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THE ESS FAST BEAM INTERLOCK SYSTEM: FIRST EXPERIENCE OF OPERATING WITH PROTON BEAM

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Abstract

The European Spallation Source (ESS), Sweden, currently in its early operation phase, aims to be the most powerful neutron source in the world. Proton beam pulses are accelerated and sent to a rotating tungsten target, where neutrons are generated via the spallation effect. The damage potential of the ESS proton beam is high and melting of copper or steel can happen within less than 5 microseconds. Therefore, highly reliable and fast machine protection (MP) systems have been designed and deployed. The core system of ESS Machine Protection is the Fast Beam Interlock System (FBIS), based on FPGA technology. FBIS collects data from all relevant accelerator and target systems through 300 direct inputs and decides whether beam operation can start or must stop. The architecture is based on two main building blocks: Decision Logic Node (DLN), executing the protection logic and realizing interfaces to Higher-Level Safety, Timing System and EPICS Control System. The second block, the Signal Condition Unit (SCU), implements the interface between FBIS inputs/outputs and DLNs. This paper gives an overview on FBIS and a summary on its performance during beam commissioning phases since 2021.

INTRODUCTION

At ESS [1] the MP system has been designed in order to have an optimum balance between appropriate protection of equipment from damage and high beam availability [2]. Since the proton beam power of 125 MW per pulse (5 MW average) will be unprecedented and its uncontrolled release can cause serious damage of equipment within a few microseconds an FBIS is required to provide a minimum latency. The FBIS is responsible for collecting several types of information from different kind of so-called Sensor Systems. As for example slow systems (Vacuum, magnets and position of insertable devices) or fast systems (Radio Frequency Control Systems and Beam Instrumentation). These are inputs for signal processing units that make the decision on maintaining or not the beam production.

ARCHITECTURE OF FBIS

The FBIS architecture is fully redundant to ensure it can reach the Protection Integrity Level requested by the Protection Functions. Hundreads of Sensor Systems connection are foreseen along the 600m Linac, leading to a specific architecture with two component types: the “Signal Conversion Unit” (SCU) and the “Decision Logic Node” (DLN).

Signal Conversion Unit (SCU)

The SCU, Fig. 1, is a concentrator for Sensor Systems connections. It is based on a cPCI standard chassis with custom electronic cards. An SCU hosts up to 12 Mezzanine Cards (MC) on which Sensor Systems connect. Two more cards, called Serializers, host a MPSoC Zynq Ultrascale+ to manage the connection to the MC by the backplane, and the communication with the DLN through serial links, redundant optical connections using the Xilinx Aurora 64b/66b core IP.

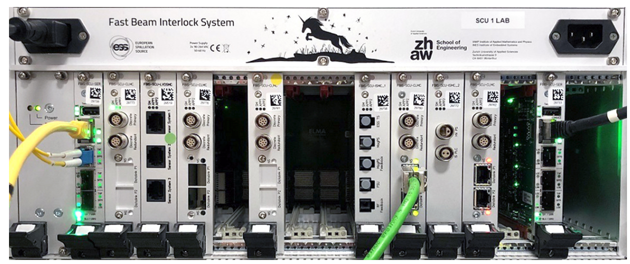

Figure 1: Signal Conversion Unit - SCU.

Several kind of MC were designed to interface with various types of Sensor Systems. One of them manages PLC-based Sensor Systems [3], and two others fast electronic Sensor Systems, mainly FPGA-based. Twenty five SCUs are foreseen along the Linac and in the Target building. The two first SCUs, installed close to the Ion Source, host also specific MC to interface with five hardware Actuators, acting to stop the Beam Production upon DLNs request.

Decision Logic Node (DLN)

The DLN, Fig. 2, performs the protection logic implemented by the FBIS. It also realizes the interfaces to the Higher-Level Safety, Control System and the ESS Timing System. It is based on mTCA, using the 3U chassis to host the redundant DLN carrier boards, heart of the FBIS functionality. It also contains the Timing System Event Receiver EVR, and a Concurrent CPU to host the FBIS EPICS Control System IOCs.

Figure 2: Decision Logic Node - DLN.

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A DLN can connect up to 12 SCUs, but in real the maximum will be 5. The full deployment will be of 8 DLNs connecting the 25 SCUs as shown on the schematic on Fig. 3. To stop Beam Production, DLNs share a Global Beam Permit (GBP) through a dedicated optical interface called Optical Protection Loop (OPL). The communication of the GBP is based on a Xilinx Aurora 8b/10b core IP. The SCUs hosting Actuators MC read the OPL state to request a Beam Stop.

