IFMIF EVEDA RFQ Local Control System

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***Abstract*–In the IFMIF EVEDA project, normal conducting Radio Frequency Quadrupole (RFQ) is used to bunch and accelerate a 130 mA steady beam to 5 MeV. RFQ cavity is divided into three structures, named super-modules. Each super-module is divided into 6 modules for a total of 18 modules for the overall structure. The final three modules have to be tested at high power to test and validate the most critical RF components of RFQ cavity and, on the other hand, to test performances of the main ancillaries that will be used for IFMIF EVEDA project (vacuum manifold system, tuning system and control system). The choice of the last three modules is due to the fact that they will operate in the most demanding conditions in terms of power density (100 kW/m) and surface electric field (1.8*Ekp). The Experimental Physics and Industrial Control System (EPICS) environment provides the framework for monitoring any equipment connected to it. This paper reports the usage of EPICS and industrial controls to the RFQ power tests at Legnaro National Laboratories.**

I. Introduction

THE main objective for IFMIF (*International Fusion Materials Irradiation Facility*) [1] is the construction of a linear accelerator for neutron irradiation effects on materials that will be used to realize future fusion reactors**.**

Current knowledge on the behavior of materials in harsh environments such as those found in a similar plant (eg. radiation emitted from the plasma) does not allow to predict the changes in terms of mechanical, thermal and electrical behavior. It is therefore fundamental fill this gap of knowledge in order to ensure the security and integrity of a facility of this kind.

The IFMIF facility will provide an accelerator-based neutron source that produces, using deuterium-lithium nuclear reactions, a large neutron flux with a spectrum similar to that expected at the first wall of a fusion reactor (Fig.1). The main components of the apparatus for the neutron beam production are therefore the following:

- the generation system of deuterons, consisting of two linear accelerators in parallel each producing a current of 125mA beam and made up of an ion source, a low energy beam transport system (LEBT) which guide the beam from the accelerator source to the radio frequency quadrupole (RFQ), a medium energy beam transport (MEBT), superconducting cavities and an high energy beam transport (HEBT);
- the system constituted by the target in the lithium and the associated circuit for the evacuation of the produced power;
- test cell inside which are arranged the samples of the materials to be tested.

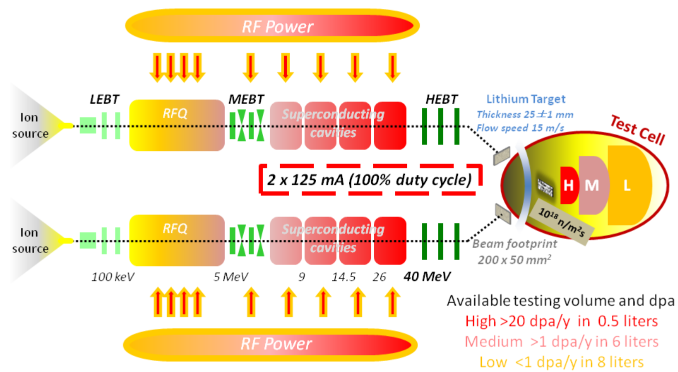

Fig. 1. Schematics of IFMIF facility: two parallel accelerator lines provide the final beam required for the production of deuterium-lithium nuclear reactions.

Because of the complexity of the project, its implementation requires a preliminary step related to the validation of the prototype. For this reason, IFMIF-EVEDA (*Engineering Validation Engineering Design Activities*) involves the construction of prototypes of three different components mentioned above.

In this scenario the Italian contribution to the IFMIF-EVEDA project is comprised of two main aspects:

- the construction of the RFQ system, in charge of INFN-LNL;
- the construction of the neutron target, in charge of ENEA.

In according to the specifics required by the project, the RFQ apparatus results to be one of the most powerful machines in the world, due to manage deuteron beams at high energies (125mA deuteron beam in continuous wave (*CW*) up to 5MeV).

As consequence, the RFQ Local Control System (*LCS*) has to implement all the services and features required in a control system and, at the same time, following the project requirements in order to optimize the integration in the final main control system during the commissioning phase.

