and require little maintenance.

Schematic of the detector is shown on figure 1, while its main properties are summarised in table 2. The detectors are filled with nitrogen at 1.1 bar which is sealed inside a stainless-steel cylindrical container. The active volume of the detector consists of 61 parallel electrodes,

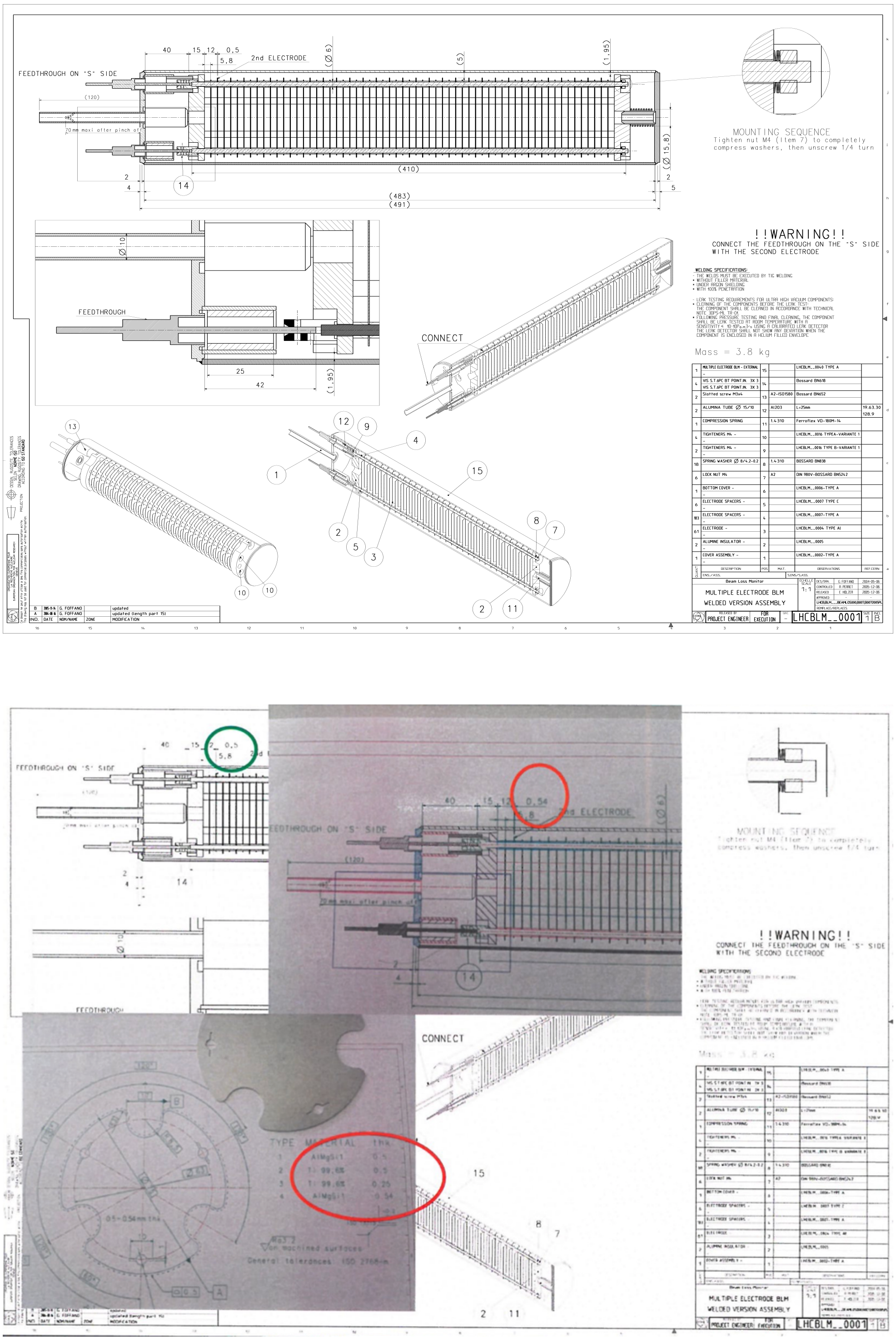

Figure 1: Schematic of an LHC type ionisation chamber for ic08 production (top [8]) and differences in comparison to ic17 production (bottom).

Detector property	Value
Container cylinder:	
tube wall thickness	2 mm
bottom/top plate thickness	5/4 mm
inner length	480 mm
Sensitive volume:	
diameter	85 mm
length	388 mm
detector gas	N_2
pressure	1.1 bar at 20 °C
Electrodes:	
material	Al alloy AlMgSiTi
num. of electrodes	61
electrode spacing	5.75/5.71 mm
electrode thickness	0.5/0.54 mm
electrode diameter	74 mm
operating voltage	1.5 kV
Ionisation:	
max e^- drift time	300 ns
max ion drift time	80 μs
$<$energy$>$ to create	
ion-e^- pair in N_2	35 eV

Table 2: icBLM detector properties (ic17 production).

where the gap between the electrodes serves to reduce the charge drift path and recombination probability of the ions and electrons, which results in a desired linear response of the detector. The gap size was set to 5.75 mm in the ionisation chambers produced in 2008 (ic08). In case of the chambers produced in 2017 (ic17) this gap size is reduced to 5.71 mm for every second electrode while keeping the spacer length unchanged. Thus, in case of ic08 the electrodes are made of 0.5 mm thick aluminium while in the case of ic17 the thickness of every second electrode is increased to 0.54 mm.

Each signal electrode is surrounded by two bias electrodes maintained at 1.5 kV during normal operation of the detector. 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.

The stainless-steel (AISI 316L) container cylinder is 483 mm long and 2 mm thick in case of ic08, while in case of the ic17 detectors the cylinder length is reduced by 1.5 mm on both sides. The bottom and the top cover are 5 mm thick with diameter of 87 mm.

For biasing the detectors to 1.5 kV, series SHV connectors (type 22SHV50-0-6/133NE) are used, while the signal is collected through a coaxial BNC connector (type R141 605 000W). The connector insulating material can withstand an ionising dose of up to 10 mGy (mixed particle field). PEEK and polystyrene were selected as the insulating material for the ic08 and ic17 production respectively. The two materials exhibit similar properties in terms of radiation hardness but different temperature limitations.

In order to stabilise the high voltage, a low pass filter ($R = 10\,\text{M}\Omega$, $C = 0.47\,\mu\text{F}$) is mounted on the high voltage (HV) input of the detector assembly.

Various test have been performed with the icBLM detectors. A full summary of the results if given in reference [28].

2.6 Expected particle fluxes and spectra

Preliminary studies based on Monte-Carlo (MC) simulations of lost protons for various loss scenarios along the DTL part of the ESS linac have been performed [6], [7]. This gave a rough estimation on expected beam related particle fluxes and spectra along the DTL section. A study focused on the SC parts of the linac is ongoing.

2.7 Expected dynamic range

The lower and upper limit of the dynamic range for the system are set by the L4 PBI requirements #2 and #3 in table 1 respectively. The values in terms of detected particles or detected signal can be estimated through MC simulations of lost protons and depend on detector location and in the case of upper limit on beam parameters and accidental loss scenarios as well. However due to a large number of possible accidental scenarios and lack of their time dependent loss maps, some simplifications and assumptions must be made. A strategy of how this is planned to be handled is given in [6], [7]. Preliminary studies based on MC simulations of lost protons for various loss scenarios along the DTL part of the ESS linac [6] gave a general view of expected particle rates along the DTL. However more work is needed to determine the icBLM detector signals, either taking these results as an input to an independent MC simulation of detector response or as new simulation runs with actual detector geometry in the model. The work is ongoing.

Nevertheless, icBLM is the main monitor in the SC parts of the linac, hence studies focused on DTL parts are of less importance in the context of the system requirements. In the past some rough estimations on expected dynamic range of the system in the SC part of the linac have been made [9]. Here it was required that the BLM is able to measure at least 1 % of 1 W/m loss during normal operation and up to 1 % of the total beam loss during an accidental loss scenario. These requirements led to estimation of the expected icBLM detector signal current to be in the range $\sim$800 nA and few mA, which gave preliminary values on the requirements for the signal acquisition (see section 2.11.1). However, these values need to be reassessed for various reasons, one of them being the fact that the highest signal is likely to be found in the detectors placed around the bend magnets and not along the accelerating structures as was considered in the study. Also, the condition for the upper limit of the dynamic range has not been properly justified.

2.8 Background

The background is expected to be mostly due to the RF induced low energy photons (X– and γ–rays). Additionally, low energy neutrons that are not related to the prompt beam losses can be expected. The RF induced background is mainly due to the field emission electrons from the cavity walls, resulting in bremsstrahlung photons created on the cavity or beam pipe material [1]. The levels of this background are difficult to predict numerically as they depend on the quality of the cavities, time and operation conditions. However, energy spectra can be estimated due to the known cavity field gradients and physical process involved in the production of this background (bremsstrahlung). These estimations show that photons with up to few tens of MeV can be expected [10].

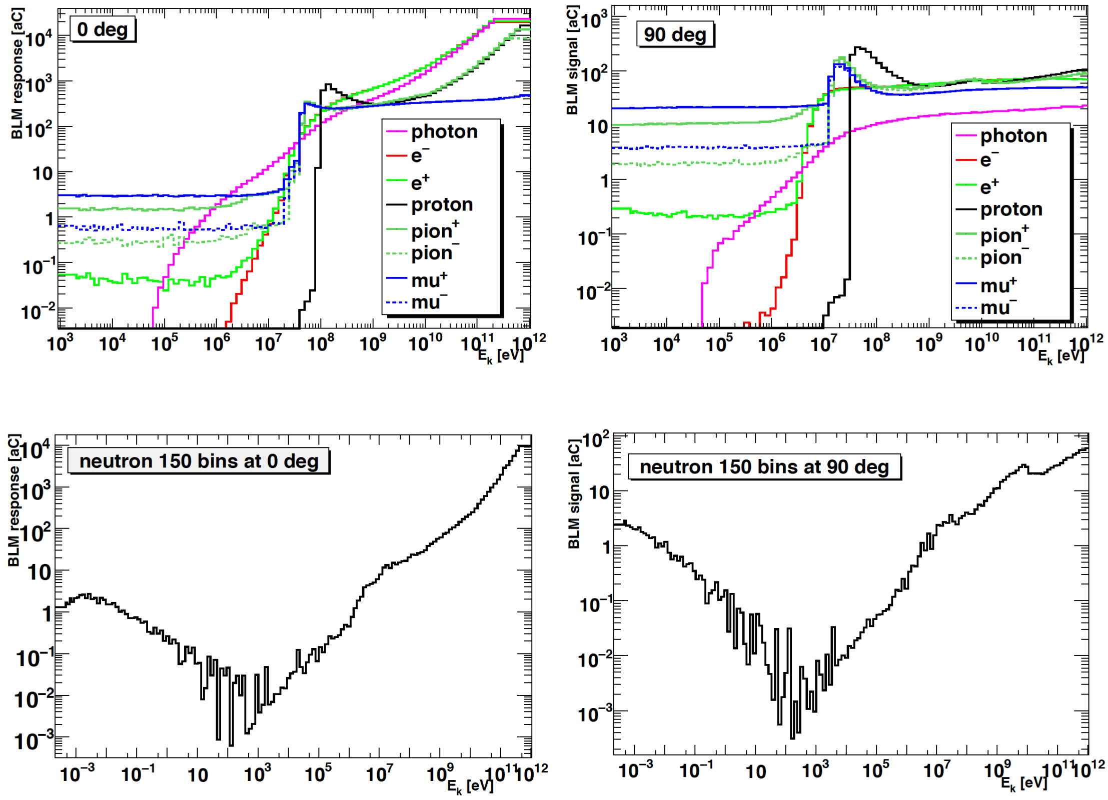

Figure 2: LHC type ionisation chamber (ic08) response functions (per primary particle), Left plots are for particles impacting the detector along the detector axis (i.e. along the tube) and fight plots for perpendicular incidence angle.

