ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUMBCM030

EPICS BASED TOOL FOR LLRF OPERATION SUPPORT AND TESTING

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Abstract

Interruptions in linear superconductive accelerators LLRF (Low-Level Radio Frequency) systems can result in significant downtime. This can lead to lost productivity and revenue. Accelerators are foreseen to operate under various conditions and in different operating modes. As such, it is crucial to have flexibility in their operation to adapt to demands. Automation is a potential solution to address these challenges by reducing the need for human intervention and improving the control's quality over the accelerator. The paper describes EPICS-based tools for LLRF control system testing, optimization, and operations support. The proposed software implements procedures and applications that are usually extensions to the core LLRF systems functionalities and are performed by operators. This facilitates the maintenance of the accelerator increases its flexibility in adaptation to various work conditions and can increase its availability level. The paper focuses on the architecture of the solution. It also depicts its components related to superconducting cavities parameters identification and elements responsible for their tuning. Since the proposed solution is destined for the European Spallation Source control system, the application has a form of multiple IOCs (Input/Output Controllers) wrapped into E3 (ESS EPICS Environment) modules. Nevertheless, it can be adjusted to other control systems - its logic is universal and applicable (after adaptations) to other LLRF control systems with superconducting cavities.

INTRODUCTION

The crucial aspect of the accelerator's functioning is its availability. It is vital to provide an operation period without any downtimes or interruptions that could limit users' time for experiments. The availability of an accelerator could be considered in terms of two aspects. The first is the accelerator's flexibility to adapt to various modes of functioning or to different operational conditions. Working conditions can be understood for example as operating in pulse mode or continuous wave mode. They can be also seen as maintaining proper parameters when conditions such as environmental temperature have changed. It is worth mentioning that the broader set of operational conditions offered may appeal to potential users of the facility and present possibilities for different types of experiments. The second aspect is to ensure that the accelerator operates properly without interruption caused by faulty components or misconfiguration of equipment or control system. The control system itself must detect dangerous situations and try to prevent them or at least limit their effect by shutting down proper subsections of the accelerator.

One of the potential solutions to the described challenges is to introduce a certain level of automation to testing and operation support procedures. Automation helps to keep consistency in particle beam control. It allows for continuous and uninterrupted operation, optimizing efficiency and it limits downtimes needed for recovery after a failure. With minimal downtime for maintenance and streamlined processes, accelerators can operate at their optimum potential, maximizing productivity and contributing to the cost-effectiveness of research and industrial applications.

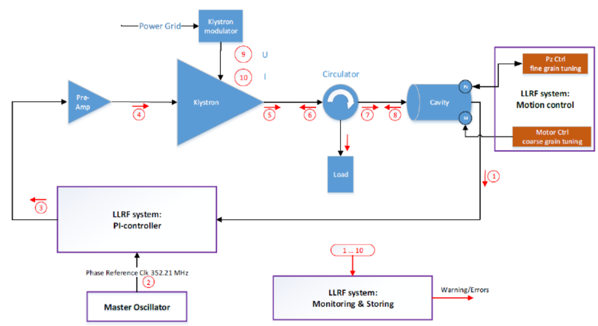

Figure 1: Schematic of superconducting (SC) RF system [3].

LLRF CONTROL SYSTEM

Role of LLRF Control System

The superconducting part of the accelerator is responsible for particle acceleration. It is made of niobium and resonant cavities. For each cavity, the electromagnetic wave with the appropriate gradient and frequency must be delivered. The LLRF (Low-Level Radio Frequency) control system manages the phase and amplitude within the cavity by gauging the field and comparing these measurements with a predefined set of target values [1]. In ESS (European Spallation Source), the control system uses a PI controller with the addition of adaptive feedforward compensation [2]. The schematic of the RF system is presented in Fig. 1. It is assumed that the LLRF should generate an input signal to the amplifier that drives the cavity to a field with an amplitude and phase precision that are within 0.5% and 0.5 degrees of a set value that is unique for each cavity [3,4].

Another responsibility of the LLRF control system is compensation for cavities deformation caused either by Lorentz Force detuning (LFD) or microphonics effects. The cavities are tuned with two types of motion controllers: step

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motors and piezo elements. The step motors are used for slow-tuning during the preparation of the resonator for specific operating conditions. They compensate for instance changes in ambient temperature. The piezo components' task, as fast tuners, is to eliminate microphonics and LFD that lead to power losses while accelerator functioning [1].