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II. THE RFQ LCS ARCHITECTURE

According to the standards adopted by the project, the entire control system has been based on EPICS [2]-[3], a control system framework composed by a set of tool and applications which let developers define a distributed control environment.

The RFQ Control System Architecture approved is designed to optimize the reliability, robustness, availability, safety and performance minimizing all the costs related to it (purchase and maintenance). Following this philosophy and the IFMIF-EVEDA Guidelines, we proposed to realize a control system network composed by two different kind of hosts:

- physical hosts for critical control system tasks;
- virtual hosts in machines where no particular functional tasks or hardware is required.

The architecture (Fig 2) realizes the 3-layer structure described in the Guidelines: every layer defines a proper hosts group (equipment directly connected to the apparatus, control devices, human-machine interface) while the EPICS framework provides the interface between them.

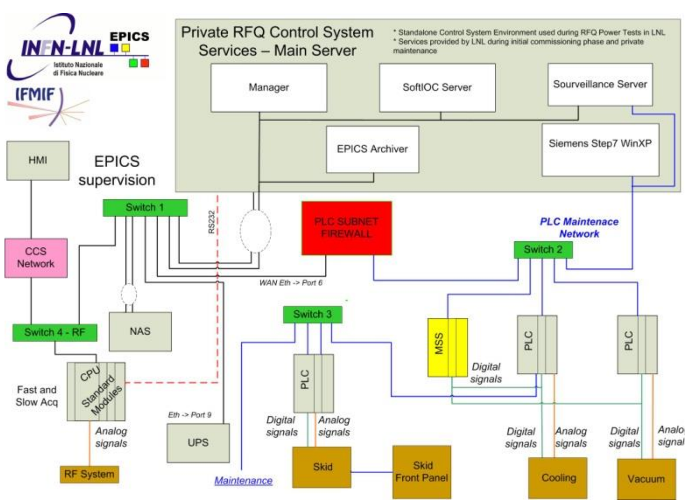

Fig. 2. RFQ local Control System Architecture.

The main server provides capabilities that enable controls engineers to deploy customized environments for their application perfectly aligned with the Common Software Guidelines provided by the project's core team developers. More that this regular EPICS services, like the archiving, are backup-ed regularly and can be moved and cloned easily.

A key enabling technology for this is virtualization and the provisioning through KVM [4] and Cobbler [5]. These software are completely supported under the RedHat Enterprise Linux (*RHEL*) Operative System and used in a wide range of network system solutions. This approach saves Rokkasho floor space, power, and cooling per unit of processing capacity. In addition, operations, administration, and maintenances can be addressed more efficiently and less expensively.

The server disk is setup with hardware RAID and use the Logical Volume to partitioning it. Today's Linux servers have reached a level of maturity in the enterprise that calls for more file systems that are more versatile, configurable and manageable. Linux Logical Volume Management (*LVM*) [6], using Physical Volumes and Volume Groups, provides a great degree of freedom and flexibility in develop and maintenance phases and let users to optimize resources in every.

For our application, logical volumes have been implemented for every strategic system: we use this solution to define machines (physical and virtual) partition table with proper mount points. In this way, using LVM capabilities, we can manage any resourceful saturations in according to the free resources provided by the main server, giving us the possibility to extend, clone and manage comfortably all the hosts.

On this architecture, the control part has been developed in order to guarantee the project's requirements.

Analyzing the RFQ apparatus, it is a complex machine composed by many kinds of subsystems (radio frequency, vacuum, water cooling, etc.) developed using different hardware solutions. The system has been designed and realized using these assumptions:

• PLC hardware has been chosen in tasks where security is the most critical feature;

• VME system is used where the acquisition speed rate is crucial

As a consequence, a key point in the implementation is the integration between these two different hardware and software solutions and, in the final stage, the integration of this LCS in the main Central Control System (CCS).