Ionisation chambers are like any other charged particle detectors sensitive mostly to charged particles though not insensitive to photons or neutrons. Figure 2 shows simulated response functions of the LHC type chambers (ic08) for various particles at two extreme incidence angles [11]. Here one can estimate the cut off energy below $\sim$2 MeV for photons (and electrons) and$\sim$30 MeV for protons, while drop in the neutron response functions with minimum around 10 keV can be observed. Thus, some background contribution from both RF induced photons and thermal neutrons can be expected. The RF induced background is planned to be assessed experimentally in environments as close as possible to the ESS linac. This is available at LINAC4 with environment close to what is expected at the ESS DTL and at the ESS test stands with SC linac cavities.

The background due to the thermal neutrons can be estimated to some extent through MC simulations of lost protons along the linac, however special care must be taken due to the focus on the thermal neutrons. Rough estimations in the DTL regions are available in results from studies in [6]. Studies focused on the SC parts of the linac are ongoing.

2.9 Detector count and layout

Being the primary loss monitors in the SC parts of the ESS linac, the icBLM detectors are almost exclusively located in these parts with exception of 5 detectors in the DTL. In general, there are 3–4 icBLM devices per lattice cell in the SC linac, namely 4 where there is a cryomodule and 3 in the transport section. Here 3 detectors surround the two quadrupole magnets located in each Linac Warm Unit (LWU) while 1 detector is positioned at each cryomodule. The full detector layout for both icBLM and nBLM is given on figure 3 and a summary of detector count in table 3.

2.10 Detector mounting

The same concept for icBLM detector mechanical supports in Spoke and Elliptical LWUs has been adopted. The conceptual design for these supports has been integrated in the ESS Plant Layout (EPL) 3D model as shown in figure 5. Here the detector supports are attached to the LWU supports and hold the detectors 45° from the vertical axis with detectors centred on the beam line. The angle of 45° has been chosen as a baseline though other orientations and positions around the beam axis can be achieved by replacing the holder.

The same design as in the case of Elliptical and Spoke LWU supports is planed to be reused for the A2T and dump line sections of the linac. The mechanical integration will proceed once the updated A2T and dump line models are available.

Two options for the mechanical support of detectors located at cryomodule positions are available. The detectors can be either attached to the cryomodule through a metal band or attached to an aluminium profile hanging from the ceiling. The former option is planned as the baseline solution with the later as a backup. The work is ongoing.

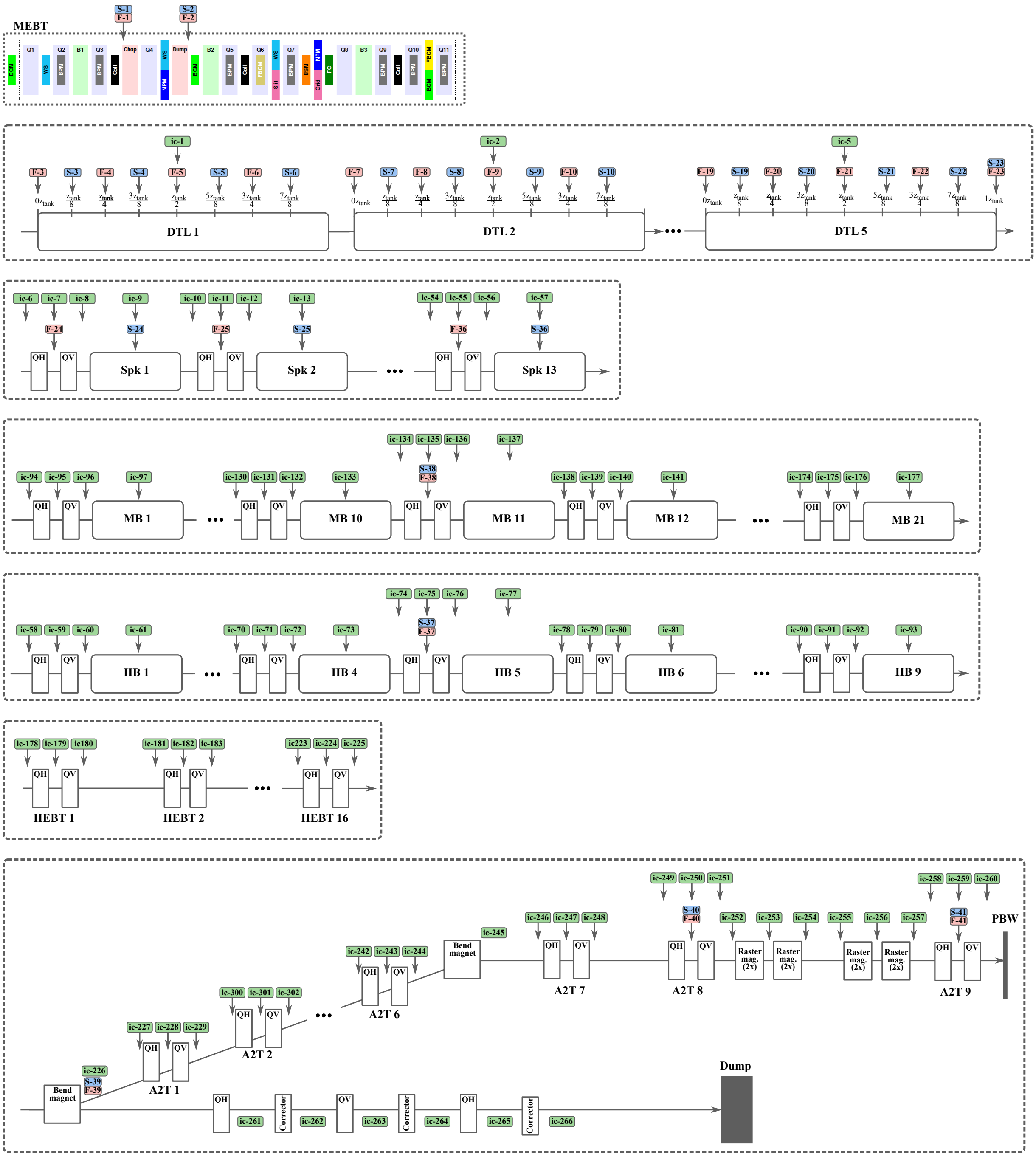

Figure 3: nBLM and icBLM detector layout along the ESS linac [12].

Linac section	Num. of devices			
	icBLM		nBLM	
	comment	count	comment	count
MEBT		/		2F+2S=4
DTL	1/tank	5×1=5	8/tank,2/end	5×(4F+4S)+1F+1S=42
Σ		5		23F+23S=46
Spoke	1/cryo,3/2q	13×4=52	1/2q, 1/cryo	13×(F+S)=26
MB	1/cryo,3/2q	21×4=84		1F+1S=2
HB	1/cryo,3/2q	9×4=36		1F+1S=2
MEBT	3/2q	16×3=48		/
A2T				
ramp	1/bend,3/2q	6×3+2×1=20		1F+1S=2
to target	3/2q, 3/4rast.	3×3+2×3=15		2F+2S=4
dump	1/mag.	6		/
Σ		261		18F+18S=36
ΣΣ		266		41F+41S=82
ΣΣΣ				348

Table 3: icBLM and nBLM detector count in each of the ESS linac section. Here "q", "bend", "rast.", "mag." and "cryo" syand for quadrupole magnet pair, bend magnet, raster magner, magnet and cryo module.

The DTL icBLM detectors are planned to be attached through a holder on the rail supporting the nBLM detectors with their holders (see figure 4). The icBLM holder design is under development.

In sections where the mechanical support integration is not finalised yet, the space for detectors has been claimed in the EPL model. All Elliptical and Spoke LWU detectors are placed on the walk side of the beam line while others are placed on the walk side where possible.

A layer of G10 is planned to be used between the holders and detectors in order to electrically isolated the detectors from the support.

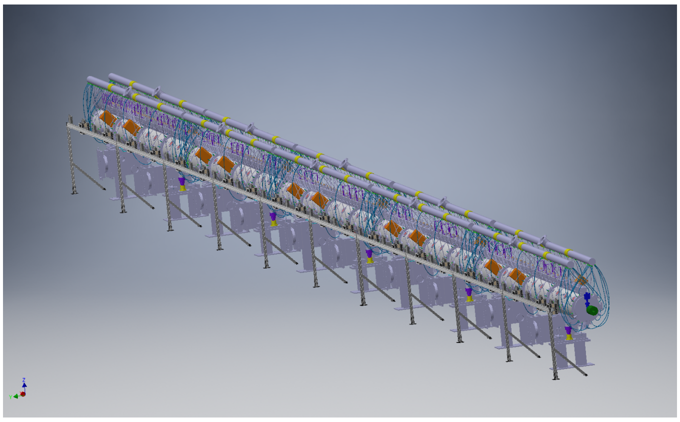

Figure 4: nBLM detector mounting in MEBT section [33].

