ISBN: 978-3-95450-238-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2023-TUPDP085

EPICS AT FREIA LABORATORY

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Abstract

The FREIA laboratory is a **F**acility for **RE**search **I**nstrumentation and **A**ccelerator development at Uppsala University, Sweden. It was officially opened in 2013 to test and develop superconducting accelerating cavities and their high-power RF sources. The laboratory focuses on superconducting technology and accelerator development and conducts research on beam physics and light generation with charged particles, accelerator technology and instrumentation. From the very beginning EPICS has been chosen as a control system for all the infrastructure and equipment in the lab. Use of EPICS allowed us to build a robust, expandable and maintainable control system with a very limited man power. The paper will present the choices we made and the problems we've solved to achieve this goal. We will show the current status of the control system and the strategy for the future.

INTRODUCTION

FREIA laboratory was established as part of the Department of Physics and Astronomy at Uppsala University. A 1000 square meter experimental hall has been built at the Ångström Laboratory campus [1]. The construction started in May 2012 and was ready for installation of the equipment in June 2023. The laboratory was jointly funded by Uppsala University and a grant from the Swedish Government. The helium liquefaction plant was sponsored by the Kurt and Alice Wallenberg Foundation.

In the initial phase of operation FREIA was functioning as a cryogenic centre, delivering liquid helium and liquid nitrogen for the users at Uppsala University and other institutes in Uppsala and as a test facility for superconducting RF cavities followed by the testing of the cryomodules for the European Spallation Source (ESS) in Lund, Sweden. After installation and commissioning of a, so called, vertical cryostat, tests of bare superconducting cavities and superconducting magnets have been conducted for CERN and other European laboratories. Figure 1 shows an overview picture of the experimental hall. Behind the bunker there is a liquefier and the vertical cryostat (below the floor level) as shown in Fig. 2.

The decision to use EPICS [2] as a control system was made from the very beginning. The idea was to connect all the equipment and instrumentation to a common platform that would support a uniform access and services like alarms, archiving, save/restore etc. The choice of EPICS was highly influenced by the fact that ESS supported us with equipment running EPICS: LLRF controls, timing system as well as stepper and piezo motor controllers for the cavity tuning systems.

The specification for all ordered subsystems included the requirement for easy integration with EPICS.

Figure 1: FREIA hall.

Figure 2: FREIA hall – liquefier and vertical cryostat.

INFRASTRUCTURE AND EQUIPMENT

Helium Liquefaction Plant

The first equipment installed in FREIA laboratory was a helium liquefier system. It is a system delivered by Linde capable to produce up to 140 l/h of liquid helium at 4 K. It came with its local controller based on the Siemens S7-300 series PLC and an operator's interface built on WinCC. The PLC gives us read-only access in EPICS to almost all process variables and operator level write possibilities. The engineer level controls are possible only through WinCC.

Sub-Atmospheric Pump Station

The station, consisting of 7 pumps working together, is used for cooling the 4 K liquid helium down to 1.9 K. The total capacity of the pumps is 4.3 g/s at 15 mbar. The local controller delivered by the vendor is based on Siemens S7-

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300 series PLC. All essential process variables are R/W (Read/Write) accessible from EPICS.

RF Power Stations

The next two big pieces of equipment are the high-power RF amplifiers. They both use tetrode vacuum tubes in the final stage and can deliver 400 kW of 352 MHz rf pulses. The maximum pulse length is 3.5 ms and the repetition rate 14 Hz. These parameters are the same as the requirements for the power amplifiers of the ESS linac's spoke cavity acceleration section. The RF stations came with their own controllers – one based on Siemens S7-1200 series PLC, the other with the vendor's proprietary micro-controller. All process variables are R/W accessible from EPICS.

Horizontal Test Cryostat

The cryostat [3] (named Hnoss) is used for testing RF cavities or any other device in temperatures between 1.8 and 4.2 K. It's located in the bunker visible in fig. 1. Hnoss has a diameter of 1.2 m and a length of 3.3 m. Hnoss has been delivered by the vendor with its own control system built on Siemens S7-300 series PLC and WinCC as an operator's interface. All process variables are R/W accessible from EPICS.