Automation of LLRF Tasks

In the field of LLRF control systems, there are (among others) two main areas where automation can be introduced:

- testing,
- operation support.

Testing To minimize the risk of the failure of the accelerator components, it is important to get information on the basic parameters of the cavity and the system's behavior. In most cases, this can be done only during the initial stage (before installation) of the accelerator's operation since testing conditions may not be possible always to achieve in the regular accelerator environment. That is why the tests need to be carefully planned. The proposed list of test procedures is as follows:

- Lorentz Force Detuning static and dynamic coefficients,
- characterization of Piezo elements tuning range and polarity control,
- identification of the main longitudinal mechanical modes,
- slow tuner sensitivity and backlash identification,
- loop performance evaluation,
- input antenna coupling vs. temperature characterization.

Although the list is not completed, all mentioned tests are crucial to examining each cavity and verifying whether the system is able to operate.

Operation Support To increase system flexibility and facilitate its adaptation to changing conditions, automation of certain procedures can be useful. The support tools should be able to help with the system startup, its maintenance, and other procedures. This leads to a reduction of user interaction with the system which can be the source of potential issues. The procedures to be automated:

- cavity parameters identification (bandwidth and detuning),
- automated characterization of piezo tuning range and polarity control,
- far tuning,
- piezo range optimization,
- DAC (Digital-to-Analog Converter) offset compensation,
- piezo capacitance measurement,
- slow and fast cavity quench detection,
- virtual probe signal monitoring.

The proposed set of tools is designed based on the ESS infrastructure. That is why they will be implemented as EPICS (Experimental Physics and Industrial Control System) IOCs (Input/Output Controllers) wrapped into E3 (ESS EPICS Environment) modules. Only that part of the algorithms that have to fulfill tight synchronization requirements will be developed as a low-level layer.

EPICS AND E3

EPICS

EPICS is an open-source software toolkit to design distributed control systems for large research facilities such as particle accelerators and observatories. EPICS utilizes communication methods like Client/Server and Publish/Subscribe to facilitate interaction among different computer systems. Usually, distributed control systems in such experiments are composed of hundreds of computers. In EPICS-based systems, modules - IOCs (Input/Output Controllers) handle I/O actions, and share relevant data through a network protocol named CA (Channel Access) or its newer version pvAccess. Typically, IOC is a set of code, databases, sequences, and/or startup script snippets that provide generic functionality for a particular device type or logical function. Thanks to the large, collaborative community and its flexibility, EPICS is widely used and become a standard control system framework for many laboratories [5, 6].

E3

E3 is a number of EPICS environments and a front-end for users and developers at ESS to use, as well as a collection of utilities to set up and maintain the mentioned environments. EPICS modules can vary in structure and each developer who uses EPICS has their own style and conventions, which will be reflected in the source code. Those modules may have different dependencies of various versions. E3 addresses this issue by creating an interface for all modules. It is called a wrapper and it links to the module source code and identifies module dependencies and versions. It also introduces ESS-specific changes [7].

E3 has been designed to unify EPICS development helping developers not to focus on EPICS infrastructure but on specific functionalities like data processing. What is more, E3 not only simplifies the work of system integrators but also makes maintenance easier and less time-consuming.

EPICS BASED AUTOMATION TOOL

An EPICS-based automation tool is a set of IOCs encapsulated into E3 modules with various algorithms to support user operations and test LLRF control system components. The paragraph describes the details of the proposed solutions together with a sample of IOCs.

Requirements

There are some basic requirements that all the tools have to meet:

- all the tools must be integrated with E3 environment and EPICS framework,
- providing GUI (Graphical User Interface) for tool management and monitoring,

