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EPICS BASED HIGH-LEVEL CONTROL SYSTEM FOR ESS-ERIC EMITTANCE MEASUREMENT UNIT DEVICE

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Abstract

The European Spallation Source (ESS) [1] will be a neutron source using proton beam Linac of expected 5MW beam power [2]. The beam commissioning of low energy beam transport (LEBT) started on 2018 and currently expected to reach to the end of Medium Energy Beam Transport (MEBT). Several diagnostics are installed to characterize the proton beam and optimize the beam matching in radio frequency quadrupole (RFQ) section and rest of accelerator. Among all diagnostics, Allison scanner and Slit-Grid type emittance measurement units (EMUs) will aid by characterizing the beam in transverse plane (both horizontal x and vertical y) in LEBT and MEBT, respectively. Here in this paper the Slit-Grid EMU is explained and the software layer developed in EPICS [3] and realized to orchestrate the entire apparatus and control the different sub-systems will be described.

INTRODUCTION

The emittance measurement unit (EMU) aims to measure the transverse emittance by sampling the transverse phase space. At European Spallation Source (ESS) the Alison Scanner and Slit-Grid EMUs will be used to characterize the proton beam transversely in keV and MeV energy ranges, respectively. The Slit-Grid units, designed and delivered by ESS Bilbao [4], are installed in both transverse directions in MEBT, in order to characterize the beam after RFQ, see Figure 1. According to the baseline parameters, the MEBT will operate with peak current of 62.5 mA, energy of 3.63 MeV and RMS size of 2 mm. The Slit-Grid will be used to optimize matching of the beam to the other sections of the accelerator.

Considering the control system aspect, a single EMU device is composed of different sub-systems (acquisition, motion, etc.) which are harmonized and managed by EPICS, the distributed control system framework adopted as standard for the ESS Project. This article reports the upgraded on low-level and high-level control system.

EMITTANCE MEASUREMENT

The transverse emittance is an invariant quantity describing the distribution of the particle beam in transverse phase space (horizontal x and vertical y).

The RMS emittance formula commonly used is the following:

$$\varepsilon_{RMS} = \sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle x \cdot x'\rangle^2} \tag{1}$$

where $\langle x^2\rangle$ is the variance of the particle's position, $\langle x'^2\rangle$ is the variance of the angle the particle makes with the direction of travel in the accelerator and $\langle x \cdot x'\rangle$ represents an angle-position correlation of particles in the beam.

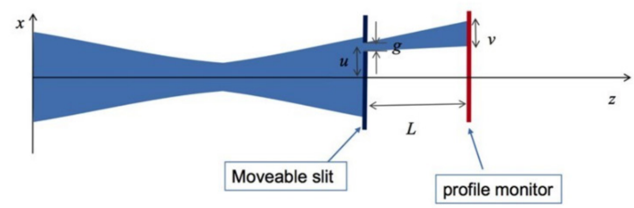

Figure 1: Scheme showing the Emittance measurement using Slit-Grid EMU. Source: Cheymol, R. Miyamoto, *"Preliminary Design of the ESS Slit and Grid System"*

INSTRUMENT DESCRIPTION

A Slit-Grid EMU is composed of a slit and a grid unit, mounted on separate moving actuators to scan the beam entirely. The slit samples small slices from the beam at almost equal position following drift space, the angular distribution of the particles is transformed into a position distribution and sampled using a profile monitor, in our case a secondary emission grid. By scanning the slit across the beam, the whole phase-space is reconstructed, see Figure 2.

