ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA145

EVOLUTION OF THE CERN LINAC 4 INTENSITY INTERLOCK SYSTEM USING A GENERIC, REAL-TIME COMPARATOR IN C++

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Abstract

During the commissioning phase of Linac 4, three watchdog interlock systems were used to protect the accelerator and its equipment. These systems cut the beam if losses, calculated by combining the intensity measurements at various locations, exceed some predefined thresholds. While the existing systems were designed to be simple and robust to ensure safety, the future connection of the linac to the Proton Synchrotron Booster (PSB) requires new instances of these systems with additional requirements. Such requirements include the remote communication of the watchdogs with the intensity measurement systems to decouple any physical dependency between the two systems, and the arithmetical / logical combination of the measured data based on the watchdog location. As the Controls Interlocks Beam User (CIBU) hardware interface to the Beam Interlock Controller (BIC) is simple, the software part of the system can be redesigned to be generic and application agnostic giving a single decision (beam permit in this case) after performing a configurable set of comparisons. This paper describes the transformation of the existing watchdog interlock system into a generic comparator by its software upgrade, enabling its usage for other applications.

INTRODUCTION

While the accelerators of the proton injector chain at CERN deliver beams to the Large Hadron Collider (LHC) within specification, the requirements for the upgraded High-Luminosity LHC (HL-LHC) exceed their capabilities. The LHC Injectors Upgrade (LIU) project aims to address this by upgrading the proton injectors to deliver the high brightness beams needed by the HL-LHC [1].

In the framework of the LIU project the PSB is undergoing a profound upgrade including the connection to the new Linac 4 injector. Linac 4, a normal conducting H^- ion accelerator, started being constructed in October 2008 and is foreseen to be connected to the PSB in 2020 [2]. The linac is foreseen to produce many different beam types which will be sent to various different locations throughout the subsequent injector complex, such as beams to the LHC, the CERN North and East experimental areas, the CERN antimatter facility and the ISOLDE facility. During its construction period, Linac 4 was commissioned with beam in several stages including a Half-Sector Test (HST) in 2016/17 where half of the PSB injection chicane was temporarily installed and tested [3].

In order to provide safe and successful commissioning and operation, numerous beam diagnostic devices that measure the various parameters of the beam have been developed [4]. Amongst others, several Beam Current Transformers (BCT) have been installed along the linac to provide continuous beam intensity information via a dedicated digital acquisition module - the Transformer Integrator Card (TRIC) [5]. By combining the intensity information in two locations of the accelerator, the beam transmission between those locations can be derived. Such information is essential not only for ensuring the quality of the delivered beam, but also the safety of the accelerator and its equipment as low transmission indicates particle losses.

Linac 4 is protected by a Beam Interlock System (BIS) that comprises a mixture of various hardware, software and external conditions in order to cut the beam and prevent any damage in case of a failure [6]. The BIS is based on the evaluation of several interlock signals from User Systems that are collected via the dedicated user interface to the BIC, the CIBU [7]. To enable the proper operation of the new linac and maximise the beam availability, the user systems should take the future destination of the linac beam pulse into account while providing their interlock signals.

One such user system is the Beam Current Transformer Watchdog that monitors the beam transmission in key locations of the accelerator and provides its interlock signal to the CIBU via a custom VME module. Such a signal is derived from a combination of high loss detection for a particular destination and a bad pulse counter on a beam type basis. To fulfil the requirements and provide the needed flexibility to the operators a hybrid design was chosen by complementing the hardware based watchdog with real-time C++ software responsible for implementing the business logic of the system.

MOTIVATION

During the commissioning phase of the Linac 4, three watchdogs were installed to protect its source, its dump and the temporary HST. Inter-Process Communication (IPC) structures were used to transmit the intensity and time stamp information from the BCT acquisition software to the watchdog making the sharing of the hosting CPU by the two systems a prerequisite [8].

As Linac 4 gets its final form with all the lines being constructed and in view of its future connection to the PSB, new instances of the Watchdog system with additional requirements are needed to protect the full injection chain [9]. As it can be seen in Fig. 1, the temporary watchdog that protected the HST is no longer needed and will be removed, whereas the ones installed at the source and the dump will remain. Two additional watchdogs will be installed to protect the full accelerator line and the beam transverse emittance measurement line (LBE).

