ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA008

LIPAc RFQ CONTROL SYSTEM LESSONS LEARNED

L. Antoniazzi, A. Baldo, M. Giacchini, M. Montis, INFN-LNL, Legnaro, Italy
A. Jokinen, A. Marqueta[1], F4E, Garching, Germany

Abstract

The Linear IFMIF Prototype Accelerator (LIPAc) [1] Radio Frequency Quadrupole (RFQ) will accelerate a 130 mA deuteron beam up to 5 MeV in continuous wave. Proton beam commissioning of RFQ cavity, together with Medium Energy Beam Transport Line (MEBT) and Diagnostics Plate, is now ongoing to characterize the accelerator behavior [2]. The RFQ Local Control System (LCS) was designed following the project guideline. It was partially assembled and verified during the RFQ power test in Italy [3]. The final system configuration was pre-assembled and tested in Europe, after that it was transferred to Japan, where it was installed, commissioned and integrated into LIPAc Central Control System (CCS) between November 2016 and July 2017, when the RFQ Radio Frequency (RF) conditioning started [4]. Now the RFQ LCS has been running for 2 years. During this time, especially in the initial period, the system required several adjustments and modifications to its functionality and interface, together with assistance and instructions to the operation team. This paper will try to collects useful lessons learned coming from this experience.

THE LIPAC RFQ LCS

The RFQ Local Control System (LCS) architecture is designed to optimize the reliability, robustness, availability, safety and performance, minimizing the costs related to its purchase and maintenance. Following this philosophy and the IFMIF EVEDA guidelines, the control sys-tem network is composed by two different kinds of hosts:

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

The architecture realizes the 3 layer structure described by the IFMIF-EVEDA guidelines, each layer defines a proper hosts group (equipment directly connected to the apparatus, control devices and Human Machine Interface), while the EPICS framework provides the interface between them (Figure 1). In the final stage LCS is integrated in the LIPAc Central Control System (CCS). The upper layer of the CCS implements all the general services required by a control system architecture and provides them to all the LCSs; EPICS Channel Access protocol is the bridge between the CSS and LCSs for control parameter exchange [4]. The architecture is designed to work either as a standalone environment, as used during the RFQ power test in Legnaro National Laboratories [3,5,6] and as part of the LIPAc control system environment.

The RFQ system is a complex apparatus composed by many kinds of subsystems (radio frequency, vacuum, water cooling, etc.) developed using different hardware solutions. As a consequence every part of this structure must be properly integrated to obtain the desired degree of control.

Following these criteria, the system is de-signed and realized using these assumptions:

- PLC hardware is chosen in tasks where security is the most critical feature;
- VME system is used where the acquisition speed rate is crucial.

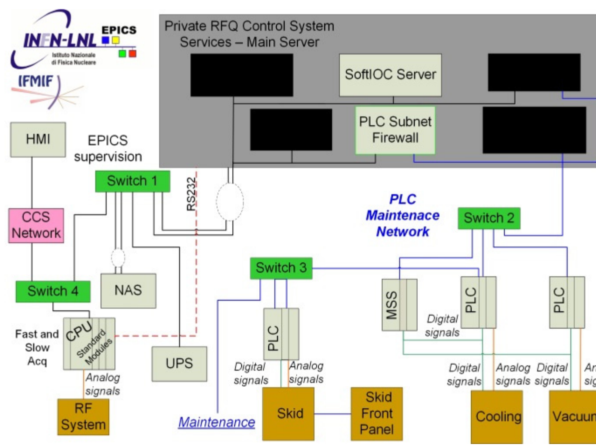

Figure 1: LIPAc RFQ LCS architecture.

The main functionalities of LCS are:

- Fast acquisition system for the RFQ cavity power;
- Vacuum system;
- Cooling system;
- Machine Protection System (MPS).

The fast acquisition is based on VxWorks real time OS which run over a VME architecture. The most important signals about RF power are sampled with a maximum rate of 1MEvents/s (250kEvents/s on 8 channels).

Vacuum, Cooling and MPS functionalities are entirely realized by SIEMENS® S7-300 PLCs and modular safety system (MSS). The integration of these PLCs into the EPICS control network is accomplished by S7plc EPICS driver, developed by SLS (Swiss Light Source) [7].

