ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA091

ESS MEBT CONTROL SYSTEM INTEGRATION

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Abstract

The high power linac of European Spallation Source, ESS, accelerates 62.5 mA of protons up to 2 GeV in a sequence of normal conducting and superconducting accelerating structures. The normal conducting part is being commissioned in Lund, Sweden. The Medium Energy Beam Transport (MEBT) line has been designed tested and mounted at ESS Bilbao premises to guarantee tight requirements are met. Installed in Lund during summer 2019, and its commissioning is foreseen to the second quarter of 2020.

The main purpose of this 3.62 MeV MEBT is to match the RFQ output beam characteristics to the DTL input requirements both transversally using quadrupoles, and longitudinally RF buncher cavities. Additionally, the beam is also cleaned by efficient use of halo scrapers and pulse shape by means of a fast chopper. Besides, beam characterization (beam current, pulse shape, size, emittance) is performed using a comprehensive set of diagnostics.

Therefore, firstly, control integration of magnets and steerers power supplies, for quadrupoles, as well as synchronism, triggering, linked to high voltage pulsers within the chopper control, is part of the commitment for the present work. Secondly, the control developments of beam instruments such as Faraday Cup and Emittance Meter Unit will be described. All the integrations are based on ESS EPICS Environment (E3) [1].

INTRODUCTION

The ESS MEBT is the section of the accelerator where proton beam is of 3.6 MeV and current of 62.5 mA with pulsed shape of 2.8 ms length at 14 Hz.

At these energy levels, specific interceptive beam instrumentation can be still inserted into the beam trajectory, whereas at higher energy stages, beam radiation and high temperatures does not allow their use. Eleven (11) quadrupoles are set for matching the proton beam transversally, 11 steerers will redirect the trajectory of the beam, 3 RF buncher cavities are set for conditioning the beam longitudinally, a stripline fast chopper shapes the beam pulses, and a Beam Dump.

As depicted in Fig. 1, the beam instruments inserted tightly in the 3.81 m length MEBT. The layout includes 3 Wire Scanners (WS), 8 Beam Position Monitors (BPM), which are housed inside 8 of the quadrupoles with very strict tolerances. In addition, one Fast Chopper, 3 x 2 Scraper blades (SC), 1 Faraday Cup (FC), 1 Emittance Meter Unit (EMU) provided by one pair of horizontal and vertical slits, and one pair of horizontal and vertical grids, 2 Beam Current Monitors (BCM), Fast Current Beam Monitor (FCBM), Non-Invasive Profile Monitor (NPM) and Bunch Shape Monitor (BSM) are part of the Beam Diagnostics set for MEBT.

In terms of control, ESS-Bilbao is responsible for the FC, EMU, motion of the SC, Fast Chopper, Quadrupoles, Steerers and Buncher Cavities. Therefore, Fig. 1 is representing only interfaces that affect to these elements.

ESS-Bilbao is also in charge of the control management of cooling and local protection system interlocks as a part of the control of those elements.

HW and SW architectures are thoroughly studied to provide a consistent standardized system for the control development.

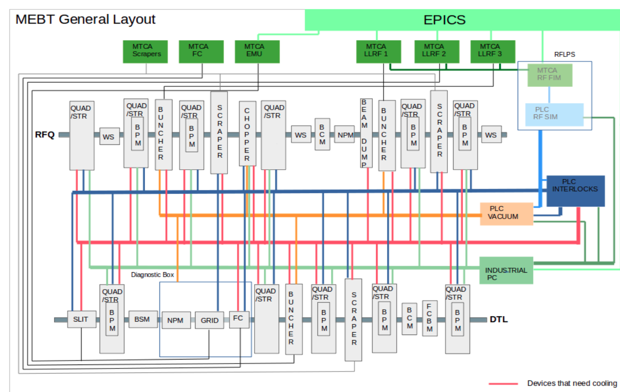

Figure 1: Control layout for ESS MEBT.

CONTROL ARCHITECTURE

MicroTCA has been the technology adopted for high speed processing and communication interfaces. MicroTCA crate provides a fundamental module Micro Carrier Hub (MCH) which adds management and communication functionality to the system such as Intelligent Platform Management Interface (IPMI), clock distribution and generation, switching functionality, increasing architecture robustness with the possibility of MCH redundancy.

The fact of using MicroTCA.4 standards, provides the architecture versatility of Advance Mezzanine Card (AMC) and Rear Transition Module (RTM) boards along with precise time characteristics.

An initial stage, while waiting for the maturity of some MicroTCA HW boards, have been developed using VME technology. It has been properly studied as a previous step to MicroTCA migration.

