ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA104

UPGRADE OF THE ALPI LOW AND MEDIUM BETA RF CONTROL SYSTEM

D. Marcato*,[1], L. Antoniazzi, D. Bortolato, E. Fagotti, F. Gelain, E. Munaron, R. Ponchia, I. Rakotobe Andriamaro, M. Roetta, G. Savarese, INFN Legnaro National Lab., Legnaro, Italy
M. Bellato, INFN Padova, Padova, Italy
[1]also at University of Padova, Department of Information Engineering, Padova, Italy

Abstract

The ALPI accelerator radio frequency (RF) control system at LNL (Legnaro National Laboratories) is currently undergoing a series of upgrades which will extends its lifetime and provide enhanced performance. This is a multi-year project where the upgrades are delivered incrementally while avoiding disruptions to the accelerator schedule. The first phase includes the development of new Low Level RF (LLRF) controllers, tuner and coupler stepper motor boxes and power amplifiers interfaces. The control system software and graphical user interfaces have been completely rewritten based on EPICS, supporting both the new and old LLRF controllers. A second phase is undergoing with the installation of the new software and hardware, while still using the old LLRF controllers, on the low and medium beta cavities of the ALPI accelerator. In the next phases the upgrade of the whole accelerator to the new software will be completed and the new LLRF controllers will be installed. This paper describes the technical solutions adopted and the status of the project.

INTRODUCTION

ALPI (Acceleratore Lineare per Ioni, which stands for Linear Accelerator for Ions) is a linear accelerator at Legnaro National Laboratories (LNL) based on superconducting radio frequency (RF) cavities (Figure 1). It is composed of three main sections: low, medium and high beta, which are characterized by different cavity design and operating frequencies. The cavities on the low beta line are made of pure niobium and resonate at 80 MHz, while the ones on medium and high beta lines are made of niobium sputtered copper and have a resonance frequency of 160 MHz.

The original RF control system was developed internally at LNL when the accelerator was first commissioned in the early 1990s. It has performed well and enabled the operation of the machine for more than 25 years but is now obsolete. Old hardware is hard to maintain and the software can't be updated easily. Thus, an upgrade plan has been designed. This is composed of three phases: in the first one the future control system has been designed and its components developed. A new digital LLRF controller based on an FPGA was designed, capable of controlling up to 8 cavities [1]. In addiction the hardware controllers for the stepper motors and the interface for the power amplifiers have been completely redesigned based on Beckhoff modules, in order to fully replace the old VMEs. On top of that, the software has been completely rewritten based on EPICS (Experimental Physics and Industrial Control System) [2] and a new graphical user interface (GUI) has been introduced based on Control System Studio (CSS). The second phase foresee the installation of the new software along with the new hardware for the stepper motor and amplifier interface, while maintaining the existing LLRF controllers and amplifiers. This allows to use the new software without changing the LLRF controller which is the most complex part of the system, reducing the commissioning time and introducing early the advantages of the new software. Finally, in the last phase all the LLRF controllers will be upgraded with the new model, thus completing the dismissal of the legacy control system.

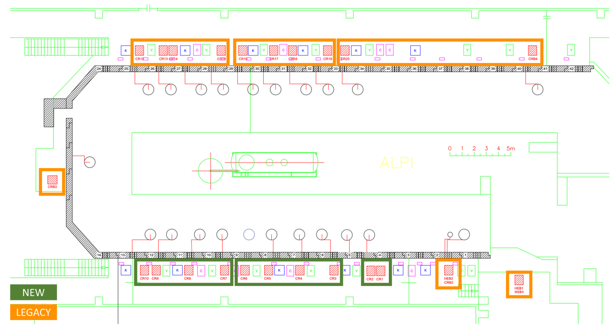

Figure 1: ALPI Layout.

This process was designed so that the accelerator schedule is not affected. In fact, it's possible to upgrade a small portion of the accelerator to the new software while using the old one on the other cavities. Furthermore, the hardware was designed with retro-compatibility in mind, meaning that it is fully compatible with the existing devices on the field and so it's possible to reuse them, including the existing cables and connectors.