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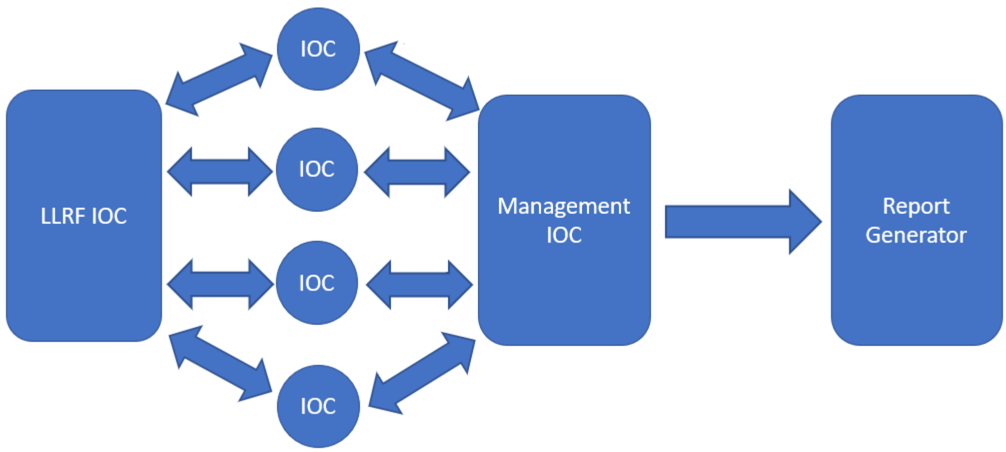


Figure 2: Architecture of designed solution.

- some of the algorithms must fit into a predefined time frame (pulse time),
- accessibility for other systems,
- providing result reporting system.

Architecture

The architecture of the solution is shown in Fig. 2. It has been decided that the EPICS-based automation tool will be composed of one, major IOC whose task is to control procedures and report their results, and other IOCs responsible for conducting particular tests and performing support operations. The management IOC communicates via CA with other IOCs and reads proper PVs (Process Variables) values with values specific to each IOC. It can start/stop IOC, and read the current status of the procedure, and the final results. Single IOCs, as mentioned before, provide a test configuration interface, and perform tests and procedures like piezo element identification or cavity parameters calculations or others.

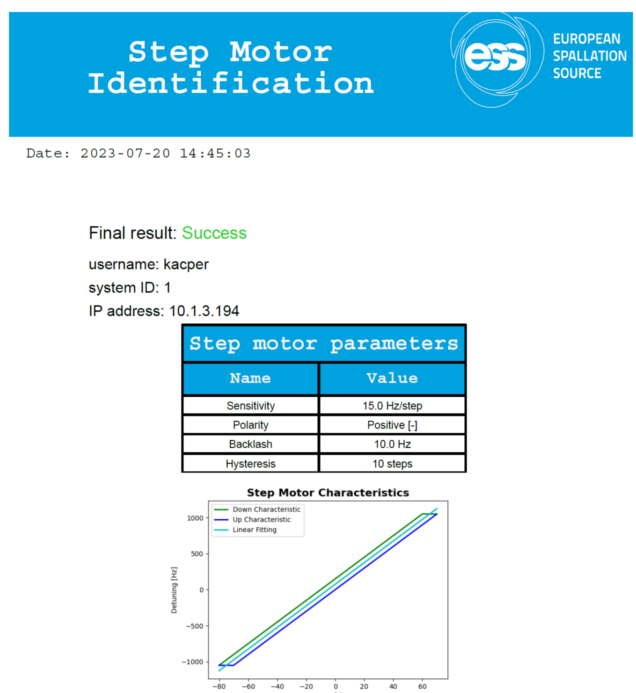
Thanks to that architecture, procedure IOCs are independent from each other. They only rely on the LLRF interface and its PVs. The management IOC can work with missing IOCs, it will only report a lack of communication with some of the modules. It is also useful in case of any IOC failure, it does not affect the other, properly functioning IOCs.

The last element of the tool is a report generator module. It converts status and results into PDF reports.

Test and Support Operation IOCs

Each single IOC represents one test procedure or operation support algorithm. The algorithm logic is designed as a state machine implemented as an EPICS Sequencer module, written in SNL (State Notation Language). The structure of any IOC is as much as possible unified. It means that they have a group of PVs responsible for initial configuration (setting up LLRF control system and component under test i.e. piezo IOC). This chain of PVs remembers changed values to bring them back when the procedure is finished.

Furthermore, there is a set of PVs destined for procedure customization available for users. The algorithm procedure can be started only if status PVs, which check the current LLRF state and other crucial parameters, allow it. The changes in those parameters are monitored during run-time as well. Those IOCs have a fixed set of results and error-reporting PVs that later, together with measured or calculated values are used for report generation.


