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MACHINE PROTECTION SYSTEM AT SARAF

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Abstract

CEA Saclay Irfu is in charge of the major part of the control system of the SARAF LINAC accelerator based at Soreq in Israel. This scope also includes the Machine Protection System. This system prevents any damage in the accelerator by shutting down the beam in case of detection of risky incidents like interceptive diagnostics in the beam, vacuum or cooling defects. So far, the system has been used successfully up to the MEBT. It will be tested soon for the super conducting Linac consisting of 4 cryomodules and 27 cavities.

This Machine Protection System relies on three sets: the MRF timing system that is the messenger of the "shut beam" messages coming from any devices, IOxOS MTCA boards with custom FPGA developments that monitor the Section Beam Current Transmission along the accelerator and a Beam Destination Master that manages the beam destination required. This Destination Master is based on a master PLC. It permanently monitors Siemens PLCs that are in charge of the "slow" detection for fields such as vacuum, cryogenic and water cooling system. The paper describes the architecture of this protection system and the exchanges between these three main parts.

INTRODUCTION

SNRC and CEA collaborate to the upgrade of the SARAF accelerator to 5 mA CW 40 MeV deuteron and 35 MeV proton beams (Phase 2) at 176 MHz [1]. The CEA control team is in charge of the machine protection system (MPS), which plays a crucial role in the accelerator's operation. It requires special attention to ensure it can shut off the beam promptly in the event of accidents, thereby preventing any potential damage. To achieve this, the MPS relies on robust hardware components, including FPGA electronic cards and PLCs. Over the years, CEA has accumulated experience with these technologies, leading them to select three primary technologies for implementing the system:

- Siemens PLC for the Beam Destination Master (BDM) part, that consists of checking the Local Control System conditions depending on the beam destination requested.
- MTCA IOxOS cards for the Section Beam Current and Transmission Board (SBCT) developed in FPGA, facilitated by the IOxOS development platform, enabling precise control of the beam status throughout the accelerator with a response time as fast as 5 µs.
- MTCA cards of Micro-Research Finland (MRF) will play a dual role within the system. They will serve as the foundation for the timing system and will also function as the central component of the MPS, acting as the messenger for 'shut beam' commands throughout the entire machine.

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MACHINE PROTECTION PRINCIPLE

Overview

In the Machine protection system, we can distinguish two types of equipment: detectors and beam stoppers. On the one hand, detectors are responsible for identifying potentially hazardous situations and will initiate a 'shut beam' request to prevent any damage to the machine. On the other hand, beam stoppers are designed to deactivate the beam rapidly when they receive a request from the detectors. Figure 1 illustrates the architecture of the MPS, highlighting the various detectors positioned around the three beam stoppers and illustrating their interactions.

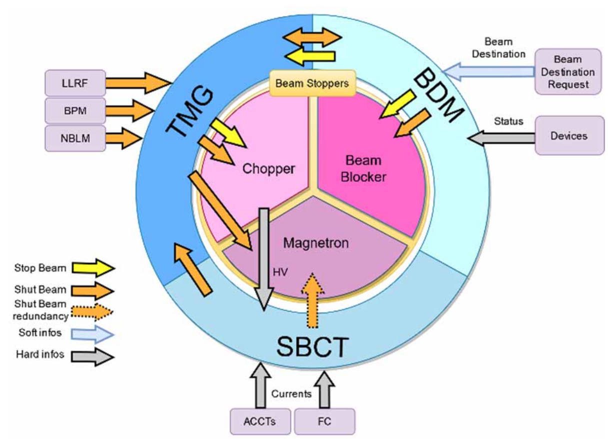

Figure 1: Architecture of the SARAF MPS.

Detectors

- LLRFs: The primary function of an LLRF (Low-Level Radio-Frequency) system is to manage and regulate the amplitude and phase of the electromagnetic field within the accelerating cavity. It is designed on the MTCA.4 platform and uses an EPICS driver, with the entire system being developed by Orolia [2].
- BPMs: The role of a BPM (Beam Position Monitor) is to furnish data regarding the beam's position, phase, and current at various locations along the accelerator line. The control is designed on the MTCA.4 platform and uses an EPICS driver, with the entire system being developed by Orolia [3].
- NBLMs [4]: The neutron beam loss monitor (nBLM) system is based on Micromegas gaseous detector sensitives to fast neutrons produced when beam particles

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hit the accelerator materials. These detectors offer robust neutron detection capabilities and rapid response times. It is designed on MTCA.4 platform with an EPICS driver developed by CEA [5].