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The architecture defined for Beam Instruments, consists in a MicroTCA crate, provided with AMC, RTM and FMC boards necessary for the specific application of each Instrument, including digitizer and timing boards. Figure 2 shows MicroTCA crates for FC and EMU.

Although several beam instruments could be managed from one MicroTCA crate, in terms of reliability and maintenance improvement, each MicroTCA crate will control one beam instrument.

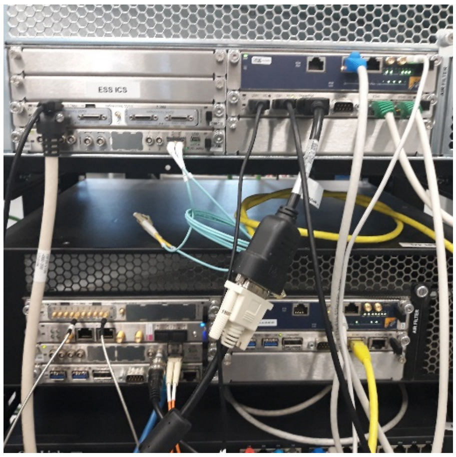

Figure 2: MicroTCA crates for FC and EMU.

Motion utilities for the instruments are developed using Beckhoff PLC modules [2], directly controlled by the embedded system central processing unit (CPU) in the MicroTCA crate. Thus, other purpose slow analogue and digital inputs and outputs will be using Beckhoff modules which will be controlled through the mentioned CPU as well. Figure 3 shows Beckhoff rack for motion control.

In case of fast response Inputs and Outputs (I/O), those are controlled over AMC boards. This is the case of Fast Chopper using an MRF UNIV-TTL-DLY board with restricted timing requirements. Experimental Physics and Industrial Control System (EPICS) [3] integration and Channel Access communication links the systems.

Figure 3: Scraper pair, motion control Beckhoff rack.

Virtual machines are used for controlling devices through communication protocols.

Twenty two (22) CAENels Current and Voltage-Controlled Bipolar Steerer Power Supplies (PS) are controlled through a proprietary protocol encapsulated over TCP/IP frames, programmed in EPICS.

Eleven (11) Elytt Unipolar PSs for quadrupoles are controlled through Modbus TCP/IP from EPICS.

On the other hand, Fast Chopper consists of an EPICS integration of several devices, where an embedded system is needed for the IOCs controlling pulses timing and synchronization. Thus, the communication for configuration of positive and negative pulsers is controlled from the crate embedded CPU. It uses both IOCs to generate a serial communication proprietary protocol.

Slow interlocks are controlled through Programable Logic Controller (PLC) Siemens S7. An EPICS module is developed for each MEBT device type. Then, a soft-IOC running on a virtual machine is developed for each device. The IOCs require the particular EPICS PLC communication module and sp7plc module, for ethernet interconnection with the PLC.

MicroTCA Hardware

The basic MicroTCA infrastructure consists in 3U crates with six AMC slots, managed by the NAT-MCH-PHYS carrier hub from NAT. The AMC cards are IOxOS IFC1410, which contains a Xilinx Kintex Ultrascale FPGA and two slots for FMC cards. The FPGA Mezzanine Card (FMC) digitizer boards used for these applications are designed by IOxOS who provides also the drivers to direct access through the FMC connector to its CPU FPGA.

The main CPU is AM 900/412-99 developed by Concurrent Technologies has four (4) Ethernet ports, two in the front panel and two in the backplane.

Ethernet connections are needed for external access as well as a dedicated PHY for the EtherCAT bus to control the Beckhoff modules.

Synchronization with the general accelerator timing is made via events received through the MRF MTCA EVR-300U board, an event receiver board manufactured by Micro Research Finland (MRF).

At an initial stage while waiting for the maturity of some MicroTCA HW boards, initial developments have been done using VME technology.

Control Software

The system SW environment and architecture are based in a Linux system. The MicroTCA CPUs have a local hard drive with CentOS 7 installed. ESS ICS plans to use Embedded Linux based in Yocto Project on a diskless configuration for the final operations.

The SW includes FPGA firmware, Linux modules drivers, integration EPICS drivers and modules. Specific instrument application EPICS modules are also developed. The EPICS environment is the E3 ESS defined and it is compatible with the standard EPICS.

Several EPICS Input/Output Controllers (IOC) are developed to achieve the MEBT control integration. The engineering GUIs have been developed with CSS BOY.

BEAM INSTRUMENTS INTEGRATION

Emittance Meter Unit

For low energy linear accelerators, a typical method for measuring the transverse emittance is using a slit and grid

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system. For each slit position, the narrow aperture allows the passage of a beamlet populated by particles that have almost equal position x and a certain angular distribution, that impact over grid wires.