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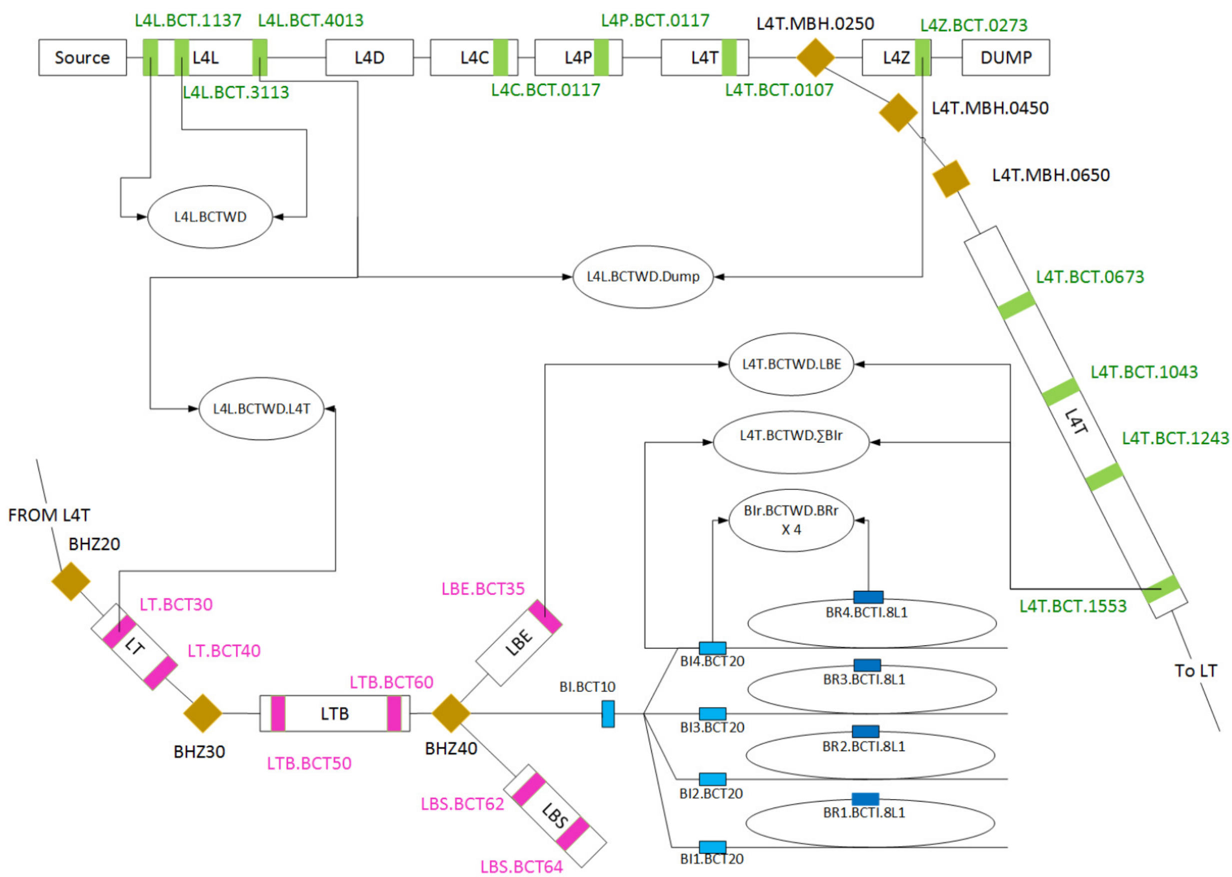

Figure 1: Linac 4 Watchdog Layout showing the 6 Watchdog instances and their related BCTs.

Furthermore, the PSB injection will be protected in two stages, the transfer line at the end of Linac 4 up to the injection to the PSB and the PSB injection itself. With the PSB comprised of 4 superposed rings [10], the former require the arithmetical combination (summing) of the intensity measured at each PSB ring injection line to be comparable with the intensity measured at the end of the linac. Accordingly, the overall injection efficiency requires the logical combination of the 4 individual injection transmission values from each PSB ring to cut the beam from the linac in case of problems in any of the rings.

The increased number of watchdog instances (more hardware modules) can be problematic due to space limitation in the new accelerator. In addition, the longer distances involved for the new comparisons would require long and expensive cabling solutions. Thus, the decoupling of the physical dependency between the BCT and the watchdog systems is essential. Furthermore, the additional functionalities of the arithmetical and logical combination of the intensity information require the refurbishment of the software part of the system as they were not taken into account during its initial design.