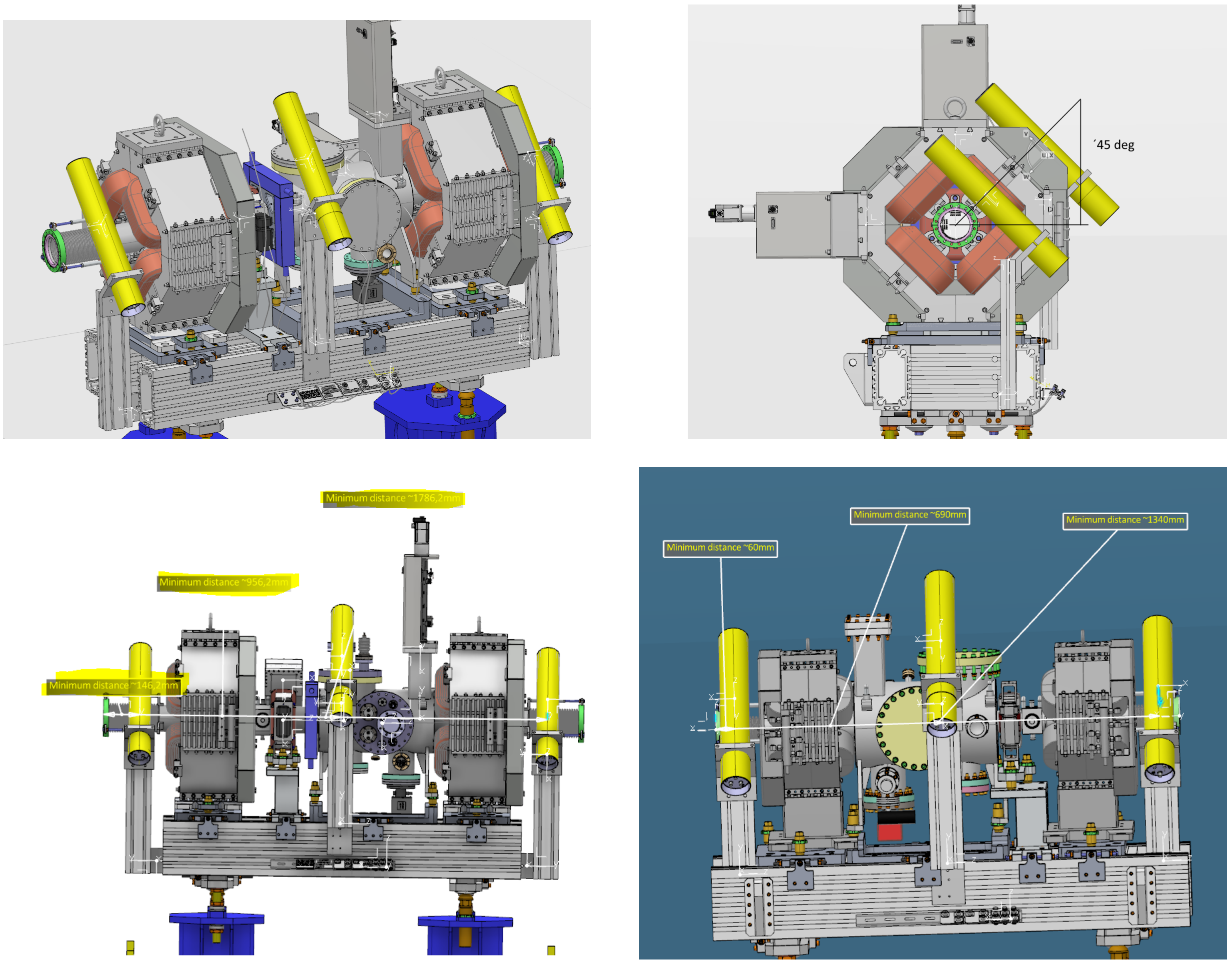

Figure 5: Conceptual design of the icBLM detector mechanical supports in Elliptical (top and bottom left) ans Spoke (bottom right) LWUs [27]. Minimum distances along the beam line form the LWU start are indicated on the bottom figures.

2.11 Components overview

Analogue signal from each icBLM detector located in the ESS tunnel are routed through a twinax cable to the klystron gallery, where it connects to the Back-End Electronics (BEE). Here the signal is first digitised by an acquisition unit and then processed by a processing unit. The unit was selected to be the μTCA based IOxOS IFC1410 AMC board equipped with an FPGA [13]. The board includes a CPU as well, however a Single Board Computer (SBC) has been selected instead of the embedded CPU for the final icBLM design. The choice is consistent with the design of nBLM and other beam diagnostics systems. The main role of SBC is to provide an interface to the ESS control system. The SBC type is compliant with the ESS standards. Similarly, an ESS standard timing module (Event Receiver – EVR) is used to interface the ESS timing system.

Signal cables running from the tunnel to the klystron gallery are enclosed in cable conduits for additional shielding. It is planed to have each conduit housing signal cables from several different systems (icBLM, nBLM, BCM). The work on requirements and design of signal cables is ongoing.

The detectors are biased with 1.5 kV through a 1 channel ISEG High Voltage Power Supply (PS) unit (DPr 40 305 24 5_CAB High Precision HV-PS, DPS series [14]). The unit feeds a group of 5–7 detectors in parallel.

Figure 6 shows a schematic overview of the icBLM system conceptual design, while details about cable and connector types is given on figure 7.

2.11.1 Signal acquisition unit and long–haul signal cable choice

The following lists requirements for the icBLM signal acquisition unit:

1. Input current dynamic range shall at minimum cover 10 nA to 10 mA - derived from system dynamic range estimations (see section 2.7).
2. The signal acquisition card shall have a resolution of at least 20 bits - relates to the lower limit of the dynamic range mentioned in the point above.
3. The signal acquisition cards shall have a typical noise better than 10 nA in its lowest range, including temperature induced noise.
4. The signal acquisition card shall feature a bandwidth of at least 300 kHz and a minimum sampling rate of 1MS/s - derived from the required minimum response time (see section 2.3).

Two options for the acquisition unit have been considered:

1. **Customised Pico card**, which is an FMC for monitoring bipolar currents based on CAENels FMC-Pico-1M4 [15] customised to fit to the icBLM system needs in terms of bandwidth and input signal current range. Modified board characteristics are:

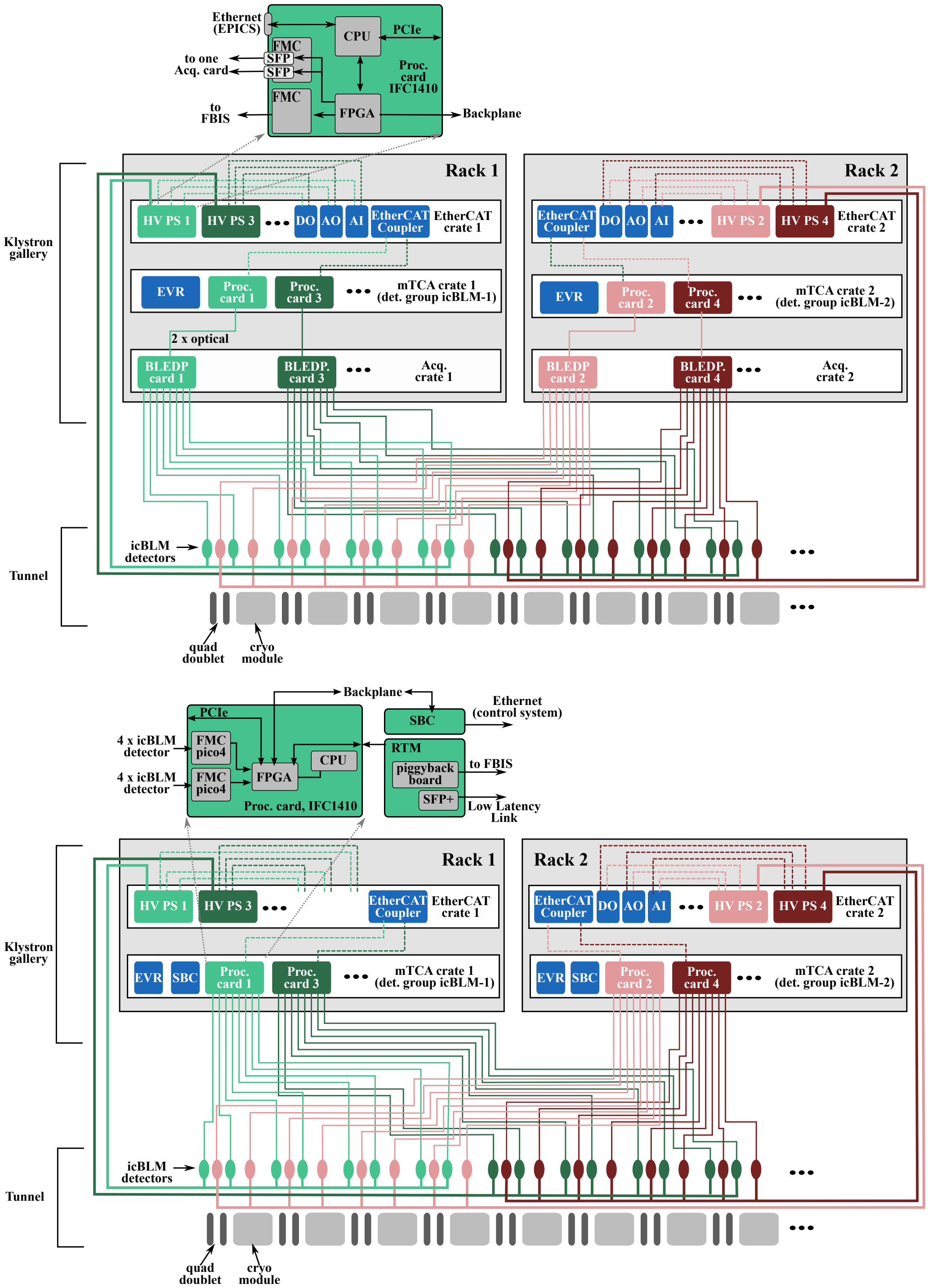

Figure 6: icBLM system conceptual design in case of BLEDP card (top) or customised pico4 (bottom) option for the acquisition unit. Formation of odd (marked with green) and even (marked with red) group of detectors is explained in the section 2.12.

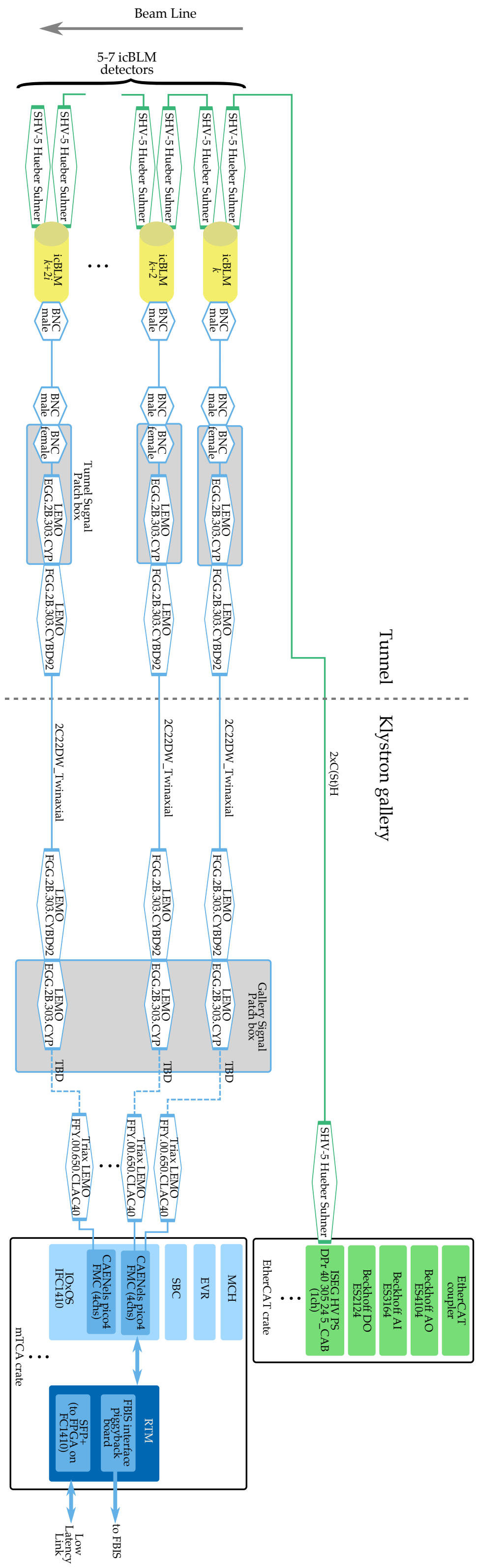

Figure 7: Overview of icBLM components per one processing unit together with cable and connector types.

- It is a 20–bit 4–channel bipolar sampling ADC.
- Has input bandwidth of $\sim$300 kHz.
- Operates in two ADC measuring ranges of $\pm$10 mA and $\pm$500 µA. The transition between the ranges is not automatic but can be done manually on the fly.

In this solution, the pico FMC is mounted on the processing board IFC1410.

2. **BLEDP card** (Beam Loss Electronics - Double Polarity acquisition module) [16], an 8–channel current digitiser card developed for the new BLM system at the CERN injector complex with the following characteristics:

   - The input current measurement is performed by two different techniques:
     - Current to frequency converter (FDFC) is used in the range of 10 pA–10 mA and
     - Direct ADC (DADC) acquisition in the range of 100 µA–200 mA.