THE LCS DEVELOPMENT

Power Test

As anticipated, the first version of the RFQ LCS was assembled in 2014 to perform the power test of the RFQ power couplers and cavity [3, 5, 6].

The RFQ power test was executed to validate the most critical RF components of the cavity and, on the other hand, it allowed to test the performances of the main ancillaries as vacuum, cooling/tuning and control system.

[1] now at ITER Organization, St.Paul lez Durance, France

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA008

In that case, the standalone configuration of the LCS included additional network service (such as archiving, alarm, etc., as in Fig. 2) and functionality (as the RF control and PPS), as well as different configurations of the controlled systems (vacuum, cooling, MPS, RF signal acquisition, 1-wire system and RF signal generator).

In this configuration PLC/EPICS interface was implemented by an OPC (OLE [Object Linking and Embedding] for Process Control [8]) DA (Data Access) server hosted by a dedicated Windows embedded industrial PC which hosted the Simatic Net OPC server, the IOC application and device support. In a next stage, due to reliability and maintainability issues detected both in the injector and RFQ LCS (during the power test), LNL and project coordination agreed to adopt the S7plc EPICS driver, originally developed by SLS (Swiss Light Source) [7] as standard interface for EPICS/PLC communication.

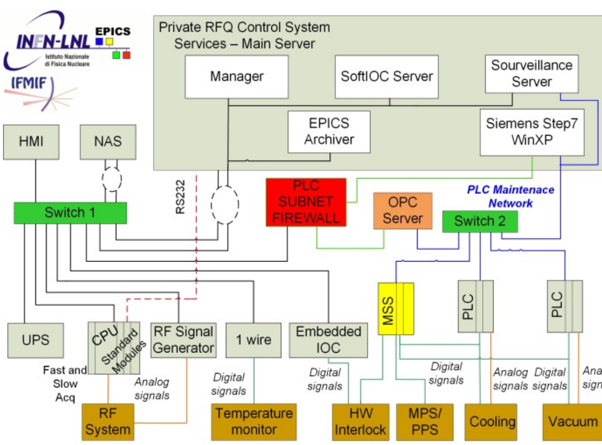

Figure 2: LIPAc RFQ LCS architecture for high power test at INFN-LNL.

The RFQ high power test, executed at LNL in 2015, was a great test bench to debug and improve the control routines. It also provided to the control team a better understanding of the controlled system and a clearer view of the activities for the final installation such as for example the calibration of the RF acquisition system. During this time, vacuum routines were validated, while the cooling and frequency tuning procedures and control loops were defined and tested. Implementation of the cavity frequency close loop control together with the internally developed RF system control allowed to understand the interaction between these systems, defining the exchange variables for the integration with the LIPAc RF system provided by the CIEMAT.

Verification and Factory Acceptance Test

After the high power test, the RFQ control system hardware was dismounted to be reassembled in its final configuration: 5 racks instead of the 3 used for the power test. The final hardware assembly was internally designed and realized in order to minimize the installation time in Japan; for this reason all the connection were connectorized and aggregated wherever it was possible.

The EPICS part was extended to cover the final size of the RFQ LCS, as visible in Table 1: while the number of PVs exploded, the number of IOCs decreased due to the fact that some of the functional sub-systems were required only for the test stage. For the Graphical User Interface (GUI), a renewal was required in order to complete monitor and control the full RFQ apparatus.

Table 1: LCS Comparison Between the Power Test and the Final Stage

Object	Power Test	Final Stage
IOCs	6	4
Databases	17	25
PVs	1153	8852
Archived PVs	970	450
Control Panels	17	21

In the first half of 2016 all the 5 cubicles and the 3 junction boxes were temporarily assembled and connected together at INFN-LNL for the last checks before the shipment (Fig. 3). A meticulous checkout was executed by an external contractor entrusted to verify the congruency between the diagrams and the installed hardware, the correct design and execution in relation to the electrical standards and regulations. At final stage all the LCS apparatus were power supplied to verify the correspondence between the physical I/O and the software channels. At the end of the test a certificate of compliance was released.