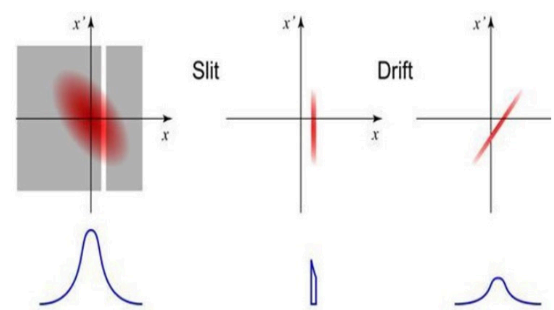

Figure 2: Phase-space sampling using a slit-grid system. Source: B. Cheymol et al., *"Design of a New Emittance Meter for Linac4"*

Particular aspects and design solution adopted are the following [5]:

For the EMU slit, it was shown that graphite is the chosen material to withstand irradiation. As consequence two graphite plates that form the slit are mounted in the slit head

- The EMU slit is designed in order to scan all the beam aperture. Since the beam envelop is ϕ40 mm,

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the blades width has to be >40 mm, for a total height >80 mm. therefore the design for the graphite plates is plates of 40 mm x 54 mmx 3 mm;

- For the slit, the reference values are an aperture of 100 µm and a slit thickness of 200 µm
- The distance between the Slit and the Grid is 400 mm.
- The grid has 24 tungsten wires, 35 µm diameter and the pitch of the grid is 500 µm.
- The resolution of the actuators is at least 25 µm.

The hardware described is shown in Figure 3.

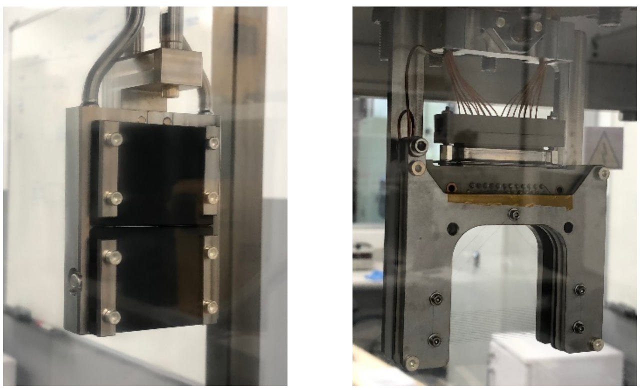

Figure 3: Slit and Grid devices composing the EMU apparatus.

HARDWARE AND SOFTWARE ASSUMPTIONS

The EMU system has been designed in order to satisfy the ESS-ERIC requirements in terms of hardware and software standardization. In particular the system is following these criteria.

Hardware

According to the diagnostic apparatus, it is possible to observe two different functional systems: motion and data acquisition [6].

The EMU motion system is actuated with stepper motors, controlled by a motion controller; slits (horizontal and vertical) and grids (horizontal and vertical) will be stepped across the beam with separate stepper motors (for a total of 4 axes). Two pair of limit switches are installed on each EMU actuator, one for the motion control system, and the other one for the Beam Interlock System.

The EMU data acquisition is devoted to acquire signals from the grid sub-system and provide the information to the high-level software layer designed to elaborate and provide the emittance measurement. The hardware related to the acquisition is composed by an analog front-end for signal conditioning and a digitizer board; in addition to the acquisition chain, a bias voltage supplying line is applied to the grid and an Event Receiver Timing board is required to synchronize the acquisitions with the accelerator global timing.

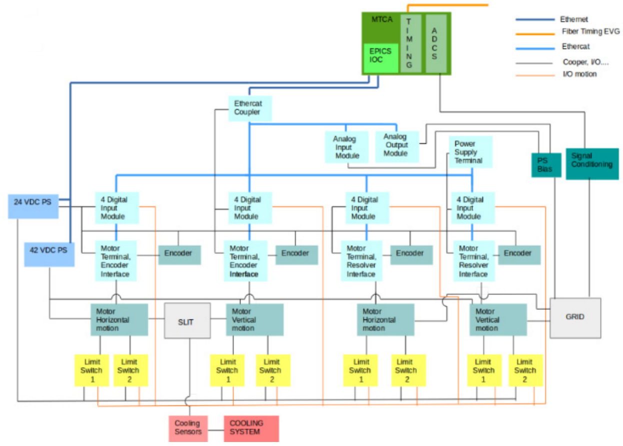

Figure 4: EMU hardware scheme. (Source: I. Mazkiaran, *"EMU Development Document"* [6])

According to the ESS-ERIC guidelines, these two systems are based on Beckhoff® EtherCAT modules [7] for the motion and µTCA® standard for data acquisition [8]. The main schema related to the hardware is shown in Figure 4.