     The transition between the ranges is managed by an FPGA.
   - Minimum acquisition period is 2 µs.
   - The card dynamic range is
     - from 31 nA to 200 mA at minimum acquisition period of 2 µs and
     - from 10 pA–200 mA for integration times above 6 ms.
   - Input bandwidth of the card is 1 MHz.
   - The card has a fully differential front end and two SFP output connectors (gigabit optical).
   - The card provides a 16–bit current measurement in the DADC and 20–bit in the FDFC mode.

   The card in its current firmware measures only positive currents. Tests at ESS confirm this, though configuration issues might potentially explain the behaviour.
   The digitised icBLM output signal in this solution is routed through an optical link to an SFP port on an FMC card located on the IFC1410 board, where the FPGA based data processing takes place. The BLEDP cards are placed in a custom-made crate located in the klystron gallery.

The decision between the two acquisition unit options has be taken towards the end of 2018, when pico4 option has finally been chosen. Despite its better performance the BLEDP card in terms of noise, the decision was based on the difference in level of maturity between the cards and limited ESS resource to work on the BLEDP card.

Preliminary tests performed at ESS demonstrate superior performance of the BLEDP over the customised pico4 card in terms of noise [17]. The BLEDP card shows almost no dependence on the cable type and length while the pico4 card exhibits stronger dependence on these variables. Thus, a good quality ultra-low capacitance long–haul signal cable is desired for the pico4

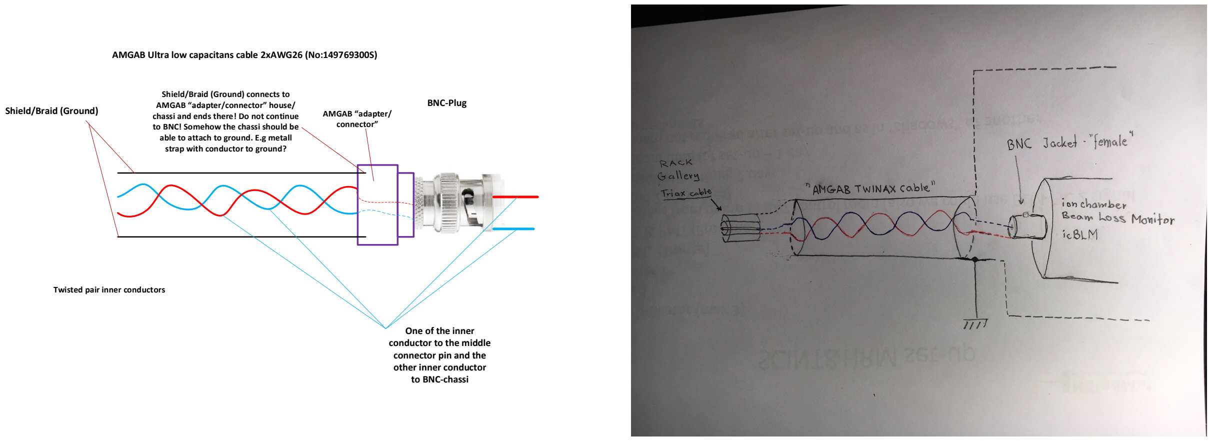

Figure 8: Schematic of the icBLM twinax signal cable connection on the detector side [18]. Note that Belden cable instead of the AMGAB was chosen for the final design.

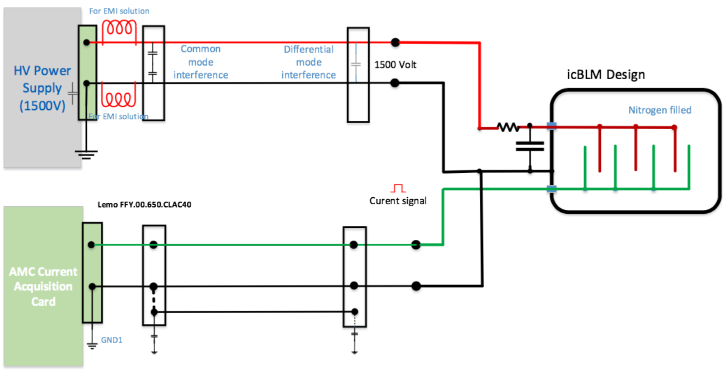

Figure 9: Overall connection and grounding scheme for one detector [29].

option. Two different twinaxial cables have been considered. A twinax cable with 15 pF/m theoretical capacitance (conductor-conductor), custom made by AMGAB or a COTS cable from Belden with slight higher capacitance. Though slight worse in terms of capacitance, the latter was chosen for the final design due to cost constraints. Figure 8 shows the signal cable connection scheme on the detector side. The overall connection and grounding scheme for a detector is given on figure 9. Further details are given in [29].

Several tests of the final digitiser and long–haul cable types have been performed. The results are summarised in [29, 30, 31].

2.11.2 HV PS control

The ISEG PS, provides a small voltage modulation to the icBLM detectors, in addition to the applied 1.5 kV DC HV. This results in modulation of the measured detector current, which offers a way to diagnose failures in the system by simply monitoring the detector currents and checking for the presence of the modulation. This is done by the FPGA, located on the processing unit (IFC1410). The status of modulation is reported to the user in control room, which can further diagnose the problem and act accordingly in case of missing modulation. Potential automatic actions by the FPGAs may be foreseen in future upgrades of the system once its behaviour is understood.

The ISEG PS unit is located in an EtherCAT crate in the Klystron gallery, together with an AO (Beckhoff ES4104 [20]), AI (Beckhoff ES3164 [21]) and DO (Beckhoff ES2124 [22]) modules. Both modulation and DC voltage are driven point by point through the IO modules, which are connected to the ISEG unit via a D-SUB 9 connector for controlling and monitoring purposes. The real-time kernel [35], running on the SBC, is responsible for computing the voltage set points. The communication between the IO units and the real–time kernel is performed via Ethernet connection with the EtherCAT coupler unit located in the EtherCAT crate, which serves as an interface to the IO units.

The EVR module is used to send 14 Hz triggers through the EL1252-0050 DI module [38] to the real–time kernel in order to synchronise the modulation phase to the accelerator timing. The DI module is powered by EL9505 module [39].

Modulation tests [36] have been performed with a HV unit which was previously considered as a candidate for the icBLM system. The tests show that the working modulation frequency and amplitude are on the order of few 0.1 Hz and few 10 V respectively. Note that the modulation must be low enough not to disturb the loss measurement as modulation correction is planned to be part of pre–processing only for the upgrade of the system. The final selection of modulation amplitude and frequency depends on the background loss level, noise level and averaging. Note that the tests were performed with short cables and the situation may be different in the real system when long cables used. The test with long cables is planed to be performed in the near future.

2.11.3 FBIS interface and Low Latency Link connection

A piggyback card providing a set of electrical interfaces to the ESS Machine Protection Fast Beam Interlock System (MPS FBIS) has been foreseen. The card may either be used through an FMC or RTM card [19] that can be paired with the IFC1410 platform.

All BLM subsystems are required to use the same FBIS hardware interface options and be able to process up to 8 detector channels. The IFC1410 card has two FMC slots available. In case of nBLM, only one FMC slot is occupied (with 8-channel ADC3111) and the other one can be used for the FBIS interface. However, in case of icBLM, the RTM solution is the only available choice if the pico4 card (4 channels) is selected as the acquisition unit, while both RTM and FMC solution are possible in case of BLEDP (8 channels) selection.

As the pico4 option has been chosen in the final design of the icBLM, the RTM based interface to FBIS has finally been selected. However the RTM card is currently still under development and is anticipated to be available only in September 2019. Therefore an intermediate solution based on a IOxOS DIO3118 DIO FMC [23] has been foreseen as an intermediate solution for test purposes, though this option does not fulfil the FBIS interface requirements. The interface document between BLM systems and FBIS is available in reference [40]. The exact definition of all signals exchanged with the FBIS is not finalised and is under discussion with Machine Protection (MP) team.

An option to combine the data originating from different processing units is foreseen for the future upgrade. This can among other things enable identification of coincident signals between two different BLM channels that are not processed by the same BEE card or even between a BLM channel and certain condition on a BCM channel. The approach requires a functioning Low Latency Link (LLL). At least one SFP+ connection to the FPGA has been foreseen to be provided through the above mentioned RTM card. In case of nBLM and icBLM systems the connection is planned to be used for LLL communication.

2.12 Electronics layout

Each card, crate or rack is responsible for handling several detectors. In case one of these units experiences malfunction, the system may cease to be able to report beam losses over several subsections of the linac and in the worst case even fail to react on dangerous beam conditions. This poses a threat to the safety of the machine elements and if a larger part of the system becomes unavailable inhibiting beam production may be inevitable.

In order to avoid these situations and to increase the system availability, the detectors are collected in two types of groups, odd and even, depending on their location number which monotonically increases along the linac. The general idea is to separate these two types of detector groups down to the rack level and place all electronics needed for each of the groups in a separate rack. In addition to this, HV connections follow exactly the same separation scheme and grouping as the signal connections. Hence,:

1. The number of detectors connected to each processing card equals to the number of detectors powered by one HV unit (i.e. one HV channel). Both of these units are located in the same rack.

2. The number HV units in each EtherCAT crate equals the number of processing units in a μTCA crate located in the same rack. The detector distributions among the units is identical for both type of units.

3. The number of HV crates equals the number of μTCA crates for signal processing. Both are located in the same rack. The detector distributions among each of the crates is identical for both type of crates.

The idea is schematically presented in the figure 6.

In reality the system will occupy several racks while following the above-mentioned scheme. The layout is presented on figure 11 and summarised in table 4, while the full overview is available in [24]. Note that the odd and even detector groups are separated down to the rack level for major part of the linac, while in the end parts (A2T, Dump line and towards the end parts of HEBT) the separation runs down the crate level in order to avoid the cable length exceeding the 100 m limit. Separation down to the crate level refers to the fact that both crate types (i.e. those with only odd or only even detectors connected to it) are located in the same rack instead of separate ones.

Long haul signal cable lengths were estimated based on the layout shown on figure 11 under the assumption that the cables will be routed through the closest stub also shown on figure 11. A typical length of a long haul signal cable is estimated to be between 45 m and 70 m, though lengths close or around 100 m are reached for detectors located in the end parts of the linac.

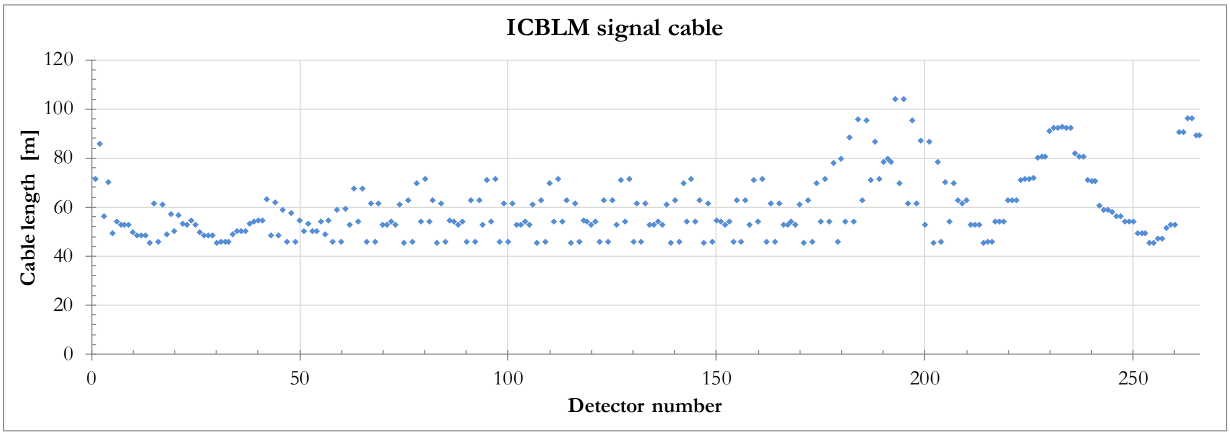

Figure 10: Estimated icBLM signal cable length.