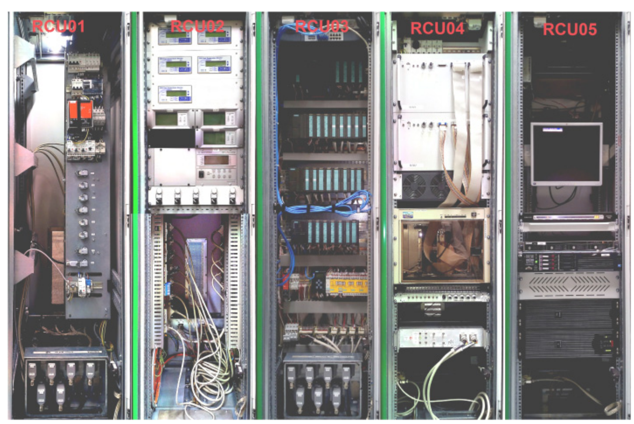

Figure 3: LIPAc RFQ LCS installed at LNL.

INSTALLATION AND COMMISSIONING

Installation and commissioning of RFQ LCS was executed in several phases in accordance with project schedule for the RFQ accelerator and ancillaries systems [4]. The system was first partially installed and used in standalone configuration during the RFQ baking. After that, installation and final integration into CCS were performed: in this stage the functional checkout of the control system, the commissioning of the controlled systems (vacuum, cooling, etc.) and integration with other LIPAc sub-systems were executed.

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA008

Installation and Integration for the RFQ Baking

During the second half of 2016 all the parts of the LCS were installed in Rokkasho, with exclusion of the final connection to the devices on the RFQ, to allow the execution of the baking procedure, which required the installation of only part of the vacuum system to be executed. The whole installation process including:

- connections between the cubicles, junction boxes and power supply secondary board;
- installation of cable tray along the RFQ;
- installation of HMI console (Fig. 4);
- first stage of LCS integration into CCS;
- preliminary check-up of the system;
- predisposal of the LCS to perform the RFQ baking;

took only 3 people for 12 working days, thanks to the design choices, planning and verification done at LNL.

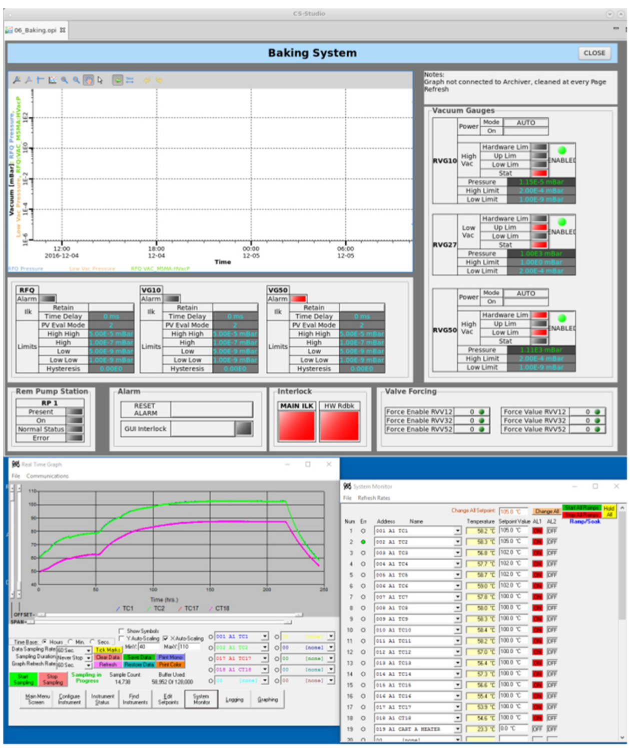

Figure 4: View of vacuum system and heater HMIs for the RFQ baking procedure.

The high-level control part was partially integrated in order to allow a minimum operation of the vacuum system via the Human Machine Interface (HMI) and to store the data in the RFQ archiver service. In this hybrid solution, the entire RFQ LCS was used as standalone control system; under network aspect, all the hosts were already integrated into the main CCS network.