Vertical Test Cryostat

The cryostat [4] (named Gersemi) is used for testing of bare RF cavities as well as the superconducting magnets at 4 and 2 K. Gersemi is placed in a 6 m deep hole in the FREIA floor. The size of the device under test (DUT) is limited to a diameter of 1.1 m and a length of 4.7. Additionally, due to the capacity of the crane the weight of the DUT is limited to 7.2 tons. Gersemi has been delivered by the vendor (the same as for Hnoss) with its own control system built on Siemens S7-300 series PLC and WinCC as an operator's interface. All process variables are R/W accessible from EPICS.

Superconducting Magnet Tests Related Equipment

Power Converters and Polarity Switch We have two unipolar power converters that can deliver up to 2000 A. They come with intelligent function generators for controlling the arbitrary current profiles in the magnet. In order to be able to drive the coils with currents of both polarities two motor-controlled polarity switches are placed between the outputs of the power converters and the coils. The Epics device support gives R/W access to the PVs needed to operate the magnet whereas the parameters describing the magnet's characteristic and interlock levels are only available through a dedicated program.

Energy Extraction System There are two energy extraction systems that protect the magnets in case of a quench. The PV for monitoring the system is available in EPICS.

Quench Detection and Fast Measurement System These are stand-alone systems that are connected to other subsystems by hardware interlocks signals. There is no direct connection to EPICS - the state of the interlock signals is accessible from EPICS via other systems.

Local Protection System A local protection system is built using a Siemens S7-1500 series PLC. The data from other subsystems (power converters, energy extraction, cryogenics, etc) read by the PLC is combined and the output interlock signals are produced to allow safe operation of the magnet and the related instrumentation. The system if fully controllable from EPICS**.**

Cavity Tests Related Equipment

All the equipment (with full EPICS support) listed below has been developed at ESS and its in-kind partners and is borrowed by FREIA for the testing of cavities and cryomodules.

LLRF Control The LLRF control is based on a µTCA system with an SIS8300-L digitizer module, a DWC8-VM1-LF vector modulator and the timing receiver mTCA-EVR-300U from Micro-Research Finland.

Timing System The timing system from Micro-Research Finland consists of PXI-EVG-220 event generator, VME-FOUT-12 fibre fan-out and mTCA-EVR-300U timing receivers.

Cavity Tuning System There are two tuning systems – a slow system operated by a stepper motor and a fast system using piezo motors. The controller for the stepper motor uses Beckhoff's EK1100 EtherCAT coupler connecting EtherCAT terminals to the CPU running Linux.

Radiation Protection and Monitoring

The radiation (X-rays) produced during the cavity tests is monitored for both the staff health protection as well as for diagnostic purpose. The system is based on a distributed set of radiation detectors connected to Data Processing Units (DPU) from Rotem Industries. The DPUs are read directly with EPICS, via an RS485-ethernet adapter, replacing the proprietary monitoring software.

Cooling Water

The deionized cooling water system consists of a couple of pumps and a number of sensors measuring temperature, flow, pressure and water conductivity. The pumps and sensors are connected to Siemens S7-300 PLC.

Other

There are a number of diagnostic devices like ambient temperature sensors, atmospheric pressure sensors, oxygen level meters that are all connected to EPICS either through the PLC I/O modules or directly via different field-buses (RS-232, RD485, Ethernet). Laboratory instruments like oscilloscopes, spectrum and network analysers, signal generators and others are all connected to EPICS via Ethernet.

CONTROL SYSTEM

Most of the sub-systems that were delivered from industry came with their local control systems. They have been

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integrated in the FREIA control system with the help of dedicated EPICS Input/Output Controllers (IOCs) using support modules developed by the community. Other devices and instrumentation have been connected using standard interfaces like ModBus, SCPI commands over Ethernet and proprietary communication protocols over serial busses. We practically had no need to develop our own device support modules. Our main tasks in building the control system for FREIA were the following:

- Creating the EPICS databases.
- Creating the protocol files for the devices connected via streamDevice.
- Building operator's screens in Control System Studio/Phoebus.
- Writing programs for the sequencer
- Deployment of the IOCs
- Running and configuring the Archiver Appliance.
- Running and configuring the Alarm Server.

Hardware

Ethernet Our control system is running on two private subnets, one for the communication between IOCs and PLCs, the other for everything else. The connection between the university network and control system network is done via D-Link DSR-1000AC router. All network equipment and the cabling support Gigabit Ethernet. There are about 50 active nodes on the PLC network and about 100 nodes on the other network.