Detector group	Rack	#Detectors	Det. group type	#Proc. cards	Detector distribution
ICBLM-01	SPK-010ROW	7	odd (green)	1	{7}
ICBLM-02	SPK-030ROW	20	even (red)	3	{7+7+6}
ICBLM-03	SPK-050ROW	26	odd (green)	4	{7+6},{7+6} (or {6+5+5+5+5+5})
ICBLM-04	MBL-020ROW	20	even (red)	3	{7+7+6}
ICBLM-05	MBL-050ROW	16	odd (green)	3	{6+5+5}
ICBLM-06	MBL-090ROW	16	even (red)	3	{6+5+5}
ICBLM-07	HBL-050ROW	16	odd (green)	3	{6+5+5}
ICBLM-08	HBL-090ROW	16	even (red)	3	{6+5+5}
ICBLM-09	HBL-120ROW	16	odd (green)	3	{6+5+5}
ICBLM-10	HBL-160ROW	19	even (red)	3	{7+6+6}
ICBLM-11	HBL-200ROW	15	odd (green)	3	{5+5+5}
ICBLM-12	HEBT-010ROW	14	even (red)	2	{7+7}
ICBLM-13	HEBT-030ROW	21	odd (green)	3	{7+7+7} (or {6+5+5+5})
ICBLM-14	HEBT-030ROW	12	even (red)	2	{6+6}
ICBLM-15	A2T-010ROW	16	odd (green)	3	{6+5+5}
ICBLM-16	A2T-010ROW	16	even (red)	3	{6+5+5}
Σ		266		45	

Table 4: icBLM electronics layout summary. Note that the layout of signal connections is identical to the one for HV layout hence the table represents both. Each row represents a group of odd or even detectors connected to the same rack, where the group type is as defined on figure 11. The last column on the right shows the number of detectors connected to each processing or HV unit in each μTCA or EtherCAT crate respectively. The cards/units are marked by "+" sign, while "{}" distinguishes between crates of the same type.

Figure 11: icBLM detector and electronic rack layout along the linac. Green and red circles mark different types of detector groups (even and odd respectively). Different levels of these circles along y-axis distinguish between a collection of detectors connected to the same rack. Signal cables from these detectors are routed through the nearest stub (yellow squares) to the racks marked with green, red or blue squares. This routing is used to estimate the signal cable lengths shown on figure 10. The red and green colour of squares indicates which group type connects to particular rack, while the blue squares mark racks which have both odd and even detectors connected to it (located in separate crates). Hence, the 1. line of odd detectors connects to the 1. rack, 1. line of even detectors to the 2. rack, 3. line of odd detectors to 4. rack etc.

3 Data processing

The focus of this chapter is the functionality of the FPGA based data processing in icBLM system. After listing the requirements related to the topic of data processing and monitoring, specifications of the data processing functionality are explained through a block diagram.

3.1 Requirements

The following gives a summary of both processing and monitoring requirements for the icBLM system:

1. The icBLM system shall be able to run standalone and can function even when the ESS linac is not in operation.

2. Each icBLM processing card shall be able to process and provide monitoring data for up to 8 input channels (8 icBLM detectors) simultaneously.

3. The signal from each channel shall be digitised and sampled at minimum 2MS/s.

4. All BLM systems shall follow the same approach where applicable (same monitoring data, user panels, ...).

5. Monitoring data shall be available to the user in the control room either:

   (a) **On demand** through the Data-On-Demand functionality. Details of the DoD concept is available in [25],

   (b) or **periodically** with the highest frequency equal to the nominal machine repetition rate of 14 Hz.

6. Requirements on data available to the user on demand (DoD data):

   (a) This data shall be continuously buffered and accessible to the user without stopping the data processing or buffering.

   (b) Minimum 3 consecutive pulse periods of raw data and 100 pulse periods of processed data shall be available to the user for retrieval on demand. Here the pulse period is defined as 1/(14 Hz).

   (c) The user shall be able to set pre– and post–trigger. Note that here the trigger tags a particular pulse period.

   (d) In case of raw data, the post and pre–trigger can be at minimum set to select from 2 pulse periods before to 2 pulse periods after the tagged pulse period (in addition to the tagged pulse), giving together minimum 3 consecutive pulse periods per request.

(e) In case of processed data, the post and pre–trigger can be at minimum set to select from 99 pulse periods before to 99 pulse periods after the tagged pulse period (in addition to the tagged pulse), giving together minimum 100 consecutive pulse periods per request.

7. There shall be at minimum three different types of trigger requests that can issue a retrieval of the buffered DoD data:

   (a) **Post–mortem**: on post–mortem event when one of the systems connected to the machine protection system drops the BEAM_PERMIT signal.

   (b) **Periodic**: for example once per day we want check the full history of neutron counts over several pulses.

   (c) **Conditional**: when certain conditions are reached in one of the systems with available DoD functionality (for example in nBLM, when monitored pedestal value reaches a certain limit).

   The user is responsible to configure each of these DoD trigger requests. This includes enabling channels, per– and post–trigger, periodicity in case of 7b and conditions in 7c).

3.2 Specifications on data processing

A block diagram representing an overview of the FPGA functionality for one icBLM channel (detector) is shown on figure 12 and a brief summary is given in this section.

3.2.1 "Raw data type selector" block

This block switches between two options for the input raw data:

- Real raw signals produced by a detector channel, to be used during normal linac operation.
- Simulated data or previously measured data provided by the user in a form of a data file. This option is used when system performance validation is needed.

The user is able to select between the two options on the fly.

3.2.2 Pre–processing

The input signal is sampled by the pico4 based acquisition unit at 1MS/s sampling rate This raw data is first pre–processed, which currently includes only baseline subtraction. Baseline subtraction is needed in order to diminish the influence of the RF induced photon background on the beam loss measurements.

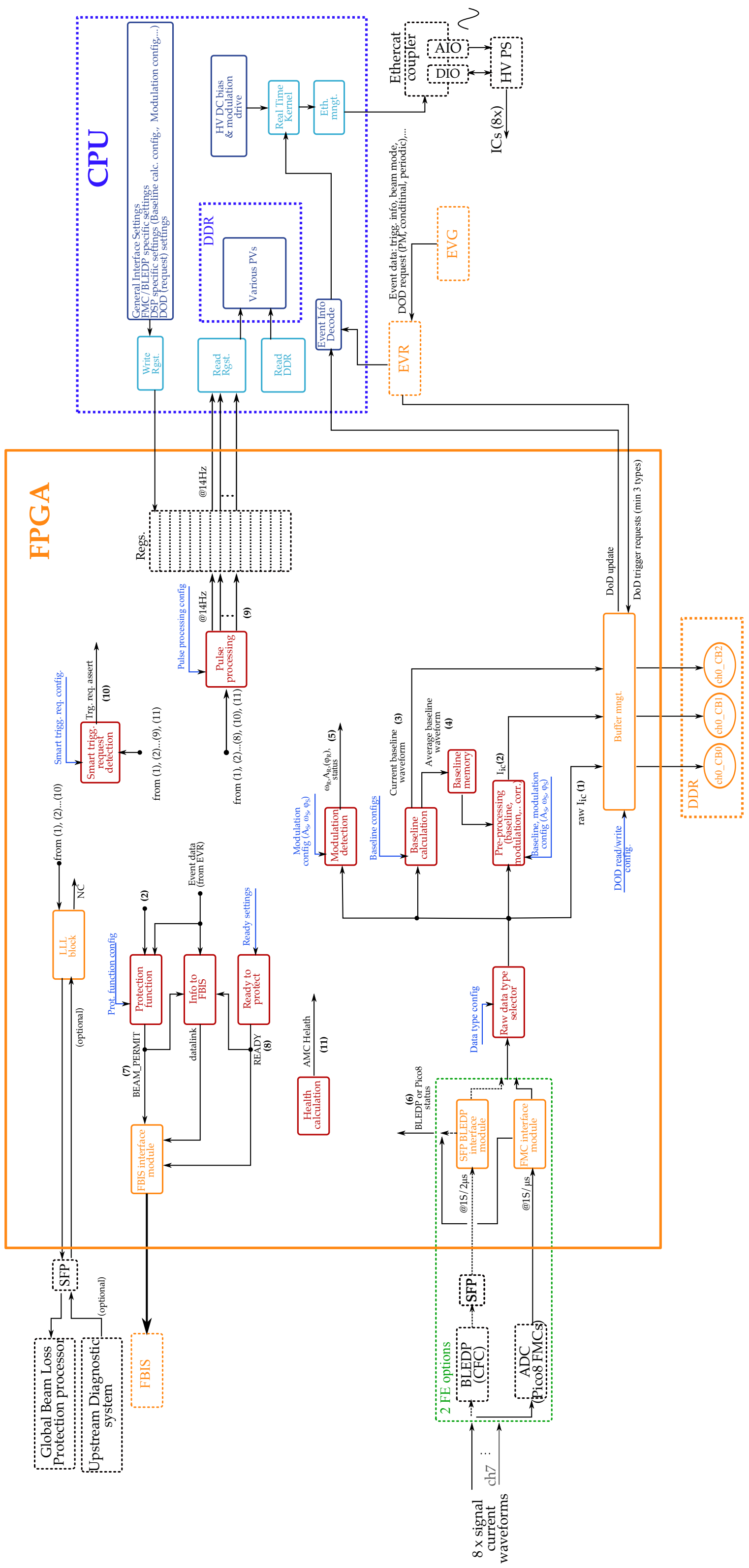

Figure 12: Block diagram of data processing in the icBLM system [26].

In this context baseline is a waveform calculated by the "Baseline calculation" block and is performed for each icBLM channel/detector separately. The waveform is subtracted for every machine pulse period with present RF_ON period from the raw data on a point by point basis in a time window including the RF_ON period. The length and start of the time window measured from the RF_ON trigger are consistent with the values defined in the "Baseline calculation" block.

Potential upgrades of this block include modulation correction and corrections for cable distortion or gain degradation due to the radiation induced damage.

3.2.3 "Baseline calculation" block

The block calculates mean baseline waveform of the RF induced photon background. This waveform is used for baseline subtraction in the pre–processing block mentioned above.

Certain number of pulses without beam are planed to be present during the linac normal operation. These diagnostic background pulses are planed to be used as a background reference for icBLM and BCM systems. Only waveforms from these pulses are considered as background qualified and are included in the baseline calculation. The mean baseline waveform is calculated as running average of certain number of last background qualified waveforms. The number is configurable. In addition to this, the waveform start with respect to the start of RF_ON period as distributed by the timing system is configurable as well in order to account for different detector locations along the beam line and thus difference in delays. Similarly, the waveform extension on each side of the RF_ON period can be configured as well.