The upper software layer of the CCS, realizes the common layer where all the different LCS will communicate and share information without any additional effort. The RFQ LCS architecture reproduces a complete control system, not only the minimum services required to control the RFQ apparatus. This approach let the developers free to execute first integration steps and operations in an independent environment, without CCS. In particular the following services have been implemented:

- Manager and Backup service in order to provide the automatic provisioning system in case of host fault (for both physical and virtual machines);
- Project management documentation server, made up of mediawiki, bugzilla and sub versioning services
- A monitor surveillance service based on OpenMonitor Distro (OMD) and Check-Mk applications [7]
- An EPICS Archiver system with PostegreSQL Relational Database backend.

This entire infrastructure has been used and tested during the Power Test done in LNL, in the middle of 2015.

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A. *EPICS Software Development*

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Different EPICS Input Output Controllers (IOC) based on virtual and physical hosts manage the different sub-systems, using the technologies based on the assumption mentioned before: for RF system, VME based technology has been used to guarantee the maximum acquisition rate and reuse data in high level control system algorithms. For vacuum and cooling systems, EPICS IOCs provide the middle communication layer between the PLC environment and the CCS.

In this final stage, the entire EPICS control system is composed by about 8000 PVs in 4 IOCs. Part of these variables must be archived and monitored by the archive and alarm systems. In our LCS, the archive service has been implemented and used during the RFQ Power Test with good results; for the final stage the total PVs involved will be about 1600. For the alarm system, the total number of PVs monitored is under study, but a preliminary estimation suggests about 600 PVs involved. In Table 1 it is possible to observe the main information related to the LCS in both Power Test and Final Stage phases.

Number of	**Power Test**	**Final Stage**
IOCs	6	4
DBs	17	37
PVs	1153	~ 8000
Channel Archived	970	~ 1600
GUIs	15	14

TABLE I. MAIN INFORMATION RELATED TO THE EPICS PART OF THE RFQ LCS

The Graphical User Interface (GUI), developed in Control System Studio (CSS) [8], is composed by a set of panels which let scientists remote control the apparatus (Fig 3): Main panel gives the global view of the experiment, while specific panels and pop-up windows, divided according the subsystems, give detailed information.

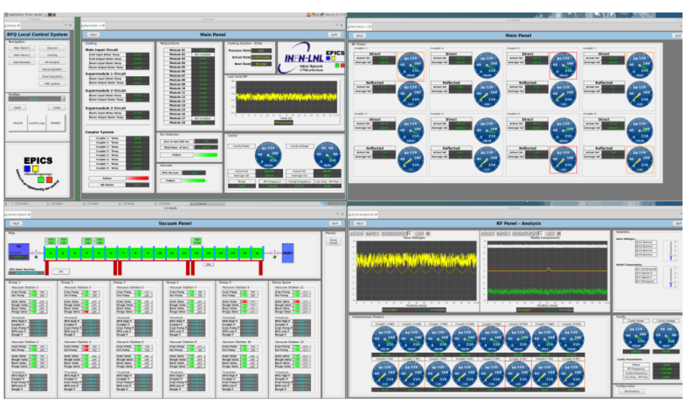

Fig. 3. GUI developed for the RFQ local control system.

B. *PLC Software Development and Hardware Implementation*

Final design of LCS cubicles consist of 5 cubicles: the first one is devoted to electrical connection, the second hosts the vacuum controllers, the third for PLCs, fourth dedicated to RF signals acquisition and the fifth which contains the main server of LCS. The Hardware upgrade includes the installation of specific electronic cards developed and produced in house, to interface the RFQ LCS with the CCS (in particular with the timing system and the Machine Protection System).

The RFQ LCS I/O interface is strongly based on wired connections to maximize the reliability; it counts almost 285 components and more than 400 cables/connections. Identification of each component and its connections require a big effort and a systematic approach.

Vacuum and Cooling sub-systems have been developed with PLC technology. In both sub-systems control system is based on SIEMES S7-300 PLC: it is in charge of low level control logic while EPICS permits the integration through dedicated driver that provides a direct communication to the PLC itself.

III. THE RFQ POWER TEST

A partial test at full power and CW duty cycle has been performed at INFN-LNL on the last elements of the RFQ, approximately two meters of structure, using a specific electromagnetic boundary element on the low energy end. The aim is to reach, in the RFQ coupled with its power coupler system, after an adequate period of conditioning, CW operation at nominal field level (132 kV between electrodes) for at least two hours without breakdown.