During the baking procedure, the RFQ was keep in vacuum, warmed up and maintained at 100°C for about 10days, to degas the surface and improve the vacuum level. The two heaters together with the relative temperature monitor and control systems were integrated in two standalone systems provided by a contractor. The interface provided by the proprietary software was constituted by a configurable log text files containing the values of the monitored temperatures. Due to a shipment delay, the baking system arrived in Rokkasho after the RFQ control team departure, but thanks to the precious collaboration of the QST and F4E colleagues, the system was properly installed and integrated with the control system. The baking was started regularly, and the temperature log, together with vacuum level data were periodically uploaded to the LIPAc SVN service to be available by remote.

Completion of the Installation, Integration and Commissioning

The second stage of RFQ LCS installation, integration and commissioning take place between February and July 2017. This phase included:

- Installation of the connections to the RFQ cavity (RF, arc detector, vacuum, temperatures, etc.)
- Installation of the connection between the RFQ LCS and the other subsystem (MPS, TS and RF system)
- Conclusion of the LCS integration into CCS;
- Calibration of RF signal acquisition
- Commissioning of the controlled system
- Acceptance Test

Once completed the cabling installation, all the I/O signals were tested from field up to the EPICS control environment, through the HMI machine, to verify transmission along the entire signal path. During these tests some wiring issues were detected on the components excluded by the checkout at LNL: cryogenic pumps and compressors, which were already shipped to Japan at that time.

Another HW issue faced out during the test of the interface with the RF system, where the ground connection of signals which were supposed to be opto-coupled required the modification of an interface electronic board.

The HW interface between RFQ LCS and MPS was carefully checked and tested under every aspect (electrical, logic, response time, etc.) detecting a special error case in correspondence to the rearming of a status signal from RFQ LCS to MPS. The signal was a dry contact and the high performance of the MPS interface detected the contact closing rebounds as a not ok status. In that case, the cause was identified in a defect of the RFQ Modular Safety System (MSS) output module, which was substituted; but it was an example of how the connection of systems with different pass bands can generate an issue.

At this stage, the RFQ LCS was already properly configured and integrated at network layer, but not under services aspect. As consequence, all the local services were shut off and replaced by the ones provided by the CCS infrastructure, with the only exception of the archiver system which was temporary left available in parallel.

All the EPICS applications and software were completely integrated in the LIPAc control system and finalized following the standards required. Executing these operations, all the LCS were completely re-checked in order to avoid the introduction of bugs at any layer (network, services configuration, control application, etc.).

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA008

RF power level acquisition at the 8 couplers and at the 44 cavity pick-ups is crucial point to monitor the RFQ status and in particular the electric field flatness and modal components. Due to the precision required RF line calibration is a critical task for the system, and the number of lines involved (60) requires time. For this reason, an automatic procedure was developed directly in EPICS to minimize operation time: the system was able to acquire measurements, calculate the linearization parameters and save them into the EPICS applications.

The LCS acceptance test was performed in order to verify the complete integration process under different aspects: hardware integration, network integration, EPICS software integration, services integration, respect of IFMIF LIPAc standards and LCS functionalities. Thanks to the strict respect of the guidelines the RFQ LCS officially passed the acceptance test in December 2017.

COMMISSIONING OF THE CONTROLLED SYSTEM

The first subsystem to be commissioned was the vacuum system, followed by the Cooling system, RF acquisition and MPS. In the meantime and in the following period the HMI panels and system services were improved and configured.

Vacuum System

Vacuum system logic was the same verified during the power test in Legnaro, while the number of devices to control increased according to the final RFQ system. The system includes several enables signal as well automatic actions which give permission or deny to operate a component such as a valve or a pump, in order to preserve the integrity of the system itself. HMI panels do not contain detailed diagnostic information about the set of conditions enabling or denying the operation. Due to that, the user needed to consult the operation manual often. This was something tedious for the user, but it established a collaboration which allowed to tune the procedures and to improve the control logic, in order to match the using case, to fix singular error as the evaluation of the RFQ vacuum level when one gauges goes out of service.