Potential upgrades of this block involve including a forgetting factor in the sliding window in order to reduce the influence of the "older" waveforms.

3.2.4 "Modulation detection" block

As mentioned in section 2.11.2, small amplitude modulation with certain frequency is added to the high voltage power supply of the detectors, which results in a small current modulation in the measured data. The purpose of this block is to detect whether this modulation present.

The outputs of this block are the detected modulation frequency together with the status bit indicating if these values are within the user selected range from the actual values that were set by the user. In case of inconsistency it is user's responsibility to further diagnose the problem and act accordingly. Potential automatic actions by the FPGAs may be foreseen for future upgrades of the block once the behaviour of the system is understood.

3.2.5 "Protection Function" block

The "Protection Function" block takes the detector signal sampled at 1MHz rate as the input. The primary task of this blocks is to assess whether conditions to inhibit beam production have been met. In case they have, the block drops the BEAM_PERMIT signal on the line connected to the FBIS through the FBIS interface. FBIS then further handles stopping of the beam production. Note that, though binary from perspective of information, the BEAM_PERMIT signal is continuously transmitted to FBIS (not in frames).

Each AMC provides one aggregated BEAM_PERMIT signal independent on the number of detector channels connected to it. The BEAM_PERMIT calculation starts with calculating the value for each channel separately, BEAM_PERMIT_c (c runs over all channels on the AMC). This is performed by checking if the beam inhibit condition on each particular channel has been reached. The final BEAM_PERMIT is then determined by AND–ing the BEAM_PERMIT_c of all channels that are not masked out from the calculation:

$$\text{BEAM\_PERMIT} = \bigvee_{c \notin \text{masked}} \{\text{BEAM\_PERMIT}_c\}. \tag{1}$$

Note that some detectors might be too noisy and may thus be excluded from the final BEAM_-PERMIT calculation. In addition to this, there may be situations when it is desirable to exclude certain detectors from the calculation (controlled losses, detectors close to Faraday Cup when it is inserted). For this reason, each channel can be masked out from the BEAM_PERMIT calculation.

In order to avoid spurious BEAM_PERMIT drops based on assessment of a single data point on a single channel temporarily polluted with noise spike(s), some filtering of the input icBLM detector signal is planned. Three different types of filtering algorithms have been identified so far as interesting for this purpose: relaxation filter, X/Y algorithm, moving average filter or simple average. For a given channel c, the output of a filter is recalculated on each new detector signal data point and compared to a certain machine protection threshold value (I_c^{MPthr}).

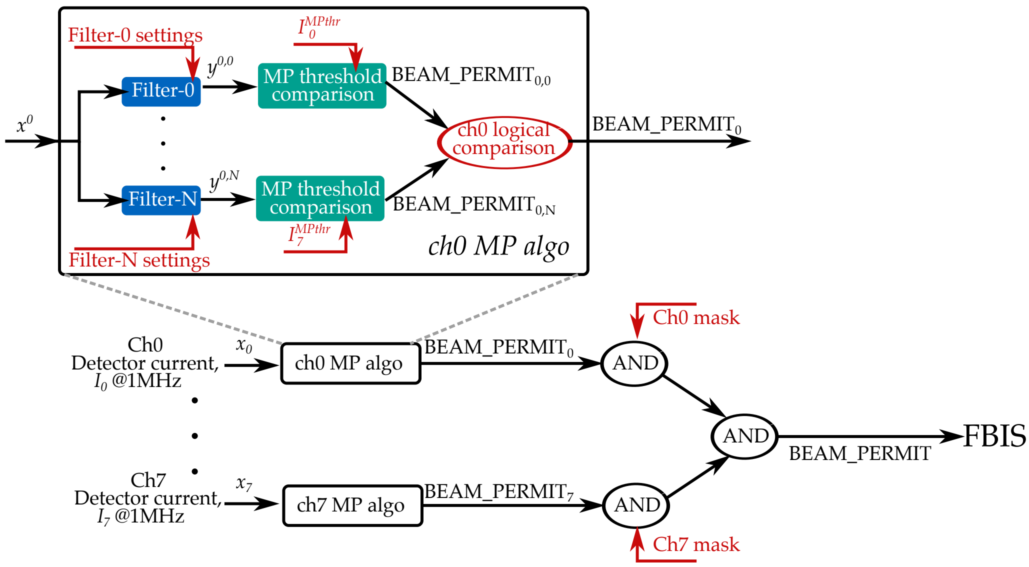

Figure 13: Schematic of the BEAM_PERMIT calculation for each AMC. Red colour marks configurables.

If the output of the f-th filter on c-th channel is above this value, then the beam inhibit condition has been reached and the corresponding BEAM_PERMIT$_{c,f}$ for the filter and channel in question is dropped to down state (0), otherwise it is left at up state (1). One or several selected filters are considered in the channel BEAM_PERMIT$_c$ calculation by logically combining their BEAM_PERMIT$_{c,f}$ through AND or OR logical operators. Selection of the filters and the sequence of logical operators used in the beam permit calculation can differ from channel to channel and is configurable by the user. A schematic representation of the BEAM_PERMIT calculation for each AMC is summarised on figure 13.

In the following a short description of filtering algorithms of interest is given.

1. **Moving average**
   Denoising in case of moving average is based on calculating a local average over the time window of t_{MA} containing the last n input data points:

   $$y_k = \frac{1}{n}\sum_{l=0}^{n-1} x_{k-l}. \tag{2}$$

   Here x_k and y_k represent filter input and output values respectively. With increasing the number of points included in the average, n, smoothing is improved, though on the expense of increasing the delay of the output y compared to the input x.

2. **Relaxation filter**
   Relaxation filter is an IIR (Infinite Impulse Response) filter of the first order with a feedback. It takes a weighted sum of the old output y_k and the new input value x_k as the new output y_{k+1}:

   $$y_{k+1} = \frac{m-1}{m} y_k + \frac{1}{m} x_k \quad \text{or} \tag{3}$$

   $$y_{k+1} = \lambda y_k + (1-\lambda) x_k, \quad \text{with} \quad \lambda = \frac{m-1}{m}. \tag{4}$$

   The parameter λ can take values $0 < \lambda < 1$. If $m \to \infty$ then $\lambda \to 1$ and the filter forgets the past values to a smaller extent. With λ very close to 1 the smoothing power is comparable to the case of a moving averag filter with a large number of points.
   The continuous equation governing the relaxation filter can be written as

   $$\tau \frac{dy}{dt} = -y + x. \tag{5}$$

   where $\lambda = 1 - dt/\tau$. The equation is equivalent to a 1-st order lowpass filter with time constant τ. The difference between relaxation filter and a typical low–pass filter is in the cutoff frequency. In case of a low–pass filter the signal of interest is in the passband and the cutoff frequency is set above the highest acceptable frequency. On the other hand, the interesting signal is in stopband in case of a relaxation filter and the cutoff frequency is set below the lowest acceptable frequency.

3. **X/Y algorithm**
   For a given channel c, the algorithm takes Y last number of counts on this channel as an input, x_k. Each of these data points is compared to the machine protection threshold (I_c^{MPthr}). If X out of Y last data points exceed the threshold, then the BEAM_PERMIT$_{c,X/Y}$ attributed to this filter and channel c is dropped, otherwise it stays in up state.
   Note that in this case the filter output is already the beam permit state itself and not the smoothed detector current measurement as in the case of the two filters mentioned above.

4. **Simple average**
   Here the average value is calculated over a certain time window inside the pulse period. The calculation is caried out with a fresh set of values on each calculation restart. The values are thus not carried forward across restarts.

Five filter instances are anticipated to be tested during the beam commissioning of the icBLM system when protection algorithms are planned to be verified, namely relaxation filter, X/Y algorithm, 2 different moving average filters differing in time constants (fast with $t_{MA,1} \sim 1\,\mu\text{s}$, medium with $t_{MA,2} \sim 100\,\mu\text{s}$) and a simple average over beam pulse (over the BEAM_ON period). However the protection functons are planned to be co–developed across the beam instrumentation systems providing beam loss information. Hence further developments are foreseen following experience gained through system commissioning and ongoing simulations.

Another way to limit the spurious BEAM_PERMIT drops, is to base the BEAM_PERMIT calculation on requiring coincidences between neighbouring channels inside certain time windows. This option requires a functioning LLL block and is foreseen for the upgrade of the system.

3.2.6 Signals propagated to FBIS

In addition to the BEAM_PERMIT, the following signals are provided to FBIS by each AMC card:

- READY signal.
  This signal is dropped whenever the system is not ready to protect the machine. Like BEAM_PERMIT the signal is continuously transmitted to FBIS through "Ready to Protect" block. Currently the only potential usage for this signal is during start up periods when certain number of pulses without the beam can be sent and allow the system to collect enough statistics for a meaningful average baseline waveform. The user can choose for transition to READY to be either manually on the fly or automatic (after a user defined number of qualified waveforms have been collected).

- Datalink.
  The Datalink signal is transmitted with certain frequency and may contain the following information

  - Redundant (current) BEAM_PERMIT signal.

- ○ Redundant (current) READY signal.
- ○ Current Beam Mode and Beam Destination configured into the processing card (or as received from EVG).
- ○ Health status of the link, which is used by the FBIS to diagnose the problems in connection between the FBIS and the processing card. The health status is simply a value of the counter incremented in every packet/frame sent to FBIS.
- ○ AMC health status indicating the status of the data processing running on the AMC in question (see 3.2.11).

The exact definition of these signals is not fully finalised and is under discussion with the Machine Protection team. First draft of the interface document between BLM systems and FBIS is available in reference [40].

3.2.7 "Pulse Processing" block

The role of this block is to provide first stage of data post–processing. It transforms its inputs into variables with the fastest outgoing frequency of machine repetition rate (14 Hz), which can further be handled by the EPICS based monitoring and controlling software. The result of this post–processing, is a set of periodically updated data available to the user in the control room for monitoring. Full list of icBLM variables that are monitored periodically (periodic data) is available in table 6.

3.2.8 Buffering of data on demand

Certain processed data as well as raw signals are being buffered and available to the user on demand through the Data-On-Demand (DoD) functionality [25]. The data retrieval can start when the DoD buffer receives the DoD trigger request distributed by the master (EVG). In general the request can be issued either (see requirement 7 in section 3.1):

- Through the "Smart Trigger" by a certain system (nBLM, icBLM, BCM, etc, conditional trigger).
- On each post–mortem event.
- Periodically (periodic trigger).

List of icBLM data that can be retrieved through the DoD functionality is given in section 4.2.

3.2.9 "Smart Trigger" block

As stated in requirements in section 3.1, the DoD data can be retrieved by issuing a DoD trigger request, where minimum 3 different types of triggers are foreseen: post–mortem, periodic or conditional. Note that not all will be enabled at all times, the user enables and configures one or more of them when needed.

The “Smart Trigger” block is responsible for issuing a conditional DoD trigger. It takes various inputs, which can be considered as waveforms (for example, neutron counts sampled at 1 MHz), and asserts a trigger request (conditional trigger) on the output in case certain conditions have been met. The conditions are configurable and set by the user. The trigger assert is then propagated to the master (EVG) which can distribute this trigger request to all systems configured to listen to it. Although "Smart Trigger” has been conceived as part of the DoD concept, it can in principle provide triggers to anything that is listening.