A GENERIC COMPARATOR

The functionality of the watchdog software is implemented in two stages: pre-pulse and post-pulse [8]. After the beam has passed, the intensity information is read out and the high loss flag and bad pulse counter are calculated by comparing the relevant measurements. Then, as the BIC is effectively re-armed before each pulse, the combined interlock signal is transmitted to the CIBU before the next beam passage in real-time.

Modularised Readout

In order to decouple the physical dependency between the BCT and the watchdog, the readout part of the watchdog software was modularised to support new types of communication while being backwards compatible. Such an approach enabled the maintenance of a single versatile version of the C++ software that supported the development and testing of new types of communication while maintaining the operational instances fully functional. Consequently, a new module was added to realise the communication remotely using the Remote Device Access (RDA) service that has been the standard for remote communication in the CERN control system for over a decade [11].

RDA is based on the Accelerator-Device-Model [12] where devices, named entities in the accelerator system (i.e. BCTs, Watchdogs, etc.) can be controlled via properties which group the related fields of each device (e.g. Settings, Acquisition, etc.). Hence, the new RDA based communication module enabled the parameterisation of the watchdog

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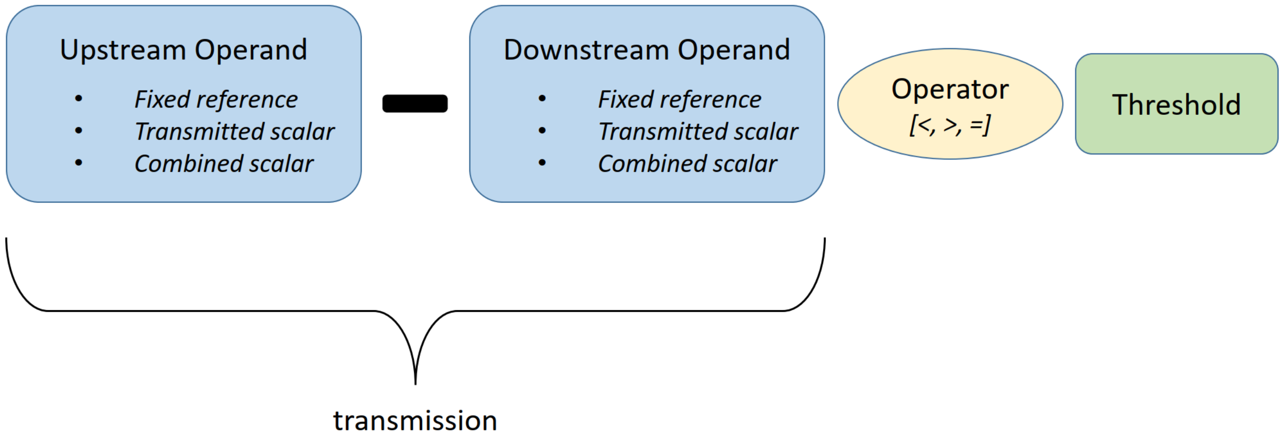

Figure 2: Arithmetic Comparison Model.

software to provide greater flexibility to the fields that can be communicated by the BCT system in contrast with the predefined hardcoded IPC structures. Thus, where it is necessary, the intensity information can be transmitted in number of charges instead of current to provide more accurate comparisons.

The Core Functionality

In order to fulfil the additional requirements for the arithmetical and logical compositions of the comparisons, the core of the watchdog software was redesigned and split into two major categories: arithmetical comparisons and logical comparisons. This fundamental change in the structure of the software leads to the instantiation of the Watchdog devices per comparison and not per hardware module that was the case until recently. Hence, various comparisons of both types can be defined which can then also be used in the composition of others.

Arithmetical Comparisons

The arithmetical comparisons are based on the simple paradigm that can be seen in Fig. 2, where a given transmission is compared with a threshold. Contrary to the first version of the watchdog software, the operands and the operator in the new comparison model can be configured. Hence, all kinds of arithmetical comparisons can be supported while maintaining the C++ code simple and common to all cases, making it more robust. More specifically, the operands can be:

- a fixed reference - useful for tests, commissioning, in case of an absent measuring device
- a scalar - transmitted from a specified device (existing situation)
- a scalar - resulting from the arithmetic combination of measurements transmitted by more than one device or of different kinds of measurements from the same device

To benefit from the arithmetical composition, the remote communication module needs to be selected. By specifying more than one field that should be transmitted by the upstream and / or downstream devices and the composition type (multiplication, addition) to be applied, the product or the sum of multiple bits of information can be derived.