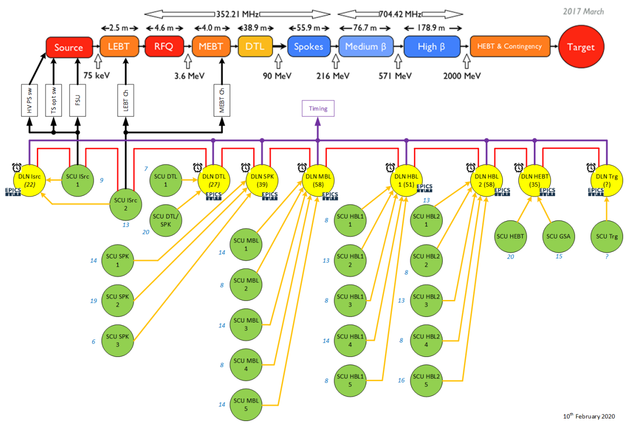

Figure 3: FBIS final deployment.

LOGICAL CHOICE

The FBIS makes decision on stopping beam mainly based on the Beam Permit used by Sensor System to request a beam stop and the Ready signal, information from the Sensor System that it is ready to operate. The FBIS stops or prevents beam for devices or systems which are relevant for the Proton Beam Mode (PBM) or Proton Beam Destination (PBD) provided by the Timing System. In parallel it cross-checks the PBD and PBM configuration from some Sensor Systems to ensure no relevant interlock is masked. An operator can inhibit the beam production pressing a button in an Operator Interface (OPI), acting as a software Sensor System for the DLNs.

The FBIS acts on the Actuator Systems using different strategies:

- Beam Inhibit (BI) function: if an input, e.g., a Ready Signal, is configured to "No Latching", the FBIS does not latch the states of the input but the signal is processed as directly received. The Beam Inhibit is automatically removed when the input is valid again.
- Regular Beam Interlock (RBI) function: if an input, e.g., a Beam Permit, is configured to "Latching states" FBIS latches that input when not valid. An external software reset (rearm button on Fig. 4) is required to reset the latched state and hence remove the Regular Beam Interlock.
- Emergency Beam Interlock (EBI) function: after a BI or a RBI, FBIS checks if the Actuator Systems have correctly reacted to FBIS Beam Switch-Off Requests . If the check is invalid FBIS escalates to an EBI.

When the FBIS is BI and RBI status, it acts on Timing System, Magnetron Power Supply, Fast Shutdown Unit and LEBT Chopper. Furthermore RBI acts also on the MEBT Chopper. When the FBIS is in EBI status it additionally interlocks the 75 KV High Voltage extracting protons from the Ion Source.

COMMISSIONING PHASES

Commissioning Activities

While the basic functionalities of the DLN and SCU firmware are identical to all DLNs and SCUs, there are individual differences for each DLN and SCU. The individual differences are parameterized before generating the firmware bitstream, they are hard-coded in the firmware and not changeable during run-time. For each DLN and SCU exists an explicit firmware bitstream. At each phase of the commissioning the configurations for SCUs and DLNs can change.

The FBIS is commissioned in phases based on the ESS overall installation and commissioning plan. The testing of the system is performed in the following steps:

- Factory Acceptance Testing (FAT): Verify functionality of hardware components and assemblies of components before installation.
- Site Acceptance Testing (SAT): Verify physical hardware installation of systems and connections.
- IO Verification: Verify the physical interfaces between all systems and the FBIS.
- Site Integration Testing (SIT): Verify the logic of the FBIS system while integrated to all the interfacing systems.
- Final Integration Testing (FIT): Verify some "full chain" functionality and verification of protection functions where beam may be required for verification.

Normal Operation Activities

All the control functions for the operational activities for direct interaction with the FBIS such as resetting, monitoring input systems and actuator status are performed via the EPICS control system infrastructure. The main OPI for the operators is shown in Fig. 4. The MPSoS High level OPI has been designed following a matrix approach composed by a set of rows (corresponding to the inputs to FBIS represented as round LEDs) and columns (corresponding to the outputs from FBIS represented as square LEDs).

The FBIS hardware OPI for the NCL commissioning phases shows the installed hardware and connections, Fig. 5, and is used by MPS experts to monitor the FBIS state and understand some beam stop chronological events through an history buffer.