The definition of “Smart Trigger” functionality is a part of the DoD concept and should be consistent among all systems partaking in the DoD service. As the DoD feature has not been developed far enough to include this definition, an initial version has been developed for the case of nBLM and icBLM systems. Though further changes and augmentations are expected in the near future as the DoD concept matures.

In the initial version of "’Smart Trigger” definition, the conditional trigger is asserted whenever a condition expression unit is satisfied. One conditional expression unit is available per each detector channel and is defined as

$$\mathscr{C}(a_i(w_j), v(a_i)) = a_i(w_j) \overset{\text{compare}}{\Longleftrightarrow} v(a_i), \tag{6}$$

where w_j represents the j-th input waveform available to the "Smart Trigger” block, while $a_i(w_j)$ indicates current value for its i-th atribute. The later is compared to the value $v(a_i)$ with operator $\overset{\text{compare}}{\Longleftrightarrow}$ which can either be $>$, $<$, $\geq$, $\leq$ or $=$. Both operator type and value $v(a_i)$ are set by the user.

As a general rule the user is able to configure a conditional trigger on any waveform w_j that can be visually inspected. In case of icBLM system the following input waveforms are available to the "Smart trigger” block as indicated in the block diagram:

- Raw data – marked with (1) in the block diagram.
- Pre–processed data – (2).
- Baseline calculation outputs:
  - Current qualified baseline waveform – (3).
  - Current average baseline waveform – (4).
- Modulation detection outputs – (5).
- Acquisition card status (if available) – (6).
- Outputs from the Pulse processing block – (9).
- Protection function outputs – (7).

- READY status – (8).
- AMC health – (11).

The numbers atributed to the items in the above list are consistent with the numbers indicated on figure 12. It may be too expensive to include smart triggering of all input waveforms on the firmware level. Thus smart triggering on certain waveforms (for example pulse processing block outputs) is moved to the software level in the actuall implementation. For further details see [34].

List of attributes that can be assigned to each input waveforme are common to all systems with available DoD functionality and are subjected to the DoD specifications. The list in the first version of the nBLM and icBLM "Smart trigger" definition includes:

- threshold on rising edge and
- threshold on falling edge.

3.2.10 "Low Latency Link" (LLL) block

This block is part of a concept foreseen for future upgrade and provides an option to combine the data coming from different system. An example of this would be, identification of coincident signals between two different BLM channels that are not processed by the same BEE card or even between a BLM channel and certain condition on a BCM channel.

3.2.11 "HEALTH Calculation" block

The goal of this block is to diagnose potential problems in data processing chain and report the "AMC health" status at a given ferquency. Calculation of the "AMC health" among other includes checking whether any part of the data procesing line is frozen or malfunctioning as well as status of the ADC FMCs. The exact calculation depends on the FW implementation details and is thus described in the document focused on the FW implementation description [34].

4 Monitoring and control

Requirements on monitoring of processed data have been specified in subsection 3.1, which collects all general requirements related to the icBLM data processing and monitoring. Hence, this section focuses solely on specifying the processed data to be monitored together with relevant settings available to the user. In addition to this, specifications related to control and monitoring of the HV are coverd here as well.

Note that all waveforms will be reported according to the ESS diagnostic standards and will have standard attributes (settings) associated to them. As this is under development, some of the settings are given in this document as a starting point. Note also that all monitoring data will have a time stamp of their origin attributed to them.

4.1 HV monitoring and control

Table 5 gives a complete list of HV PS settings and readings available to the user.

ID	Description	Type	Num. of el.	Update rate	Comment
1	DC voltage	S	1	on change	nominal value 1.5 kV
2	Voltage	R	1	1 Hz	DC + modulation
3	Current	R	1	1 Hz	DC + modulation
4	Current limit	S	1	on change	
5	Current limit	R	1	1 Hz	
6	Modulation On/Off	S	1	on change	
7	Modulation On/Off	R	1	1 Hz	
8	Modulation frequency	S	1	on change	
9	Modulation frequency	R	1	1 Hz	
10	Modulation amplitude	S	1	on change	
11	Modulation amplitude	R	1	1 Hz	
12	Voltage On/Off	S	1	on change	PS On/Off
13	Voltage On/Off	R	1	1 Hz	
14	Device ID	R	1	on change	
15	Device Name	R	1	on change	
16	Detectors	R	up to 8 elements	on change	List of detectors connected to this HV PS unit

Table 5: List of settings and readings for one icBLM HV PS unit. Column marked as "Type”. indicates whether variable is a reading (R) or setting (S).

4.2 Monitoring of processed data available on demand

Three different types of data are available on demand for each icBLM channel (detector):

1. **Raw data**
   As stated in the requirements in section 3.1, user is able to retrieve minimum 3 machine pulse periods of raw data for each detector channel on demand. This data stream is buffered in the buffer marked as CB0 on figure 12.

2. **Pre-processed data**
   This is baseline corrected raw data, arriving at the same rate as the raw data. Minimum 3 pulses of data is available to the user. The buffer associated with this stream is marked as CB1 on figure 12.

3. **Pre-processed data**
   This buffer stores consecutive background qualified waveforms used in the "Baseline calculation" block (see section 3.2.3). The rate of these waveforms equals to the frequency of the pulses without the beam. The user is able to retrieve at minimum last 100 of these waveforms. The buffer associated with this stream is marked as CB2 on figure 12.

Here pulse period is defined as 1/(14 Hz).

Below is a list summarising the information that can be extracted from the DoD data for each icBLM detector channel and available to the user.

1. **Raw data** buffer – CB0

   (1) A waveform of raw unprocessed signal with configurable start time and length. The maximum time length is not shorter than 9 ms. The user can select to overlay several consecutive waveforms with 1/(14 Hz) distance (i.e. 1 waveform per pulse) in order to be able to compare time structures in consecutive pulses.

   (2) Statistics of displayed waveforms from (1). The statistics is calculated on a configurable time window inside the displayed waveform and includes average, variance, min and max value. Here the variance is defined as the average squared deviation from the average value, Var$(x_i) = \sqrt{\langle (x_i - \langle x_i \rangle)^2 \rangle} = \sqrt{(\langle x_i^2 \rangle - \langle x_i \rangle^2})$.

2. **Baseline corrected data** buffer – CB1
   Waveform(s) and statistic as defined in item (2) but for baseline corrected data buffered in CB1 instead of raw data in CB0.

3. **Baseline waveforms** - CB2
   Waveform(s) and statistic as defined in item (2) but for baseline waveforms buffered in CB2 instead of raw data in CB0.

4.3 Monitoring of periodically available processed data

Monitoring data available to the user in the control room periodically is summarised in table 6. Note that losses scale with icBLM detector signal with scaling factor depending on the detector as well as its location, beam current and beam energy (i.e. loss scenarios). The identification of the loss source is not an easy task and in most of the cases not even possible without taking into account the information from several loss monitoring systems and channels. Thus, for each detector channel the losses are planned to be reported both as measured detector signal (deposited charge) and with a scaling factor calculated (and/or measured) by scaling to a selected loss scenario. For each detector the scenario is selected from a set of controlled loss scenarios that serve to verify the simulation (see section 5). The work related to this is ongoing.

Table 6: List of periodically available monitoring icBLM data with corresponding user settings labelled and indexed as S_{index}. Unless specified otherwise, the variable refers to one (detector) channel. Settings marked with $^{(*)}$ indicate that the same value is used for all channels. Data type can be a waveform (array) or scalar marked as w or s respectively. Column marked as "Source" specifies whether the calculation of the variable is expected to be performed on the firmware (fw) or the software (sw) level.

ID	Description	Type	Num. of el.	Update rate	Source	User settings	Comment
	Losses accumulated over certain period of time						
1	Loss over time T_1	s	1	$1/T_1$	sw		$T_1 \approx$ machine run period. Calculated from ID8.
2	Loss over time T_2	s	1	$1/T_2$	sw		T_2 ≈months. Calculated from ID8 over last T_2 (running sum).
3	Loss over time T_3	s	1	$1/T_3$			T_3 ≈week(s). Calculated from ID8 over last T_3 (running sum).
4	Loss over time T_4	s	1	$1/T_4$	sw	• $S^{(*)}_{1,\ldots,7}$: times T_1,...T_7. • $S^{(*)}_8$: toggle to switch between units (counts or loss) for all IDs from 1 to 14.	T_4 ≈day(s). Calculated from ID8 over last T_4 (running sum).
5	Loss over time T_5	s	1	$1/T_5$	sw		T_3 ≈hour(s). Calculated from ID8 over last T_5 (running sum).
6	Loss over time T_6	s	1	$1/T_6$	sw		T_6 ≈minute(s). Calculated from ID8 over last T_6 (running sum).
7	Loss over time T_7	s	1	$1/T_7$	sw		T_7 ≈second(s). Calculated from ID8 over last T_7 (running sum).
8	Loss over pulse	s	1	$1/T_{RP}$	fw		$1/T_{RP}$=machine repetition rate (14 Hz). Calculated over last T_{RP} (running sum).
9	Loss over BEAM_ON period	s	1	after each BEAM_ON period	fw	• $S^{(*)}_8$	Only beam qualified pulses included.
10	Loss over BEAM_ON period per sent proton	s	1	after each BEAM_ON period	fw		Only beam qualified pulses included. Requires info from BCM PV(s).

Table 6 – continued from previous page

ID	Description	Type	Num. of el.	Update rate	Source	User settings	Comment
	Loss time structure in 4 different time windows inside the pulse.						
11	Loss waveform inside time window (a)	w	≤ 100	after each BEAM_ON period	fw	• $S_{9,\ldots,12}$: number of points. • $S_{13,\ldots,16}$: waveform position inside the time window with respect to a certain marker (like BEAM ON or RF ON). • $S_{17,\ldots,20}$: enable/disable monitoring (only displaying, not calculation or PV update) • $S_8^{(*)}$	Like detector signal, the waveform is sampled at 1 MHz. Time windows: • (a): before BEAM ON and RF ON. • (b): between RF ON start and BEAM on start. • (c): inside BEAM ON. • (d): between BEAM ON end and RF ON end.
12	Loss waveform inside time window (b)	w	≤ 100	after each BEAM_ON period	fw		
13	Loss waveform inside time window (c)	w	≤ 100	after each BEAM_ON period	fw		
14	Loss waveform inside time window (d)	w	≤ 100	after each BEAM_ON period	fw		
	Scalars extracted from each of the waveforms in ID11–14						
15–18	Average losses inside windows (a,b,c,d)	s	1	after each BEAM_ON period	sw	Settings tide to settings in ID11–14, $S_{8,..,20}$	Calculated from ID11–14.
19–22	Var of losses inside windows (a,b,c,d)	s	1	after each BEAM_ON period	sw		$\mathrm{Var}(x_i) = \sqrt{(\langle x_i^2 \rangle - \langle x_i \rangle^2)}$ – variance. Calculated from ID11–14.
23–26	Min loss values in windows (a,b,c,d)	s	1	after each BEAM_ON period	sw		Calculated from ID11–14.
27–30	Max loss values in windows (a,b,c,d)	s	1	after each BEAM_ON period	sw		Calculated from ID11–14.