Cooling System

The cooling skid of LIPAc RFQ, included the local control system, was provided by a contractor. The RFQ cooling system integrates the skid's PLC with a second PLC, responsible of the cooling/tuning system logic, and through that up to EPICS level. The system integration was checked at LNL, where it was not possible to perform functional test on the skid due to unavailability of the needed infrastructure. Once installed in Rokkasho the cooling system commissioning suffered a stop due to the inconsistency between the starting current of one of the pumps and the relative protection. The same starting current (2 times larger respect the value in the datasheet) was measured also on a new and equal motor; at that point the issue was solved substituting the protection.

The cooling skid experienced also the premature brake of some temperature, pressure and flow sensors which required the substitution. In the meantime, modification of the interlock configurations allowed to continue the operation in a degraded bust still safety conditions, thanks to the distribution and correlation of the monitoring point.

To maintain constant the RFQ resonant frequency, the controlled variable (frequency detuning Δf) has to be provided from RF system to the tunning close loop of the RFQ cooling system. This information is not directly available in the variables shared by the Low Level RF (LLRF) system, which provide a different set of PVs to be evaluated according to the working mode of the accelerator (conditioning or beam mode) in order to get the correct Δf information for the close loop control. At this purpose the RFQ control team developed and implemented the logic to elaborate the information from LLRF taking also into account the data filtering in relation with the pulse operation period and duty cycle. The frequency close loop control will be validated once the accelerator commissioning will reach a sufficient average power.

RF Signal Acquisition

The RF acquisition system, designed for the CW operation, required RF pulses >4ms to evaluate correctly the field flatness, while the fast acquisition can, at maximum, monitor 8 signal at 250kHz, providing the envelope of the waveform at the HMI. At the beginning of the RFQ conditioning with short pulses (20µs), it was necessary to move some RF signal to an oscilloscope to improve the sample rate in order to better understand the behavior and perform measurements useful also for RF system calibration. The oscilloscope integration was not considered in the LCS design, so the preparation and frequent variation of the acquired RF signals (in the first period) was as necessary as inconvenient. Nevertheless the scope remote interface became an essential instrument during the RFQ conditioning and beam commissioning, as far as it was definitely integrated with a fixed set of signals (top right corner in Fig. 5).

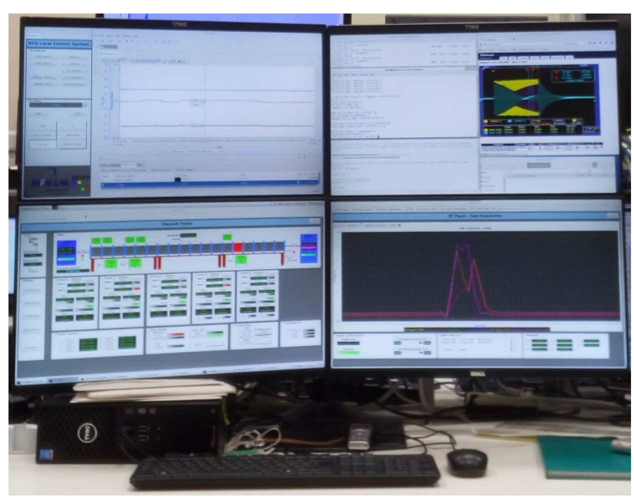

Figure 5: RFQ LCS console during the RF conditioning.

ISBN: 978-3-95450-209-7 ISSN: 2226-0358 doi:10.18429/JACoW-ICALEPCS2019-MOPHA008

HMI and CCS Services

HMI host was and physical machine placed in the LIPAc control room: it was equipped with CentOS 7 OS and all the EPICS environment (base and extensions) required to perform RFQ LCS monitoring and control.

According to the guidelines, the machine was integrated into the CCS network in order to use all the CCS services and exchange EPICS data among the different sub-systems.

The control panels were developed with Control System Studio (CS-Studio) application. The CS-Studio version used during the control deployment was freeze to V.3.2.16 for schedule reason. During LCS integration and control system maintenance (LCSs and CCS), software updates were required: in particular CCS archiver service was migrated from an RDB to the new appliance available in EPICS. As consequence, incompatibility issues and features limitation raised up between CS-Studio application and services versions: HMI software update was required, but the control panels were not completely compatible with the new application version. Because of the project time schedule, two different versions of CS-Studio were installed in the RFQ HMI machine in order to maintain RFQ control panels usability and guarantee a correct interface to the new services provided by the CCS. The control panel upgrade is scheduled in the next future.