As an example of beam instrument integration, EMU architecture and interfaces are going to be explained as a complete overview of representative beam diagnostic instrument.

The HW consists in a MicroTCA crate equipped with three AMCs: IOxOS IFC1410, AM900 CPU from Concurrent Technologies and MRF EVR 300U from MRF, as well as the required MCH card.

Plugged on the 2 FMC connectors of IOxOS IFC_1410, there are 2 IOxOS FMC ADC 3117, 20 analogue channels per board, 5 MSPS, 16 bits. It has been a challenging project to include 20 analogue channels in a MTCA.4 FMC. The requirements are 24 current wires per horizontal and vertical plane. This is reduced to 24 physical channels due to a switching function performed by a controlled multiplexor in the front-end electronics.

Moreover, further external systems are controlled from the MicroTCA crate: motion control Beckhoff modules including motor and encoder drivers are connected via direct ethernet.

The AM 900/412-99 CPU controls the Beckhoff EtherCAT bus provided with 4 axes. Each axis contains a stepper motor, an incremental encoder, home and in limit switches. Machine protection System (MPS) switches are also connected to these modules. Analog and digital inputs and outputs Beckhoff modules are connected to control adjacent functionality: power supply to provide BIAS voltage to repel secondary electrons emerging from the grid wires, or additional control functions such as plane change, front end (signal conditioning electronic) checking, wire checking and calibration.

Each beam instrument has a Local Protection System (LPS) commanded by Siemens S7 PLC for cooling supervision, where temperature and water flow are monitored through PT100 thermocouples and water flow sensors. Other slow interlocks signals are also managed such as instrument health status. This PLC has links with Accelerator Beam Interlock System (BIS), that is out of the scope of ESS-Bilbao developments. Figure 4 represents the EMU control schematic.

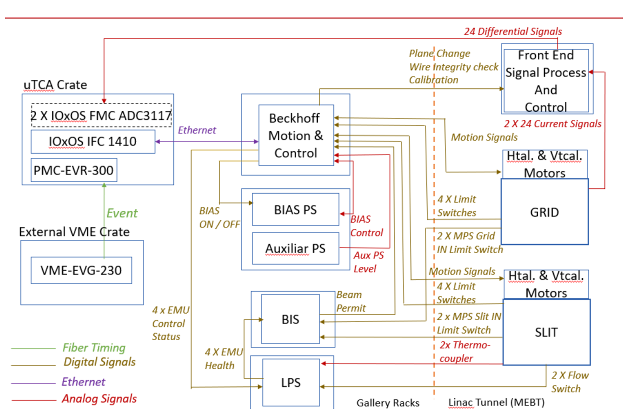

Figure 4: EMU control schematic.

In terms of EPICS developments, the EMU SW developments based in EPICS E3 Environment consist in 5 IOCs.

i) The main EMU IOC *mebt_emu* module which is based on *sscan* record control and functionalities.

ii) Digitalization IOC, that incorporates the specific digitizer driver modules and other modules such as asyn, nds3, nds3epics.

iii) Synchronization IOC which controls the EVR Event that generates a MicroTCA back plane acquisition trigger signal.

iv) EtherCAT IOCs, an IOC for the 2 axes of the horizontal plane along with further control, and another IOC for the 2 axes of the vertical plane, based on ECMC [4] module.

v) Slow Interlocks IOC is using *s7plc* module which determines the PLC interconnection. Then a *MEBT_plc_EMU* interlocks specific module is developed for signal monitoring and alarms acknowledge, this one running from a virtual machine.

Faraday Cup

The FC will be used to measure the beam current and as a beam stopper for accelerator start up. The FC is designed in order to withstand the commissioning beam modes.

The Faraday cup's main EPICS module has the next basic functionalities: i) Send insert/retract instruction to the Beckhoff I/O. ii) Control the repeller PS via Beckhoff. iii) Get the data from the FC.

The FC is controlled from another MicroTCA. In this case only an analogue channel is needed, for this purpose an IOxOS FMC ADC 3117 is used. FC has two positions: inserted and homed; movements that are performed with an electro-valve connected to Beckhoff modules.

Slow Interlocks module and IOC for communication with Siemens S7 is generated.

Figure 5 represents the Engineering GUI of the FC.