Software

The ESS-ERIC project has adopted the EPICS framework as standard to develop, implement and control the entire facility.

The structure of the control system framework has passed some evolutions in the past years in order to create and provide a solid architecture easy to use and maintain. This aspect is absolutely important in a project where stakeholders' contributions and the final maintenance in charge of ESS-ERIC internal staff are crucial points.

In order to satisfy these requirements, the last solution provided by the project is the ESS EPICS Environment (E3): it is a design concept and a toolkit intended to facilitate development by abstracting away some of the low-level complexities intrinsic to large EPICS implementations (primarily dependency management), and to allow for more manageable quality control of released modules as well as Input/Output Controllers (IOCs). It allows to easily build EPICS modules directly from source and automagically resolves module dependencies, and allows for site specific modifications to EPICS modules without needing to directly modify the source tree [9].

The entire software implemented for the EMU system and described in this contribution is entirely based on the E3 framework.

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CONTROL SYSTEM ARCHITECTURE

The EMU device (hardware and software) was originally provided by ESS Bilbao. Under software aspects, the EMU application was not developed using the last E3 environment but with a previous version of the framework. As consequence, several incompatibilities were inherited in the application and a renewal was mandatory; at the same time, additional requirements came up and they had to be developed from scratch. For this reason, a complete software redesign has been done.

The main conditions and requirements considered at this stage were:

- The entire software application must adopt E3 framework. This includes both low-level layer (hardware driver interfaces) and high-level layer (pure software application);
- Slit and Grid axes must be synchronized with data acquisition;
- The algorithm defining the logic in the high-level layer must consider the following set of information as inputs for the emittance measurement:
  - Slit/Grid plane control
  - Slit start position
  - Slit end position
  - Possibility to provide step size or number of steps (per slit position)
  - Grid micro-steps
  - Possibility to operate in *yaw* mode (slit and grid move in sync with a prefixed offset)
  - Number of samples per acquisition
  - Acquisition rate
  - Number of pulses per position
- The algorithm must include the possibility to use pre-calculated slit/grid position instead of providing start and stop positions;
- The entire measurement campaign must be stored in NeXus [10] data format.

Because the software update involves both external contributor (in-kind partner) and internal ESS-ERIC staff, a big constraint in the development stage was related to the necessity to rewrite the entire system application (high-level and low-level software) in parallel by different groups in different places: while the INFN partner was in charge of realizing the high-level control software, ESS-ERIC was in charge of the low-level software migration to the new standard. With this work organization, tasks coordination and teams' communication are crucial to rapidly get progresses.

In order to execute the different upgrades in parallel, a modular approach for the software architecture was adopted: according to the scheme represented in Figure 5, the entire system is composed by 3 main modules:

- Data acquisition (low-level)
- Motion (low-level)
- Experiment supervision and Emittance calculation (high-level)

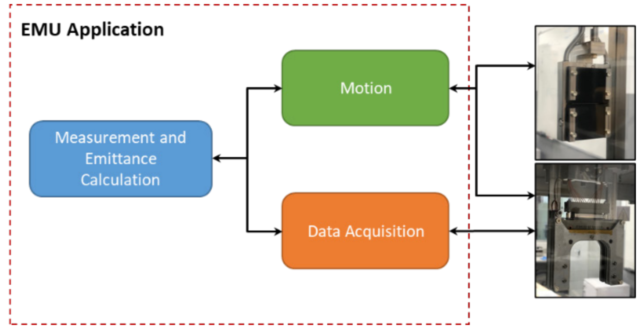

Figure 5: EMU software schema adopted during the application development: it is possible to observe the low-level applications (Data Acquisition and Motion) and the high-level orchestration.