- SBCT: Its primary function is to identify any loss of current occurring along the accelerator. Further information on this function is provided in a following chapter.
- BDM: Its purpose is to check that conditions necessary to reach a certain beam destination has been successfully validated. Further information on this function is provided in a following chapter.

Beam Stoppers

The magnetron is the first device that generates the beam. For SARAF, we use the Sairem GMP 20K that we control with EPICS and the StreamDevice device support. The Fast Shutdown Unit connected to the TMG via the optical fiber network enables rapid interruption of the magnetron's operation within 10 microseconds.

The chopper is located in the Low-Energy Beam Transport (LEBT). It shapes the beam using pulses provided by the TMG. When the TMG initiates a beam shutdown, the chopper can deviate the beam to within mere hundreds of nanoseconds.

The ECR Ion Source (EIS) Beam Blocker is located following the magnetron and controlled by the BDM. It can shut the beam within hundreds of milliseconds.

Shutbeam Sequence

The sequence in case of a shutbeam is the following:

1. There is beam in the accelerator, the TMG runs a sequence of pulses, shaping the beam as shown in Fig. 2.
2. The beam presence is determined by the intersection of the chopper, the magnetron and the RF (excluding the rising time).
3. When one of the detectors detects a hazardous situation, it sends a shutbeam event over the TMG.
4. Event Receiver (EVR) of the LLRF receives the shutbeam event and shutdown the RF Pulse for a single cycle. As shown in Fig. 3 on the next cycle the RF is reactivated. This ensures that the RFQ process is not interrupted while preventing the acceleration from any residual beam present in it during the shutbeam.
5. The EVR of the injector receives the shutbeam event, and shutdown the magnetron pulse, masks the chopper event in the sequence and requests the BDM to insert the beam blocker. Despite these actions the sequence is still running.

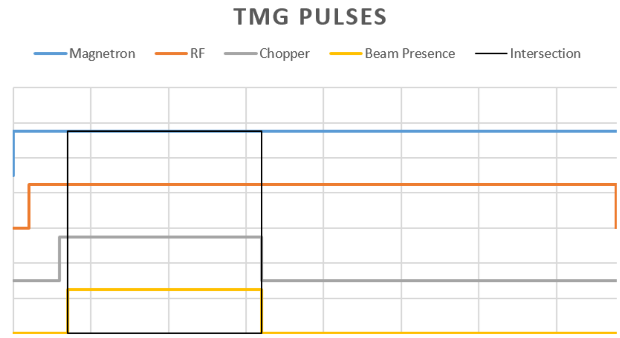

Figure 2: Sequence of pulses for a nominal beam.

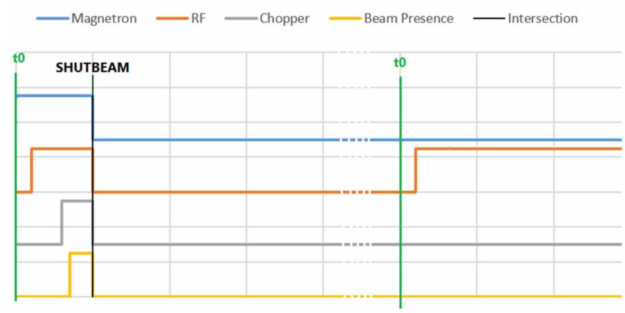

Figure 3: TMG Pulses in case of a shutbeam.

Shutbeam Redundancy

Two cases of redundancy exist, so as not to rely only on the TMG which constitutes exceptions to the previous sequence:

- If the BDM detects an error, it warns the TMG and simultaneously initiates the insertion of the beam blocker. Given the reaction time of the BDM, it is considered to get an equivalent response time in comparison with the time requested by the TMG. This redundancy ensures a shutbeam in case of any issues with the TMG.
- If the SBCT detects an error it notifies the TMG. After a specified period, if the SBCT continues to detect the presence of the beam in the accelerator, it shuts off the magnetron directly through a hardwire connection.

TIMING SYSTEM (TMG)

Overview

The main functionality of the SARAF timing system is to ensure the synchronization of the entire accelerator. However, it also serves a dual purpose by using the bidirectional MRF optical fiber network to transmit fast machine protection messages across the network (see Fig. 4).