Table 6 – continued from previous page

ID	Description	Type	Num. of el.	Update rate	Source	User settings	Comment
	Statistic on measured detector signal						
31–34	Average, Var, Min and Max for detector signal inside BEAM_ON period	s	1	after each BEAM_ON period	fw/sw		Signal sampled at 1 MHz. Statistics calculated over BEAM_ON period. Average can be extracted from ID9.
35–38	Average, Var, Min and Max for detector signal inside RF_ON period	s	1	after each background qualified pulse	fw		Signal sampled at 1 MHz. Statistics calculated over RF_ON period, for pulses that quilfied for baseline calculation (background qualified pulses, see section 3.2.3).
	Protection function block outputs - for given AMC						
39	BEAM_PERMIT	s	1	on BEAM_PERMIT change	fw		Any given AMC has one BEAM_PERMIT associated to it.
40	BEAM_PERMIT time stamp	s	1	on BEAM_PERMIT change	fw		Time stamp of BEAM_PERMIT change in ID43.
41	READY	s	1	on READY change	fw		Any given AMC has one READY associated to it.
42	READY time stamp	s	1	on READY change	fw		Reports time stamp of current READY value from ID45 .
43	Protection algo	s	1	on algo selection change	fw		Indicates which protection algorithm is currently selected for BEAM_PERMIT calculation.
	Same as ID11–30 but for Protection function relaxation filter output.						
44–47	Waveform in 4 time windows	w	as in ID11-14	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID11–14.	
48–63	Statistics in 4 time windows	s	1	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID15–30.	

Table 6 – continued from previous page

ID	Description	Type	Num. of el.	Update rate	Source	User settings	Comment
	Same as ID11–30 but for Protection function X/Y algorithm output.						
64–67	Waveform in 4 time windows	w	as in ID11-14	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID11–14.	
68–83	Statistics in 4 time windows	s	1	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID15–30.	
	Same as ID11–30 but for Protection function Moving Average filter output for time constant $t_{MA,1}$.						
84–87	Waveform in 4 time windows	w	as in ID11-14	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID11–14.	
88–103	Statistics in 4 time windows	s	1	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID15–30.	
	Same as ID11–30 but for Protection function Moving Average filter output for time constant $t_{MA,2}$.						
104–107	Waveform in 4 time windows	w	as in ID11-14	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID11–14.	
108–123	Statistics in 4 time windows	s	1	after each BEAM_ON period	fw	$S_{9,..,20}$ – as in ID15–30.	
	Other information						
124	Number of pos. ADC saturations per pulse	s	1	$1/T_{RP}$	fw		Summed over T_{RP}.
126	Number of neg. ADC saturations per pulse	s	1	$1/T_{RP}$	fw		
127	AMC health status	s	1	$1/T_{RP}$	fw		Last value of the AMC health status.
127	Smart Trigger condition status	s	1	on change	fw		Indicates if the condition to issue the conditional DoD trigger request has been met on a given AMC.

5 Startup procedure and system commissioning

The system needs to acquire enough statistics on the average background waveform in order to operate correctly. Therefore at each startup or RF configuration change a number of empty pulses (minimum 500) are foreseen just after the RF has been configured and before the operation with beam starts. Here the empty pulse refers to a pulse with RF present but no beam. The start up procedure does not require any manual action to be performed.

Certain number of pulses without beam are planed to be present during the linac normal operation. These diagnostic background pulses are planed to be used as a background reference for icBLM and BCM systems. The icBLM firmware is designed to automatically update the average whenever a diagnostics background pulse is available.

The verification tests and procedures planned to be performed during system commissioning with or without beam are detailed in [37]. In addition to this the document specifies all tests that are planed for parts of the system or the system as a whole before and after the installation. Here only a short summary of the strategy for the system commissioning is given.

The following is planned to be configured during the icBLM system commissioning:

- **Trigger delay**
  For each detector the delay with respect to the 14Hz triggers distributed by the timing master (EVG – Event Generator) needs to be configured to account for differences in cable lengths and potentially detector locations. This can be achieved in two ways:

  - By monitoring the background subtraction.
    For each trigger delay setting the raw data and background qualified waveforms are extracted through the DoD feature. The average background waveform is calculated from the background qualified waveforms. This average background waveform is then subtracted on a pulse by pulse bases from the raw data. The latter then serves to determine an average baseline subtracted waveform. This waveform is "flat" without any sign of background in case of the best trigger delay setting.
    This test requires empty pulses with no beam present.
  - By monitoring accumulated loss over beam pulse (see ID9 in table 6).
    For each trigger delay setting an average value for the loss accumulated over beam pulse is extracted. Here the beam pulse refers to the time period with BEAM_ON. The best trigger setting gives the highest average value for the accumulated loss.
    The test requires beam present. It must be repeated after each change in detector setting or cable length change which includes connecting a detector to a different digitiser channel or AMC card.

- **Verification of Monte Carlo (MC) simulations and equivalent loss scaling factor.**
  A set of controlled losses that are used for verification of the MC simulation geometry model needs to be identified. The simulation results are compared to the measurements performed during the commissioning. In case of larger discrepancies the source of those

is identified and simulation model modified accordingly. The process is iterative.
Once the simulation model is verified and understood, the results are used to extract the equivalent loss scaling factors for each detector, where each controlled loss scenario has a group of detectors assigned to. These scaling factors are used to convert measured current to the equivalent number of lost protons (see section 4.3). Note however, that the factor is referred to equivalent due to the fact that it is extracted from one of the possible loss scenarios and is therefore in general incorrect for all other scenarios.

- **Protection algorithm commissioning**
  A set of controlled loss scenarios with different time evolution of the loss needs to be identified. The scenarios are used to tune the protection algorithm through experience and simulations. The initial tuning with experience is foreseen for system commissioning. The tuning is needed whenever an unverified change in protection algorithm is considered.

- **Machine Protection (MP) thresholds**
  A set of likely accidental loss scenarios that are most damaging is identified. MC simulations coupled with thermo–mechanical ones are used to asses the damage potential for these scenarios. A risk matrix connecting damage potential and cost is then generated which serves as a baseline for MP threshold selection.

Loss scaling factors and MP thresholds may require reconfiguring after a change in detector settings. However, it might be possible to scale their values by comparing certain variables before or after the change. The exact procedure will be developed after or during the system commissioning once the system performance is well understood.

6 Document revision history

Revision	Change	Author	Date
0	Document creation and first version	Clement Derrez	2017-07-30
1	Update	Irena Dolenc Kittelmann	2018-08-08
2	Updated processing and monitoring sections, updated FBIS interface selection and added LLL connection to components overview, updated mechanical support section, added stratup proc. and commissioning section	Irena Dolenc Kittelmann	2019-01-22

References

[1] E. Donoghue et al, *Studies of electronic activities in SNS-type SC RF cavities,*. Proc. 12th Int. Workshop on RF Superconductivity, Cornell Univ., USA, TUP67 (2005).

[2] PBI L4 requirements, ESS-0078645.

[3] A. Nordt, *Beam Instrumentation interfaces to protection systems*, TAC12, https://indico.esss.lu.se/indico/event/315/session/9/contribution/32/material/2/1.pptx.

[4] C. Amstutz, *FPGA Development Standards*, available on https://confluence.esss.lu.se/display/RFG/FPGA+Development+Standards; the following tabs are of interest in case of the BLM systems: *FPGA Coding Guidelines*, *Naming of AXI ports*, *RTL Design Libraries* and *Project Organization* – where IOxOS does not provide information.

[5] L. Tchelidze, *How Long the ESS Beam Pulse Would Start Melting Steel/Copper Accelerating Components?*, ESS/AD/0031

[6] I. Dolenc Kittelmann, *Report regarding the MC simulations for the BLM - focus on the nBLM*, August 2016, ESS-0066428

[7] I. Dolenc Kittelmann, T. Shea, *Simulations and Detector Technologies for the Beam Loss Monitoring System at the ESS linac*, HB2016, THAM6Y01, 3.–8. July, 2016, MalmĂ¸, Sweden.

[8] EDMS document HCBLM_I001, available at https://edms.cern.ch/file/440528/AB/lhcblm__0001-vAB.pdf

[9] L. Tchelidze, *Beam Loss Monitoring at the ESS*, IBIC2013, WEPC45, 16.−19. Sept., 2013, Oxford, UK.

[10] B. Cheymol, *ESS wire scanner conceptual design*, ESS−0020237

[11] M. Sapinski et al., *Response function of Ionisation Chamber Beam Loss Monitor*, CERN report EDMS 1055210, March 2010, CERN

[12] I. Dolenc Kittelmann, https://jira.esss.lu.se/browse/BIG-1248

[13] https://www.ioxos.ch/produit/ifc_1410/

[14] https://iseg-hv.com/en/products/detail/DPS

[15] https://www.caenels.com/products/fmc-pico-1m4/

[16] W. Vigano et al, *10 orders of magnitude current measurement digitizers for CERN beam loss systems*, TWEPP 2013, 2014 JINST 9 C02011.

[17] C. Derrez, *icBLM electronics*, BI forum #4, Paris, France, November 2017, available at https://indico.esss.lu.se/event/917/session/3/contribution/21/material/slides/0.pptx

[18] E. Bergaman, C. Derrez, private communication.

[19] *Specification document for a RTM compatible with AMCs supporting D1.4 class*, ESS–0459017

[20] https://www.beckhoff.com/english/ethercat/el4104.htm

[21] https://www.beckhoff.com/english/ethercat/el3164.htm

[22] https://www.beckhoff.com/EL2124/

[23] https://www.ioxos.ch/produit/dio_3118/

[24] J. Norin, *PBI rack list*, ESS–0063364

[25] H. Kočevar, July 2018, *Data on demand feature*, available on https://indico.esss.lu.se/event/1073/

[26] I. Dolenc Kittelmann, *Block diagram of icBLM FW functionality*, https://jira.esss.lu.se/browse/BIG-1152

[27] T. Grandsaert, icBLM Supports (concept), https://confluence.esss.lu.se/pages/viewpage.action?pageId=269649181

[28] S. Grishin, *icBLM detcetors*, presentation at icBLM CDR1, 13. Feb. 2019, https://indico.esss.lu.se/event/1173/

[29] E. Bergman, *icBLM cables*, presentation at icBLM CDR1, 13. Feb. 2019, https://indico.esss.lu.se/event/1173/

[30] C. Derrez, *Pico4 tests*, presentation at icBLM CDR1, 13. Feb. 2019, https://indico.esss.lu.se/event/1173/

[31] C. Derrez, *icBLM electronics test report: CAENELS FMC-PICO*, report for icBLM CDR1, 13. Feb. 2019, https://indico.esss.lu.se/event/1173/

[32] C. Derrez, *pico tests*, presentation at icBLM CDR1, 13. Feb. 2019, https://indico.esss.lu.se/event/1173/

[33] L. Segui, *nBLM project CDR1.2 – final*, report for nBLM CDR3, 12. Feb. 2019, https://indico.esss.lu.se/event/1173/

[34] G. Jablonski et al, *icBLM Firmware implementation*, report and presentation ar icBLM CDR1, https://indico.esss.lu.se/event/1173/

[35] EtherCAT info detailed in https://confluence.esss.lu.se/display/HAR/How+to+build+the+CentOS+7+RT+kernel

[36] C. Derrez, test report available at https://jira.esss.lu.se/browse/BIG-1025

[37] C. Derrez, *icBLM verification plan*, report and presentation at icBLM CDR1, https://indico.esss.lu.se/event/1173/

[38] https://www.beckhoff.com/english.asp?ethercat/el1252_0050.htm

[39] https://www.beckhoff.com/english.asp?ethercat/el9505.htm

[40] *ICD between BLMs and the FBIS*,ESS−0515969, also availale on https://indico.esss.lu.se/event/1173/