While the driver software interfaces were under upgrade, dedicated simulation mockups were developed in order to provide a set of "black box" applications devoted to simulating the real hardware (Figure 6).

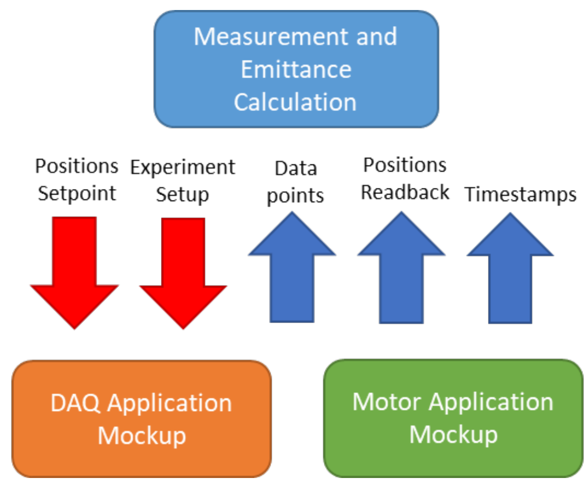

Figure 6: EMU low-level mock-ups used to simulate data acquisition and motion hardware.

LOW-LEVEL SOFTWARE UPGRADE

The data acquisition software layer used in this project is the same that has been used for all the beam instrumentation systems in ESS and it's based in areaDetector drivers. The low-level driver is implemented as an NDArrayPortDriver class, which provides the raw analog data as NDArrays that are further processed by a series of areaDetector plugins. The result of the process chain is the average of the current in each wire of the grid, calculated over a region of interest.

For the motion control, the low-level software is implemented using ECMC [11] framework, the standard platform for the accelerator systems in ESS, built as the software support for the Beckhoff hardware system. ECMC provides the high-level access of the motion system using the EPICS motor record, alongside many other features like the "PLC objects": pieces of code in ExprTK [12] language that are loaded inside the EtherCAT master kernel

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module and can perform tasks like the automation of the axis homing procedure, protection routines, etc...

HIGH-LEVEL ORCHESTRATION APPLICATION

The high-level orchestration layer is a pure software application and it defines the core part of the emittance measurement. In particular it is in charge of:

- Provide the interface between the system and the user;
- Coordinate data acquisition and motion systems;
- Calculate the beam emittance and all the relative parameters required by the user;
- Collect all the experimental data and store it via NeXus service.

One of the assumptions chosen for the application's design was to create a unique program which does not use any kind of external script or tool. The idea behind this assumption was to provide a standalone portable EPICS application. In order to follow this approach, the high-level orchestration program has been composed by the following parts:

- A set of state machine programs used to coordinate the low-level functional sub-systems;
- A set of EPICS Databases devoted to map the information exchanged between high-level and low-level and between application and final user;
- Additional custom C libraries used to implement particular functions required by the application and not available in the standard one.

The core of the main application is the set of state machines: using the common Sequencer EPICS module, different SNL programs were defined [13]. A main state machine is dedicated to control the system, taking in charge of capturing the measurement scan parameters, execute preliminary checks, coordinate and synchronize motion and data acquisition, elaborate the data coming from the field, execute emittance calculation and send the information of interest (measurement raw data and metadata) to the NeXus service. Secondary state machines have been created in order to operate minor functionalities, such as parameters calculation for measurement setup and optimization (conditions checks).

Because of the estimated size of the data of the measure campaign (number of acquisitions, samples acquired per wire, etc.), one critical point the SNL program had to manage was the allocated memory at application start-up, coming up with the definition of multi-dimensional arrays used to manipulate sets of signals coming from the field. In order to overcome this possible critical point, 2 different elements had been used in the SNL program:

- The signal coming from the DAQ system were preliminary manipulated via EPICS AreaDetector [14] and a set of its plugins: Processing plugin, ROI plugin and Stats plugin (Figure 7);
- Custom C functions devoted to define pointers, data structures and all the calculations required by the measurement campaign. These functions were grouped and managed as local library and inherited in the SNL program through the *Escape to C Code* mechanism.