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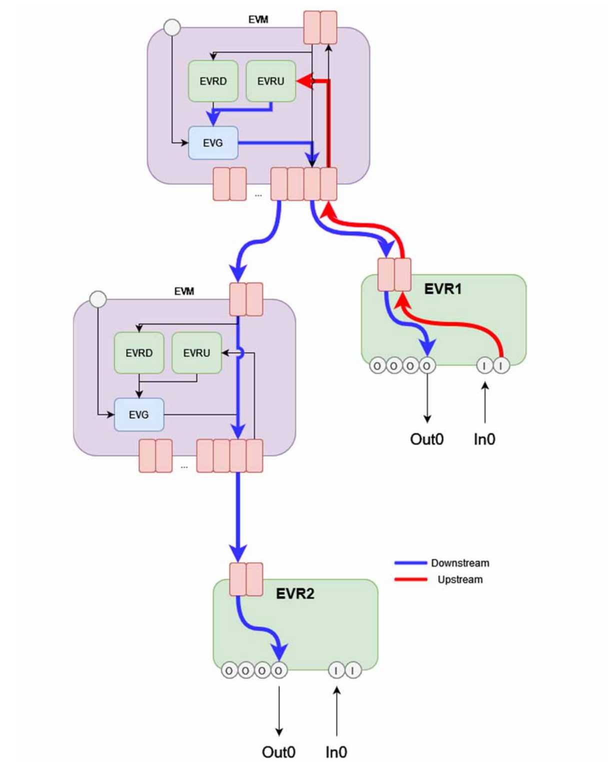

Figure 4: Upstream and propagation of an event to the whole MRF tree architecture.

Architecture

SARAF relies mainly on MTCA.4 platform, which includes the use of the MTCA-EVM-300 and the MTCA-EVR-300U provided by Micro-Research Finland (MRF). Each Event Receiver (EVR) is connected to an Event Master (EVM) which is responsible for generating the sequence of pulses as described previously. In Fig. 5 (highlighted in red), you can observe that all the detectors are connected to an EVR, allowing them to trigger "shutbeam" events when necessary.

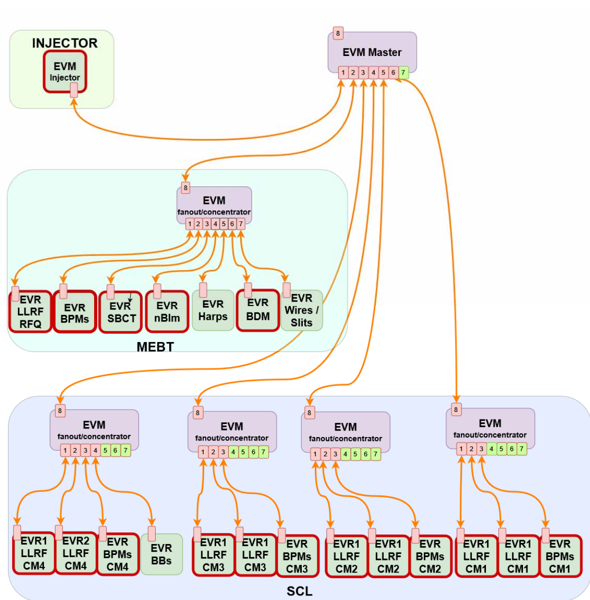

Figure 5: TMG Control architecture.

The propagation time from the most distant EVR to the EVR responsible for shutting off the beam has been determined to be approximately 2µs. [6]. According to our specification of a total response time faster than 5 µs this is sufficient for the intended purposes.

The TMG is also designed to initiate software "shutbeam" in case of trouble with the optical fiber network. Depending on the selected beam destination, the TMG will determine which EVRs are essential to reach this destination. If the reachable destination is insufficient, the TMG will not authorize the beam and will shut it off.

BEAM DESTINATION MASTER (BDM)

Overview

The BDM main functions are:

- Checking that conditions required to reach the requested destinations are respected.
- Shutting the beam if conditions are no longer respected.
- Stopping the beam if the user requests a new destination.
- Inserting the beam blocker when a shutbeam or a stopbeam occurs.

Architecture

The BDM relies on Siemens PLCs 1500. This hardware has been selected because of their recognized reliability and the CEA expertise in this technology.

During the study of the BDM we considered several architectures: hardware only, safety-focused, mixed software and hardware solutions.

The hardware-only approach demonstrated a very short response time and high reliability. However, it was found to be less flexible and challenging to implement in the context of an ongoing project.

Safety solution is the safest way to protect the particle accelerator if the reliability of the element to be controlled is the only criterion. System response time is about one second, well above the specification.

A balance between reliability and responsiveness is crucial to meet the project requirements efficiently. Mixed software and hardware is a composite solution that enables existing PLC components to be integrated into the BDM without electric study or cabinet modification. Network can manage it fast in a deterministic way. We chose it because it was the best compromise we could reach.

A master PLC gets all the required information from Local Control System (LCS) PLCs. These LCS PLCs are strategically positioned in close proximity to the equipment and exchange information via the Profinet network (see Fig. 6). The BDM EPICS communication is ensured by the Modbus driver for the output data, and with S7PLC for the input date.