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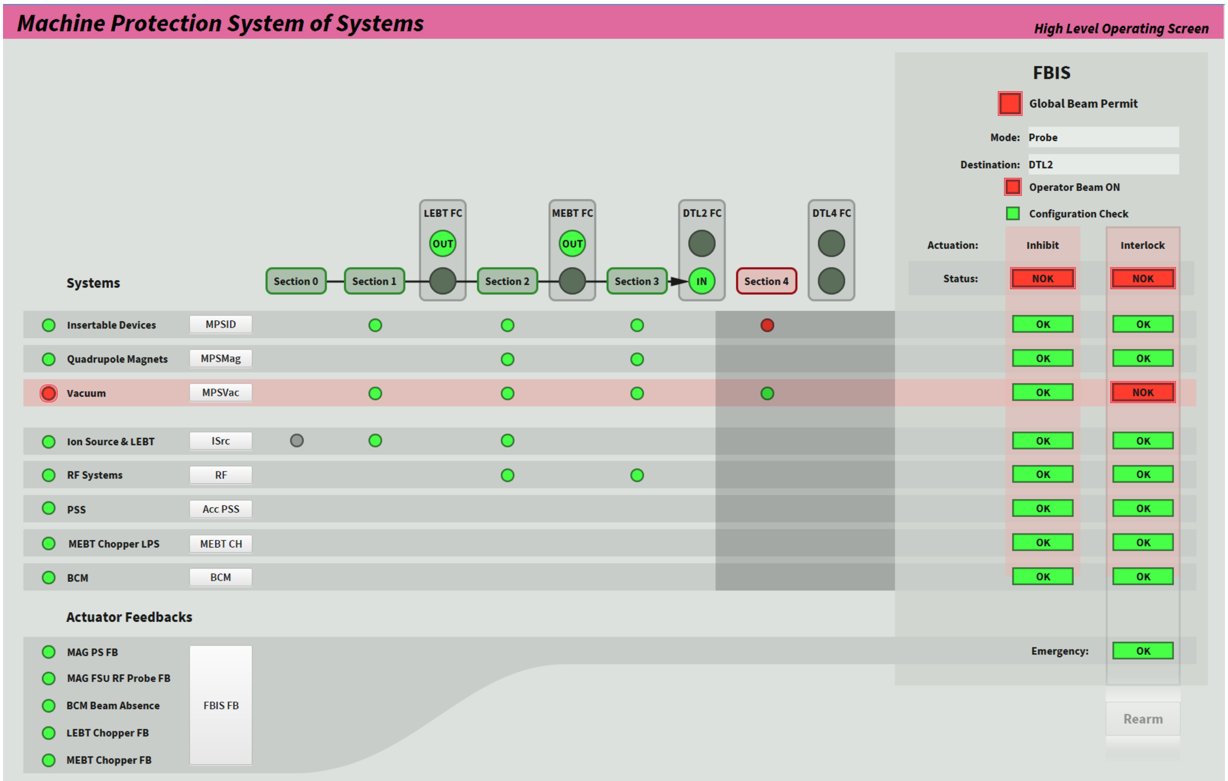

Figure 4: MPSoS main OPI.

Results from Commissioning Phases

There have been four commissioning phases, each going further as destination. Ion Source, LEBT Farady Cup (FC), MEBT FC and DTL1 FC. When a new commissioing phase occurs, new connections are added to the FBIS, and most of the commissioning activities described above need to be repeated.

So far the FBIS has contributed to guarantee the ESS machine protection in the commissioning phases up to MEBT FC and DTL1 FC. Minor bugs in the logic, in the EPICS IOCs controlling SCUs and DLNs and in the interfaces with different systems have been found and promptly fixed during the first commissioning phase. Reaction time measurements, to see how fast is the FBIS to stop the beam, have been carried out with different combinations of PBM and PBD. The measurements have proved that FBIS can stop the beam within the time that it has been designed for, which for the NCL part is 5 µs from BCM request to Actuators triggering.

CONCLUSION AND OUTLOOK

From spring 2023, the next commissioning phase (DTL4 FC) will include three more DTL tanks and some Beam Instrumentation equipment. Then there will be a big step by connecting the full Linac, including the Target instruments, for the protection of the machine in 2025. As FBIS was designed to be modular and scalable, most of the efforts are oriented towards functionality improvement and new features more than following the accelerator installation.

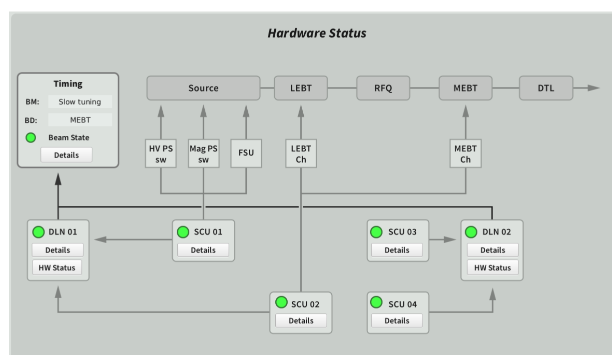

Figure 5: FBIS hardware status OPI.

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