Step Motor Identification

EUROPEAN SPALLATION SOURCE

Date: 2023-07-20 14:45:03

Final result: Success

username: kacper

system ID: 1

IP address: 10.1.3.194

Step motor parameters	
Name	**Value**
Sensitivity	15.0 Hz/step
Polarity	Positive [-]
Backlash	10.0 Hz
Hysteresis	10 steps

Figure 3: Sample of PDF report.

Report Generator

The report generator has a form of Python tool. It uses the PyEpics library to communicate with the management

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IOC and ReportLab Toolkit, which is an open-source Python library, for generating PDFs. It is a console tool, configured with flags used to define the name of the IOC for which the report is to be generated, and the values of the macros to read the corresponding values from the PVs. Additionally, users can also include metadata such as username, system ID, IP address, etc. An example of the report template can be found in Fig. 3.

SAMPLE OF WORKER IOCS

Cavity Parameters Identification

The major task of this IOC is to calculate the current value of detuning and Q factor based on the decay stage of the RF (Radio Frequency) pulse - the slope of exponentially decreasing cavity voltage and the change of phase that is linear [8]. It also calibrates measured cavity forward and reflected signals. It is essential to do this since signals can contain crosstalk and other imperfections caused by signal couplings at the pick-up [9].

Firstly, the algorithm reads raw data from LLRF IOC (cavity signals, RF end pulse, and pulse width). Then, the filtration (moving average) is performed, and calibration of the cavity forward and reflected signals. The calibrated signals are calculated according to the method described in [9] and [10]. In the meantime, the phase of the cavity signal is being unwrapped to eliminate abrupt changes in phase. Finally, the detuning is computed by fitting the linear function into the decay stage of the cavity phase on the logarithm scale and by using the cavity model to verify how it has changed during the whole pulse [8].

Piezo Identification

Piezo actuators are used to compensate for detuning caused by Lorentz Force and microphonics. The detuning can lead to significant power losses which is why it is crucial to properly characterize piezo elements to be able to efficiently control their functioning. Some key parameters are:

- tuning range,
- piezo hysteresis,
- piezo sensitivity,
- piezo polarity.

The role of the module is to identify those parameters in an automatic way, without user interaction.

Procedure's Logic The procedure's state machine is presented in Fig. 4. At the beginning, the algorithm verifies if all conditions are met to begin the procedure. If not, there is a PV chain that is activated to configure the LLRF control system for the operation. When the procedure is finished, the values of the parameters can be recovered. What is worth mentioning, during prerequisites configuration if the piezo voltage needs to be changed, there is another procedure that prevents voltage spikes and applies a voltage ramp with a fixed step to reach the initial voltage for tests.

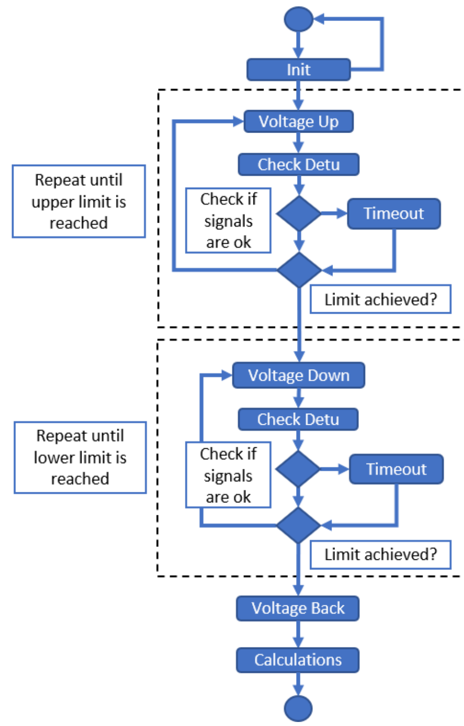

Figure 4: Piezo Identification state machine.