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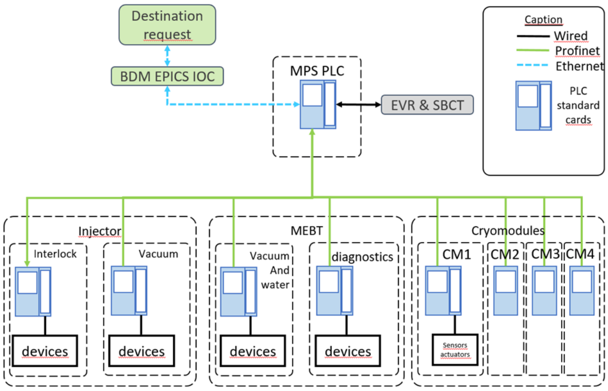

Figure 6: BDM Control architecture.

As shown in Fig. 7, it is connected to the TMG through an EVR and TTL signals.

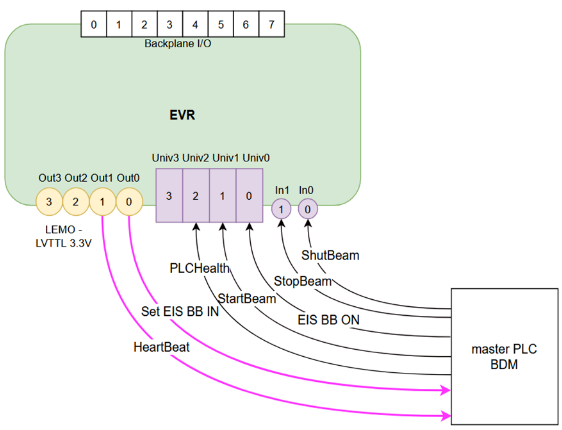

Figure 7: Connection between the EVR BDM and the BDM master PLC.

- ShutBeam: The TMG deviates the beam using the Chopper and shut down the magnetron
- StopBeam: The TMG deviates the beam using the Chopper and the BDM inserts the Beam Blocker.
- StartBeam: The TMG stops the beam by deviating it using the Chopper and allows the magnetron to restart. The BDM sends the Beam Blocker to its home position.
- EIS BB On: The BDM indicates that the Beam Blocker is inserted. The TMG authorizes the magnetron to restart.
- PLC Health: Indicates if the PLC BDM is alive, if not the TMG initiates a beam shutdown.
- Set EIS BB IN: The TMG requests the insertion of the Beam Blocker, the BDM inserts it.
- HeartBeat: Indicates if the EVR BDM is alive, if not the BDM inserts the Beam Blocker.

It is also designed to receive analogic signals from the SBCT to get status information about it.

For each destination the BDM checks that every condition is respected as shown in the Fig. 8. Comprehensive details regarding all destinations and the requisite conditions to reach them are documented by the accelerator system engineer. In this example the Medium Energy Beam Transport (MEBT) Diagnostic Box 1 (MBT DB1) conditions are all respected and the beam can be injected.

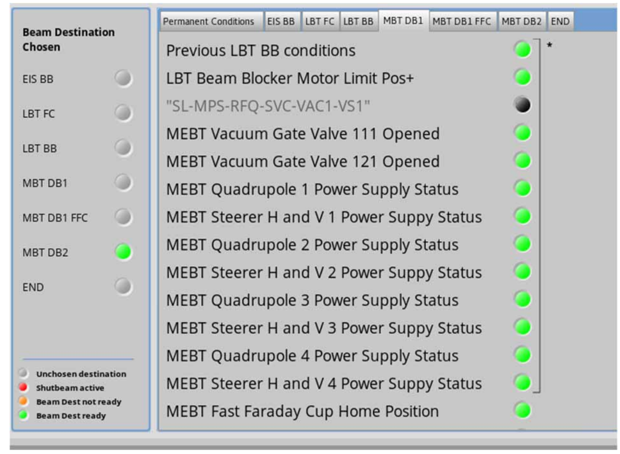

Figure 8: MBT DB2 destination conditions.

If the conditions are not respected the BDM insert the EIS Beam Blocker and requests the TMG to shut down the beam.

SECTION BEAM CURRENT AND TRANSMISSION BOARD (SBCT)

Architecture

The SBCT uses an MTCA IOxOS IFC1410 card associated to an IOxOS ADC317 FMC card and an IOxOS DIO3118 FMC Card. The SBCT was developed using IOxOS tools: TOSCA II, which is the FPGA platform enabling the interconnection of all hardware resources (FPGA, RAM, CPU, FMCS ...), and the tsclib library, which allows access to the card's resources from the Power-PC CPU via PCIe. Thanks to this library and the community's asyn support, we can access the FPGA registers from EPICS. As shown in Fig. 9, the SBCT acquires beam current in the accelerator from different ACCTs, and Faraday Cup, and also the chopper voltage.