We can have up to 35 VPN channels active simultaneously between the Internet and our control network.

Our router has also a wireless access point to the control network.

The servers We have two server computers running in the control system. Their main parameters are shown in Table 1.

Both servers have redundant power supplies and are connected to a UPS that supports more than 30 minutes operation on battery. We run a number of virtual servers on each server dedicated to various services in the control system, like archiver, alarm server, file server, etc.

Table 1: Server Computers

	Server 1	**Server 2**
Product name	HP ProLiant DL380p Gen8	HP ProLiant DL360 Gen10
CPU	2 x Xeon E5-2690v2 / 3 GHz	Xeon Silver 4214 / 2.2 GHz
Cores/CPU	20	24
RAM	128	64
Hard Disks	1500 GB	2240 GB
network	2 x10 Gb/s	4 x 10 Gb/s

IOCs Most of our IOCs run on Intel NUC computers with Intel i3 or i5 CPUs. They are diskless machines with 4 to 8 GB RAM, booting Linux Centos 7 operating system from the file server. Currently we have 4 NUCs hosting about 30 IOC programs.

We have two IOCs running on Intel CPUs in the µTCA crates containing the LLRF hardware.

Another CPU in a compact PCI crate runs the IOC for the timing system generator and another IOC, the EtherCAT stepper motor controllers.

Operator Consoles We have a number of personal computers (PCs) running MS Windows or Linux operating systems that act as operator consoles. Most of them are equipped with multiple screens. Control System Studio/Phoebus (CSS/Phoebus) is used as the main interface.

PLCs Besides the PLCs that came with the vendor supplied subsystems we have a couple of Siemens S7 PLCs that we use to connect various front-end devices like water and vacuum pumps, valves, flowmeters, etc. We have also built a general-purpose slow interlock system on one of the PLCs.

CompactRIO We have a system consisting of a cRIO-9024 Real-Time Controller, High Speed digital input and output modules and an ADC module. The general-purpose interlock logic is executed in the FPGA. The FPGA and the controller are programmed in LabVIEW to implement the interlock logic and all the functionality required by the fast interlock system. LabVIEW EPICS Client I/O Server is used to connect the compactRIO to the FREIA control system.

Terminal Servers We use Moxa NPort 5610-16 terminal servers for controlling through the Ethernet the devices having only old-fashioned RS-232 interfaces, for example vacuum gauges and a leak detector. We use it also for remote connections to the compactRIO and µTCA Carrier Hub (MCH) console ports.

Software

A lot of choices that we have made were influenced by the limited work force in the control group. We have tried to keep things as simple and easy to maintain as possible. Therefore, we decided to run all our EPICS software only on one architecture, namely linux-x86_64. The exception are few operator's consoles running MS Windows. We have tried to limit the number of different interfaces to the subsystems delivered from industry. This was possible due to the fact that we had decided to use EPICS before writing specifications for the equipment we ordered.

For the EPICS build system we use the so called E3 environment developed at ESS [5]. Due to tight connections between FREIA and ESS it was natural to take advantage of their work. For deployment of the IOCs we use an earlier version of E3 adapted to FREIA needs. Based on the configuration files on the file server the diskless computers are loading the operating system, execute necessary configuration scripts and start the IOCs. In a relatively small system like ours this scheme works very well and is easy to configure and maintain.

Most of our IOC's run EPICS base v7.0.6.1. For the new developments we use v7.0.7. Although possible, we have not yet started to use PV Access.

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IOCs We have about 35 IOCs running on 8 computers hosting over 40000 EPICS records.

We run recsync and iocstats modules on every IOC. Almost all IOCs' work as interfaces to front-end hardware but we have a couple of them that use only "Soft Channel" records. One such example is an IOC for keeping track of the helium balance in FREIA, the other is for hosting the PVs controlling the status displays shown on TV screens in FREIA using Display Builder Web Runtime [6]

Sequencer programs are used for several purposes, for example controlling the start-up of the sub-atmospheric pumps during the superconducting magnet cooling from 4 to 1.8 K.

Services We run a number of services in the FREIA control system. The most important and heavily used is the archiving. We use Archiver Appliance for this purpose which is running on one of the virtual machines on our main server. We run also a backup Archiver Appliance with the same set of PVs on our second server. We archive above 7000 process variables, the majority of them every 10 seconds.