The high power test gave us the opportunity to validate all the LCS parts in conditions similar to the operative ones, fixing bugs and making modifications when it was necessary. Closed loop controls are crucial parts in accelerator operation. For the power test we set-up several close loop controls

- Frequency Follower Control (FFC), to set the output frequency of the RF amplifier at the natural frequency of the RFQ.
- RF power level Control (RLC), to maintain constant the power inside the cavity.
- Temperature control of cooling water circuits.
- Resonant Frequency Control (RFC) to control the cavity natural frequency by means of the cooling water temperature

In the final installation FFC and RLC will be provided by the Low Level RF (*LLRF*) system developed by CIEMAT. Nevertheless power test gave us a deeper knowledge of the functions and performances required for the LLRF system.

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Controller set-up and tuning was one of the mostly time consuming activity. The set-up and tuning of cooling and frequency controls required several step:

- Fine calibration of temperature and RF frequency measures.
- Characterization of the system, in particular to understand the response times related to valves movements or power changes.
- Tuning of the close loop controllers (PID), performed online at well-conditioned power level.

Thanks to the power test, we have now a valid procedure to operate the tuning of the cavity frequency controller, which will be manually carried out also at Rokkasho. As learned during the power test, the good working of RLC and the integration with the LLRF is a condition necessary to provide the correct operation for the RFC system.

RF signals acquisition, elaboration and visualization are other fundamental parts of the LCS. The most important signals about RF power are sampled with a maximum rate of 1MEvents/s. During the test we successfully used these features including the tool which allows the automatic calibration of the characteristic curve of the acquisition channels. Moreover we collected, by the LCS users, significant feedbacks about the use of the CSS GUI (Graphical User Interface) and the data archive (Fig. 4).

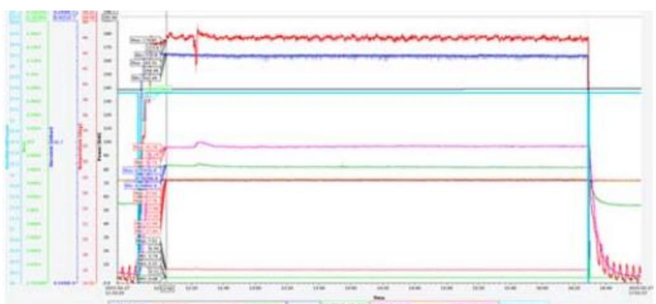

Fig. 4. Data archiver through EPICS RDB Archiver. In this particular picture it is possible to observe the successful of the power test made at LNL: the RFQ remained 4 hours at nominal field level (minimum 2 hours required).

IV. Conclusion

Preliminary tests on the singular control system tasks are done with positive results and every subsystem reaches the expected objectives. Because of the importance of the power tests for the RFQ apparatus, this is a great test bench for the entire control system architecture in order to debug the core system and a good feedback for the work realized by the team. An exhaustive test with the entire apparatus has not been executed but it will be performed when the RFQ will be totally available before the shipment: in this situation we will be able to check if the system modularity will cover all the specifications required by the acceptance tests provided by the agreements with Fusion for Energy (F4E).

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Acknowledgment

This works leveraged of years of experience on EPICS use from good engineers of other laboratories around the world: great acknowledgments to them.

References

[1] IFMIF Project: www.ifmif.org.
[2] EPICS main page: http://www.aps.anl.gov/epics/.
[3] EPICS LNL main page: https://web2.infn.it/epics/.
[4] KVM – Kernel-based Virtual Machine: http://www.linux-kvm.org/page/Main_Page
[5] Cobbler tool for provisioning service: http://cobbler.github.io/.
[6] LVM – Logical Volume Manager: http://www.tldp.org/HOWTO/LVM-HOWTO/
[7] Check-mk: https://mathias-kettner.de/check_mk.html
[8] Control System Studio: http://controlsystemstudio.org/