For security reason, the entire control system is an isolated architecture which not provides remote access services: this approach maximized system security but, on the other hand, limited the possibility to provide remote assistance during installation and commissioning stages.

USAGE EXPERIENCE AND SUPPORT

At least one member of the control group was always present during the first period of usage of the system, to support and train the user, to solve eventual issue, to improve the system implementing modification, and working for future operation stage (beam operation etc.). Key activities were also the interlocks configuration according to the system and operation conditions, as well as the organization of the screens to monitor the data (Fig. 5).

Additional support was provided also via Skype or e-mail; once again thanks to the collaboration of QST and F4E colleagues for the prompt support onsite and for the implementation of the remote instructions.

In addition to the software and control application developed for the LCS, several applications were developed in order to maximize work efficiency and optimize time operations. In particular tools for RF automatic measurement, RF system calibrations and automatic beam transmission setup were provided to the LIPAc. Many of these tools are based on Python language and communicate with EPICS environment through PyEpics module.

CONCLUSION (LESSON LEARNED)

Power test was a real step forward for the control system maturity, which gave the chance to anticipate the operation problematic, debugging hardware and software.

The quite complete installation and FAT verification was crucial to detect and fix hardware problematic. It was also a training for the final installation phase.

Installation and commissioning of the RFQ LCS and the relative ancillaries required large information sharing between the involved person and several competencies which had to be distributed among the working team and the on-site engineers in order to overcome the problematic regardless of the people available onsite.

Electrical interface shall be well defined exchanging detailed schematics between the involved persons, and executing preliminary integration test wherever it is possible. It's also fundamental to take into account the response time (pass band) of both the circuit in relation to the functionality.

Functionality involving different subsystem has to be considered and detailed defined since the beginning of the development of each system in order to don't forget parts difficult or impossible to be included in a second time.

Design of signal acquisition has to take into account the requirements of enhanced performance or functionality, not expected by the normal operation, and also the possibility of integrate additional instrumentation.

Provide the possibility to easily customize, develop and include additional functionality to the system make user proactive and collaborative.

Test and operation in real environment are mandatory steps of system commissioning; brakes and faults are part of the game.

DISCLAIMER

This work was undertaken under the Broader Approach Agreement between the European Atomic Energy Community and the Government of Japan. The views and opinions expressed herein do not necessarily state or reflect those of the Parties to this Agreement.

REFERENCES

[1] IFMIF, `http://www.ifmif.org`

[2] E. Fagotti *et al.*, "IFMIF/EVEDA RFQ preliminary beam characterization", in *Proc. LINAC'18*, Beijing, China, Sep. 2018, pp.834-30. doi:10.18429/JACoW-LINAC2018-THPO062

[3] M. Giacchini *et al.*, "IFMIF EVEDA RFQ local control system to power tests", in *Proc. PCaPAC'14*, Karlsruhe, Germany, Oct. 2014, paper WPO017, pp. 69-71.

[4] M. Montis *et al.*, "IFMIF EVEDA RFQ local control system integration into main control system", in Proc. *ICALEPCS'17*, Barcelona, Spain, Oct.. 2017, pp. 1771-1775. doi:10.18429/JACoW-ICALEPCS2017-THPHA157

[5] E. Fagotti *et al.*, "High power RF test of IFMIF-EVEDA RFQ at INFN-LNL", in *Proc. LINAC'16*, East Lansing, MI USA, Sept. 2016, paper THPLR051, pp. 975-977.

[6] M. Giacchini *et al.*, "IFMIF EVEDA RFQ local control system: power tests", in *Proc. IPAC'17*, Copenhagen, Denmark, May. 2017, paper MOPAB063, pp. 253-256.

[7] S7plc, `http://EPICS.web.psi.ch/software/s7plc/`.

[8] OPC, `www.opcfoundation.org`