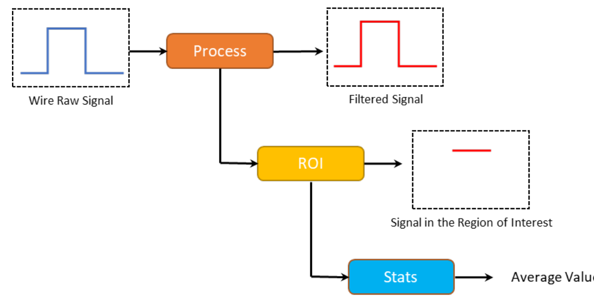

Figure 7: Wire signal processing with EPICS AreaDetector plugins.

In order to store the sensible information (raw data and experiment metadata) in the NeXus service, the ENeXAr tool [15] was used. This application a Python service developed internally at ESS-ERIC that can be used to archive PVs into NeXus files through simple CLI commands; this solution was extremely useful to easily integrate the service inside the orchestration state machine.

As previously mentioned, NeXus service is in charge of storing experimental raw data measurements and metadata using HDF5 file format [16] largely used in research environment. In addition to this storage system, the canonical EPICS Archiver service is used to store all the control variables of interest.

TEST AND FURTHER DEVELOPMENT

Preliminary tests demonstrated that the application requires a minimum 16GB of RAM to be stable. This high request of memory is caused by the number of data structures initialized by the state machine during application start-up.

The first bunch of tests were dedicated to verify the correct management of the functional sub-system (data acquisition and motion) using the simulated environments. For this purpose, the Graphical User Interfaces shown in Figures 8-10 were developed.

Once these tests will satisfy all the projects requirements in terms of functionalities, a second bunch of tests will be performed connecting the EMU application with the real hardware and with the new low-level drivers. In parallel to this task, the main application will be revised with the intention of optimizing memory consumption.

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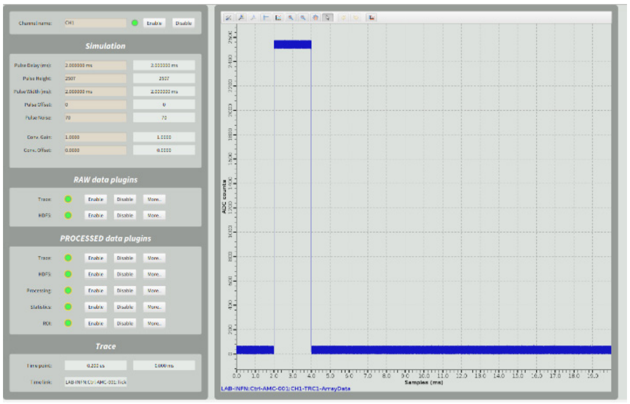
Figure 8: GUI developed for data acquisition system.

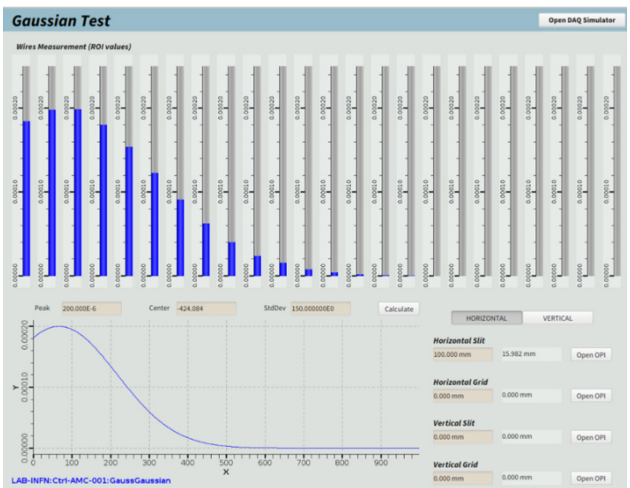

Figure 9: GUI developed for motion system.