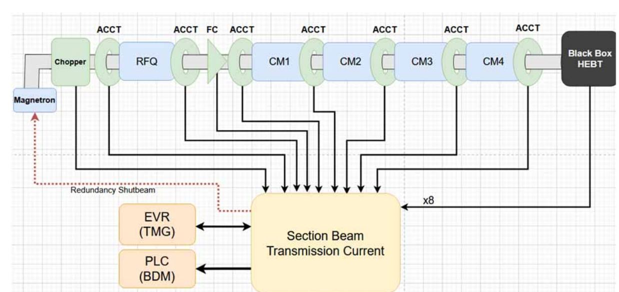

Figure 9: SBCT architecture.

Beam On/Off Management (BOOM)

The TMG uses the backplane of the MTCA to transmit a "Beam Presence" pulse defining a gate where the pulse is theoretically "On". The SBCT is responsible for verifying that the beam is both off and on precisely when it is expected to be. The SBCT includes the propagation time of the beam and the falling and rising edge of the pulse (see Fig. 10).

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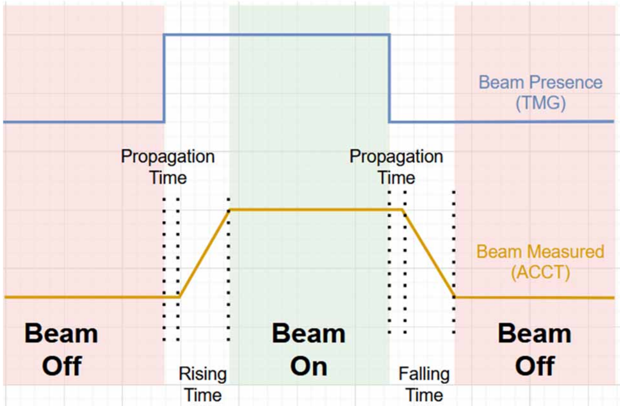

Figure 10: BOOM example.

If the Beam On or Off sequence is not respected, the SBCT asks to the TMG to shut down the beam.

Beam Amplitude Checking (BAC)

The SBCT authorizes a certain level for the signal depending on whether the beam is "On" or "Off" (see Fig. 11).

If the signal goes higher than one of the limits, the SBCT requests the TMG to shut down the beam.

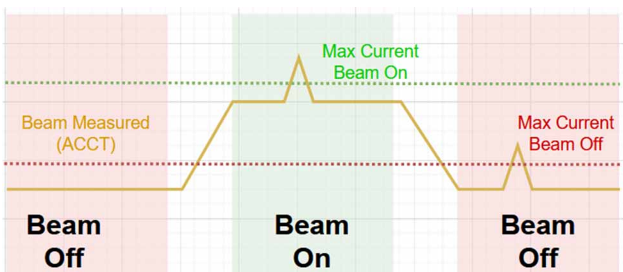

Figure 11: BAC example.

Current Differences

According to different configurations dependent on the beam destination, the SBCT will compare currents between its sensors (ACCTs, FC).

As shown in Fig. 12, if the difference between both signals are greater than a limit defined by the operator, then the SBCT requests the TMG to shut the beam.

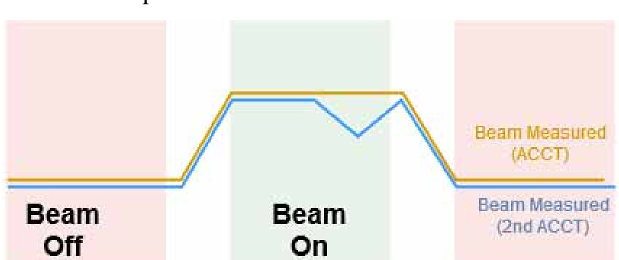

Figure 12: Current differences example.

Shut Beam Redundancy

The SBCT never directly shuts the beam, instead requests it from the TMG. However, if after a specified duration (12µs by default) it detects that the beam is still active, it directly shuts down the magnetron.

CONCLUSION

The MPS has been used and validated during the commissioning of the Saraf MEBT in 2023. It requires a learning time for the operator to fully grasp the system, but it offers comprehensive configurability to facilitate the identification of suitable tuning parameters. Moving forward, we will be incorporating updates for the four new cryomodules, one of which has just been installed and the remaining three others in the next few months.

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