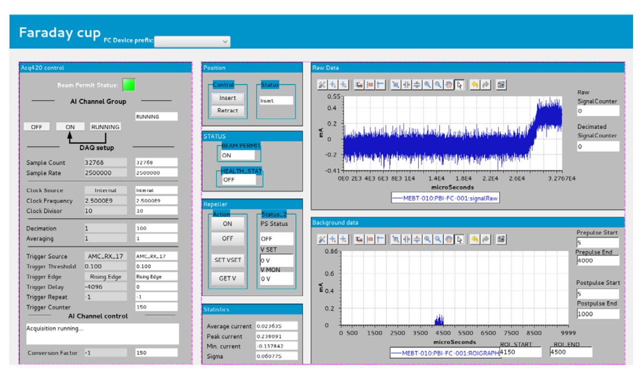

Figure 5: Engineering GUI of the FC.

Scrapers

The motion of the Scrapers consists in six axes, located by pairs, with a linear movement that are controlled each one by a stepper motor model Nanotec ST4118M1804-B with a brake model Nanotec BWA-025-5, and incremental encoder model SIKO MSK1000-11-M-E1-2-I-1-1.00 with

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a magnetic band SIKO MSK1000-1-0.3-10-0.01-St-TM-AM-0 has a resolution of 1 μm and an index signal 1 mm.

Those motion elements are controlled by the Open Source SW of ESS ERIC designed for controlling HW Beckhoff modules (ECMC).

Actuator has a stroke of 80 mm and a pitch of 2 mm. The total required torque in motor axis is 0.42193 Nm.

Axes motion has been developed in EPICS either as independent axes or as correlated axes by pairs. Figure 6 shows the engineering GUI for scraper's motion.

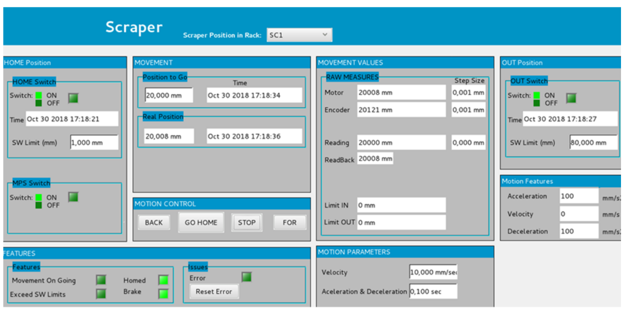

Figure 6: Engineering GUI for scraper's motion.

The limit switches are inside the interval of the HW limits. The stroke of limit switches is approximately 240 mm.

The limit switches are model OMRON SS-01Fl2-3.

Three limit switches are used. Two for motion control purposes and one for machine protection system (MPS).

There are SW limits to delimit the positions of the actuator movement. The SW limits are configured inside the control purpose limit switches trajectory.

In the homing procedure, the movement rebases the SW limits, to go the "HOME" switch. But then the actuator movement does not rebase the SW limits.

The homing procedure moves the actuator backwards until reaching the "HOME" limit switch, and then it moves forwards until the next index signal.

FAST CHOPPER

The chopper purpose is to clean the head and tails of the beam, coming out of the RFQ into the MEBT in order to avoid the beam losses. This is achieved by means of a stripline fast chopper which produces the required deflection to the beam. The chopper system is composed by two opposite polarity pulsers, stripline chopper and two dummy loads.

The chopper control configures the voltage output from the pulsers that is injected to the chopper stripline, and generates the trigger signals as the trigger inputs for each pulser. In normal operation trigger is a double squared pulsed signal coming from the Timing System. This trigger is fed to the input of each pulser and generates the voltage pulse required for the chopper. The voltage amplitude, the pulse width and other features of the output signal of the pulsers can be defined remotely. Figure 7 shows the double squared pulsed generated.

For the correct functionality of the chopper system, the two pulsers triggering must be synchronized very precisely. The MRF UNIV-TTL-DLY outputs module, plugged on the AMC MRF EVR board, is used for the outcoming trigger signals in order to have an accuracy of 10 ps. UNIV0 output is connected to negative pulser and UNIV1 output is connected to positive pulser. The rising edge of the trigger signal is a few ns, and synchronization fine delay from 2.2 ns to 12.4 ns in steps of 10 ps.

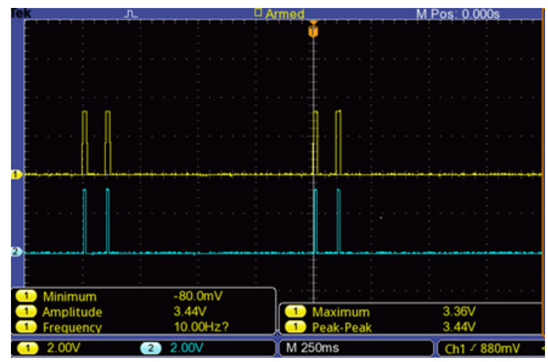

Figure 7: Double squared pulsed generated in chopper.