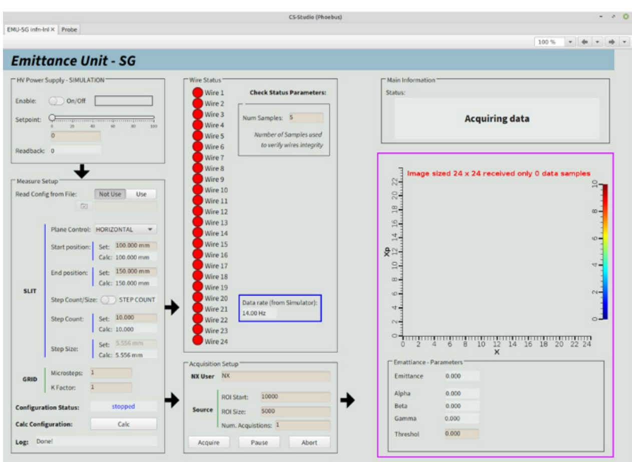

Figure 10: GUI developed for the EMU application.

CONCLUSION

The Emittance Meter Unit is an important equipment for calculating the transverse emittance related to the beam in the MEBT section of the linac. Due to the requirement and indications coming from ESS-ERIC Guidelines in terms of hardware and software standards, the application developed has been a great challenge in the matter of technical solutions adopted during the software upgrade: time optimization had a key role in the entire work.

The application has been tested with the simulated environment and the preliminary results are promising. Further tests with the real hardware are scheduled in the next period. In the meanwhile, code optimization in terms of memory usage will be done.

In addition, the long-term goal the team would achieve is using the results of this work is to establish a scanning instruments EPICS framework for the entire project, reusing it on the EMU systems in the LEBT and on the Wire Scanners instrumentation.

ACKNOWLEDGMENTS

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REFERENCES

[1] ESS – European Spallation Source, `https://europeanspallationsource.se/`

[2] R. Garoby *et al.*, "The European Spallation Source Design", *Phys. Scr.*, Vol. 93, 014001, 2017 `https://doi.org/10.1088/1402-4896/aa9bff`

[3] EPICS, `https://epics-controls.org`

[4] I. Mazkiaran, I. Bustinduy, C. de la Cruz, G. Harper, A. Rodríguez Páramo, and J. P. S. Martins, "ESS MEBT Control System Integration", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), New York, NY, USA, Oct. 2019. `doi:10.18429/JACoW-ICALEPCS2019-MOPHA091`

[5] A.R. Páramo et al., "Conceptual Design of the ESS MEBT EMU", July 2018, unpublished

[6] I. Mazkiaran, "EMU Development Document", May 2017, unpublished (Ref . MEBT-BI-EMU82-04)

[7] Beckhoff® EtherCAT System, https://www.beckhoff.com/en-en/products/i-o/ethercat/

[8] µTCA® open standard, https://www.picmg.org/openstandards/microtca/

[9] EPICS E3, http://e3.pages.esss.lu.se/

[10] NeXus project, https://www.nexusformat.org/

[11] J. Etxeberria, J. H. Lee, and A. Sandström, "EtherCAT Open Source Solution at ESS", presented at the 17th Int. Conf. on Accelerator and Large Experimental Physics Control Systems (ICALEPCS'19), New York, NY, USA, Oct. 2019. `doi:10.18429/JACoW-ICALEPCS2019-WEPHA046`

[12] C++ Mathematical Expression Toolkit Library (ExprTk), `https://github.com/ArashPartow/exprtk`, `https://github.com/icshwi/e3-exprtk`

[13] EPICS SNL, `https://www-csr.bessy.de/control/SoftDist/sequencer/`

[14] EPICS AreaDetector, `https://cars.uchicago.edu/software/epics/areaDetector.html`

[15] ENeXAr service (internal ESS documentation), `https://confluence.esss.lu.se/display/SW/ENeXAr+-+The+EPICS+NeXus+Archiver`

[16] HDF5 library and file format, `https://www.hdfgroup.org/solutions/hdf5/`

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