We also run an Archive Appliance for short-term archiving, about 3 days. It stores more than 5000 PVs every second.

Alarm Server is another program that is used a lot. We have defined nine areas covering all systems in FREIA. We have configured alarms from over 300 PVs, most of them ordinary analog and binary records but some of the PVs are created in the IOC and programmed to give alarms for a special condition. For many alarm nodes we have defined automatic actions that send email or SMS notifications to the relevant experts.

ChannelFinder together with RecSync gives us a good overview of the PVs in the FREIA control system but is so far used only for the control system maintenance.

Phoebus Scan Server, although installed has been used only few times for long term tests of the RF cavity tuning motors.

Data Builder Web Runtime is used for displaying information showing the status of different FREIA systems on the screens placed at several locations in the laboratory. It is also used for remote read only access to some synoptic screens.

Save and Restore service has been installed recently and it's not yet used in daily work. Until now we have been using PV Table instead.

LabVIEW programs We use a number of LabVIEW programs to perform tests of the superconducting RF cavities or magnets. From EPICS point of view, we can divide them in three categories. The first one is completely integrated with EPICS where all interactions are done via Channel Access. An example of such system is the fast interlock system based on CompactRIO.

The second category are the programs that use LabVIEW GUI but exchange some information with the control system by a set of PVs. The program for conditioning of the RF cavities fundamental power couplers can be an example. In both cases we use the LabVIEW EPICS Client I/O Server for communication between LabVIEW programs and EPICS.

And finally, we have a completely stand-alone LLRF control and fast data acquisition program running on a PXI platform that has no connection to EPICS.

EXPERIENCE

We have started to learn EPICS in 2013. Before that we had a long experience with writing accelerator control system software at The Svedberg Laboratory [7]. The staff working with the control system at FREIA is limited to two persons getting some help from experimental physicists, students working on their projects and occasionally external consultants.

Our EPICS learning curve was quite steep but with the help of documentation and presentations found on the web, as well as the EPICS course organized at ESS we managed to start setting up the base for our control system within half a year. During the time we've been working with EPICS we've got a lot of help from the EPICS community. The tech-talk mailing list and the answers received on it helped us to solve problems when studying the documentation was not enough. The issues filed in the software repositories where usually answered immediately and resolved quickly.

In order to develop and maintain the control system with such limited resource we tried to limit the number of different interfaces, operating systems and hardware platforms. Because of the tight collaboration with ESS we have adopted their EPICS environment. During the last ten years it has evolved from ITER based Codac [8] through various versions of ESS developed environments. Eventually we are using the latest version of ESS's so called E3 environment with some modifications, mainly due to the much smaller scale of our laboratory and limited staff. We are keeping the NFS file-server based distribution of the software, both operating system for the diskless clients running the IOCs as well as IOC binaries, EPICS databases, configuration files and the start-up scripts. Keeping all the software and configuration files in one place made it quite easy to deploy and maintain the system consisting of about 35 IOCs running on less than 10 computers.

We have chosen Siemens S7 series PLCs whenever it was possible. We were in contact with our vendors during the development phase of the PLC software and made sure that it's well prepared to work with s7plc EPICS support module. This approach turned out to be very beneficial when new features needed to be implemented and old bugs fixed which was the case for our cryostats.

The sequencer program running on the IOC turned out to be very convenient when we needed to add some process automatization, especially when it involved the PVs from different systems. In other cases this was done in the PLC.

EPICS software running on the IOCs turned out to be extremely reliable. We have never experienced any crash related to software problems and the IOCs are rebooted only in case of upgrades or installation of new code.

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CONCLUSIONS

The choice of EPICS for the FREIA control system has proved to be a very sound decision. During the ten years of FREIA Laboratory existence we have managed to build and maintain a control system covering all the infrastructure and instrumentation. This was made possible by cooperation with other laboratories (mainly ESS and CERN) and a lot of help from the EPICS community.

In the future we will continue to keep the system as uniform as possible. Our ambition is to keep-up with the recent EPICS developments and start to use PV Access where it's beneficial.

Limited resources literally force us to use an EPICS environment that is publicly available, developed and maintained by the institution that will continue to use it for a long time, that takes care of all module dependencies and is easy to use. So far the ESS' E3 environment works fine for us.

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