Similarly, the operator can be selected from [<, >, =] to enable more flexible comparisons with various types of pulses (e.g. the use of positive signals in the lab versus the negative signals obtained in the linac).

Logical Comparisons

The logical comparisons combine the results of other comparisons to provide a single outcome and are therefore always scheduled to be performed after completion of their dependencies. Following the same design pattern, they are fully parameterised by a list of Watchdog devices that should be used, as well as the logical operator [AND, OR] to apply. Such modelling enables numerous combinations that in turn allows complex protection schemes to be implemented. For this type of comparison, the communication type is irrelevant as the readout of the individual results is achieved via the internal shared data store of the software.

Hence, in the case of Linac 4, the transmission of each PSB injection ring can be defined as a separate hardware-less, arithmetic comparison (Watchdog device). Additionally, a logical comparison will combine the results of these arithmetic comparisons and give a single beam permit to the connected CIBU only if the transmission to each ring is acceptable.

Graphical User Interface

While the extended parameterisation of each comparison (Watchdog device) enables great flexibility on their type and nature, it adds a level of complexity in observing their behaviour. A Graphical User Interface (GUI) was therefore developed to facilitate such monitoring.

17th Int. Conf. on Acc. and Large Exp. Physics Control Systems ICALEPCS2019, New York, NY, USA JACoW Publishing
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Figure 3: Watchdog Graphical User Interface.

The GUI is organised in tabs per comparison (Watchdog device) where the acquisition and configuration values are shown in various formats, as it can be seen in Fig. 3

Group 1 of Fig. 3 depicts the colour-coded parameterisation of each comparison that includes the readout type, the nature of the comparison, the composition type where applicable and the loss type that was used for the computation. In addition, the BCTs whose measurements were used for the beam permit calculation are grouped in a separate table that can be seen in group 2.

The acquisition data are distinct in two additional tables for an easier overview (groups 3 and 4 respectively). Therefore, one table states the destination that the comparison should be relevant, the timestamp of the measurement, the calculated loss and whether the pulse was qualified as beam or noise. The other table groups the results relevant to the beam type, i.e. the transmission in % and how many bad pulses are still allowed before blocking the beam.

The overall comparison status is split into three colour-coded sub-statuses for a better visualisation that can be seen in group 5. The Watchdog status (active or inhibited based on the destination of the measurement), the high loss permit and the bad counter permit. These statuses are grouped in a table for each dependent comparison used in a final logical comparison that is visible in group 6. This enables the user to quickly identify the source of a potential blockage of the beam permit and act accordingly.

Finally, the acquisition values are complemented by a graph plotting the individual measurements used to calculate each result along with the applied qualification thresholds. As the number of individual measurements can grow arbitrarily large, the plots can be toggled to be individually visible via the toolbox in group 7.

In the example of Fig. 3, three arithmetical comparisons are combined logically to give a single permit. The transmission from BCT0 to BCT1, from BCT0 to BCT2 and from BCT1 to BCT2 that are visible in the group 2, is being calculated and checked against the specified thresholds to decide if there was a high loss or a bad pulse, in which case the according counter is decreased (group 4). As soon as any of the counters becomes 0, the beam permit is taken away for that Watchdog device (group 6) resulting in the final beam blockage that can be seen in group 5.

CONCLUSION & OUTLOOK

In order to be ready for the Linac 4 to PSB connection post LS2, the software part of the BCT Watchdog was redesigned. The readout was modularised and renovated to enable multiple instantiations of the system irrespectively of the physical installation of the measuring devices. Furthermore, the new comparison-based structure enabled the combination of several measurements arithmetically and logically that were needed to protect the various locations of the injection chain. Finally, a GUI was developed for an easier monitoring of the performance of each Watchdog.

The new, configurable, remote readout module together with the possibility to add additional custom ones, decouples the system from the BCTs making it application agnostic. Moreover, the extended parameterisation of the Watchdog devices that can perform a combination of any kind of comparison, enables the implementation of complex protection schemes. Hence, the final output of the watchdog hardware

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derives from such comparisons, resulting in a beam inhibit if the predefined criteria are met.

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