For the configuration of the pulsers, there is a serial communication from the embedded CPU. This is TCP/IP via Ethernet communication, with two converters from AK-NORD that are connected to change it to Serial RS-232 fiber optics, required at the input of the pulsers. The protocol is proprietary from FID GmbH, the manufacturer of the pulsers. In the final installation, Moxa device servers are used as Ethernet to serial converters.

The control of the chopper is implemented in EPICS. The main EPICS module for the Fast Chopper is the mrfioc2 module, which allows total control of the MRF EVR from EPICS.

For pulser control, the *PulserProtocol* module based on *streamdevice*, for configuring the features of the pulsers is generated, and then an IOC for each pulser is launched. Interlocks IOC communicating with its associated S7 PLC is also generated.

MAGNETS

The developments made for Magnets include the configuration and control Elytt Unipolar PSs [5] for the quadrupoles by a Modbus TCP/IP, protocol where alarm levels are also configured. An IOC running as communication slave for each PS acting as a Modbus Slave is generated, that requires the specifically EPICS module with the device Modbus map generated, and the modbus module ESS version.

Quadrupoles also require interlocks control. A PLC device is assigned for each. The EPICS communication with the PLC has a particular module and 11 IOCs supervising the safety of all of them. In Fig. 8 is displayed the CSS engineering screen of quadrupoles interlocks.

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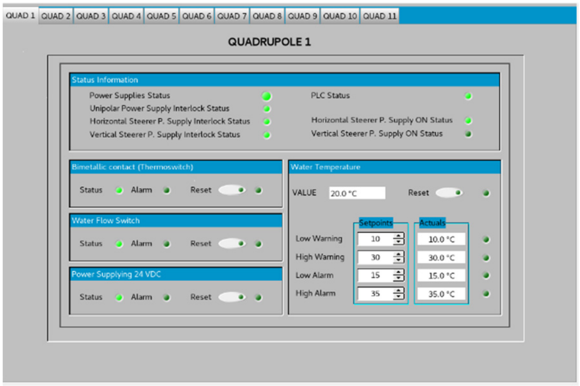

Figure 8: Engineering screen of quadrupoles interlocks.

The magnet steerers redirect the trajectory of the beam by 22 FAST-PS-2020-400 [6]. Eleven for each plane horizontal and vertical. These FAST-PSs from CAENels are independent current- or voltage-controlled digital bipolar power supply modules. Remote communication is guaranteed by means of an Ethernet 10/100/1000 autosensing socket present on the front panel of the power unit.

A specific protocol EPICS module is developed dependent on AsynDriver, and Stream Device is generated. Each steerer PS is controlled via an IOC including this module which acts as communication slave running on an IPC.

TEST BENCH AT ESS-BILBAO

One of the challenges accomplished is the integration of the FC on the Ion Source Hydrogen Positive (ISHP) at ESS-Bilbao Injector. FC acquisition triggering had to be adapted to Injector synchronization system which is handled by National Instruments (NI) devices, being PXI and CRIO into the ESS-Bilbao ISHP's control system. Signal accommodation for the current read also needed to take place as well as surge protectors are included in the electronics Front End. The results of the current measured were satisfactory as they were compared with the captured va

lues of two ACCTs located along the LEBT at ESS-Bilbao injector.

Figure 9 shows ESS MEBT FC under test at ESS-Bilbao injector.


Figure 9: MEBT ESS FC at ESS-Bilbao Injector.

CONCLUSIONS

The architecture provided has been satisfactory, for the requirements of execution times, response and functionality, that can be reused in further developments. Interfaces and signals included in the control design have managed the systems as expected.

New reusable EPICS modules, compatible with EPICS standard framework have been generated.

MEBT control integration has served to test new HW as MicroTCA is an emerging embedded architecture. Control developments have served to validate mechanical and functional design of beam instruments such as actuators, motors, encoders, gearboxes, brakes under vacuum conditions.

Signal processing vertical integrated tests have helped to test front end electronic designs connected to digitizers.

Chopper timing challenging conditions have been successfully achieved.

Pioneer MicroTCA integration with real beam at ESS-Bilbao injector has been fruitfully accomplished.

ACKNOWLEDGES

Special acknowledge to the ICS, MCA and BI groups of ESS, for the excellent collaboration and support, specially to J. Etxeberria, J. Cereijo, T. Korhonen, J. H. Lee, T. Böghershausen, A. Sandström, and T. Gahl.

To the ESS-Bilbao team mentioning S. Varnasseri, D. F. Cañoto and V. Toyos.

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