The first stage of the algorithm is to start increasing the piezo actuator voltage by default or user-defined value till the upper limit is reached. Each voltage change is verified with the readout from piezo ADC (Analog To Digital Converter) and cavity detuning. It should also meet the time limit within the specified number of LLRF pulses. Whether the voltage readout differs from the fixed step, the voltage hasn't changed within the number of pulses it is not possible to read the cavity signal, the procedure goes to the timeout state. In that state, the procedure waits for the voltage and cavity signal to reach the correct value. If this does not happen within the defined deadline, the information about the timeout for a specific point is saved and used later, for gathered data evaluation. After that, the procedure comes back to the stage where the next step is applied. This approach prevents the algorithm from being aborted if one or two readings fail. Thanks to the final approximation methods, the parameters still can be calculated correctly.

A similar logic has been applied to the stage when the voltage is being decreased till the lower limit. When both limits are reached, the voltage returns to the initial value, and calculations are performed. Depending on the number of errors and timeouts encountered during the procedure, the user is informed if the results are valid or not. After that, the PV values acquired during the initialization phase are brought back.

Step Motor Identification

The spoke cavities are fitted with a cold tuning system, which has a stepper motor for slow control. Usually, step motors are used for initial tuning of the cavity to park the

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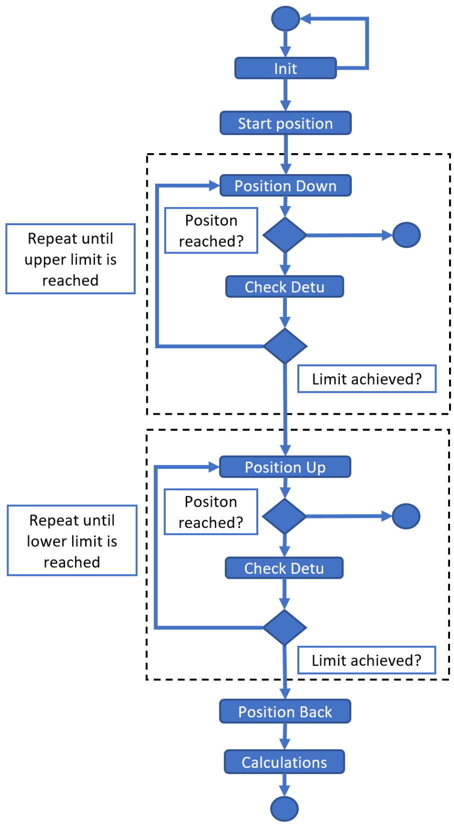

Figure 5: Step Motor Identification state machine.

cavity in a safe position for cooldown and heating [4]. Therefore, it is essential to verify step motor characteristics and find parameters such as:

- step motor sensitivity,
- step motor polarity,
- step motor backlash,
- step motor hysteresis.

Procedure's Logic The structure of the module is similar to Piezo Identification. The state machine is depicted in Fig. 5. It contains PVs that are responsible for the initial setup that stores values of the modified parameters to recover them after the procedure. There are also status and result PVs. The state machine has a form of Sequencer module.

To start the algorithm the prerequisites must be met (correct configuration of LLRF and step motor IOC) otherwise status PVs prevent from beginning the procedure. The first stage of the process is to move the step motor to the initial position. Each change of position must be carried out within the specified time. In this procedure timeout approach is different than in Piezo Identification. In case of timeout, the algorithm waits another period for the step motor to reach the set value. Whether the position is still not achieved the procedure fails. The encountered timeout cannot be ignored until the final parameters calculations since probably any subsequent position of the stepper motor would not be reached either and we would lose the correlation of detuning with the step motor position. If the procedure proceeds correctly, the stepper motor position is changed until the upper and the lower detuning limits are reached, after which the motor returns to its initial position. Finally, the wanted parameters are calculated and loaded to corresponding PVs.

CONCLUSION

The paper describes the structure and the components of the EPICS-based tool for LLRF operation support and testing. The overview of the IOCs architecture of the management IOCs and worker, single IOCs is given. The principle of the report generator is also presented. Eventually, the sample of single IOCs responsible for cavity, piezo, and step motor identification is depicted.

The tool is still under development to become fully functional and provide complex test and operation support procedures. The local tests of developed IOCs are being performed using the local test stand that includes an instance of the LLRF control system with the Cavity Simulator in the DMCS. Further tests are being carried out in the cryomodule test facility TS2 (Test Stand 2) in ESS.

It is worth mentioning that the tool is designed to be as much as possible universal. It means that the logic of the algorithms and procedures could be easily implemented in any LLRF control system.

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