This paper describes the details of the hardware and software for the second phase, highlighting the advantages and upgrades over the previous control system. In addiction it will discuss the status and achievements from the ongoing phase 2 installations on the low and medium beta beam lines in ALPI.

LEGACY CONTROL SYSTEM

The original RF control system consists of custom LLRF controller, which samples the RF power from the cavity pickup and generates the feedback correction signal. This

* davide.marcato@lnl.infn.it, davide.marcato@lnl.infn.it

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA104

controller is used to lock the cavity to a fixed RF amplitude, frequency and phase setpoint, which is required to accelerate the beam. This signal is then fed into an RF power amplifier and finally back into the cavity, thus closing the feedback loop. A stepper motor is used to tune the resonance frequency close to the resonator design frequency (80 or 160 MHz), where the controller can work correctly. Moreover, a coupler motor is used to correctly couple the cavity impedance to the the RF line one. All these devices are then replicated for each one of the ~ 80 cavities of ALPI, organized in groups of 4 for each cryostat.

A VME (Versa Module Eurocard) crate is used to connect to 16 LLRF controllers via RS232. The same VMEs are also connected to 16 amplifiers through an aggregator box. In this case the amplifiers are controlled by an analog interface. Finally, the motors are controlled through a custom made VME card and a dedicated box, which is connected to 8 motors. In control room a computer runs a C/C++ software which connects via network with all the VMEs and shows a graphical user interface which is used to operate the system. Some automation procedures are implemented on the VMEs or on the main computer to perform background tasks like power ramps or slow tuning of the cavity to reduce the frequency error with the tuner motors, but the system is mainly operated manually.

HARDWARE

This chapter presents the new stepper motor and RF amplifier interface boxes. Currently, the legacy LLRF controllers are still in use, but the VME has been replaced by a Comtrol DeviceMaster which acts as a Ethernet-serial converter and lets the software connect to up to 16 serial ports via TCP sockets (telnet).

Stepper Motor Box

The stepper motor box (Figure 2) was designed to replace the previous motor box and inherits both the physical dimensions (2u on a 19” rack) and the DB25 connectors on the rear to connect to the motor cables. Each box controls up to 8 motors with 2 limit switches each, meaning that it can be used for a complete cryostat (4 tuners and 4 couplers).

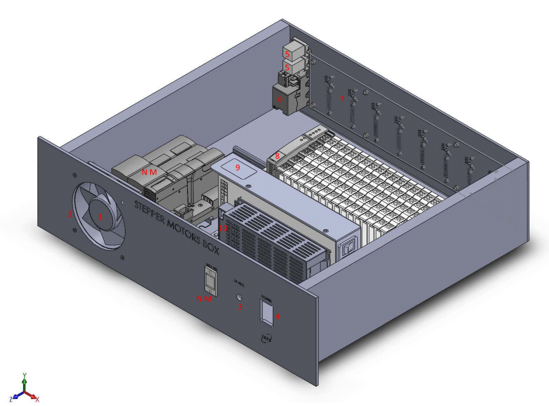

Figure 2: Stepper motor box design.

Internally, the box is based on Beckhoff modules: 8 KL2541 stepper motor drivers and a BK9100 Ethernet bus coupler. Each driver supports a stepper motor with up to 5A, 48V DC with 64 microstep, has two inputs for the limit switches and supports an incremental single-ended encoder. The BK9100 implements MODBUS/TCP network communication.

A custom PCB has been designed to easily combine the outputs of the Beckhoff modules into the 8 DB25 connectors, minimizing the effort required to cable the box. A different version has been developed with DB15 connectors and support for the encoders to be used on other parts of the accelerators (eg: diagnostic movements [3]) so that it can become a standard for all the control systems of the laboratory.

RF Amplifier Interface

The RF amplifier interface is used to read two voltage signals (0-10V) corresponding to the forward and reflected output power of the power amplifier. Moreover, it reads a the amplifier alarm and has an output to enable the power amplifier. This output can be interlocked by an external contact, used by the radioprotection or cryogenic systems to avoid having power into the cavities when its not permitted. Each box is able to control up to 16 amplifiers, corresponding to 4 cryostats, and has 4 inputs to interlock each cryostat.

The box is configured with several Beckhoff modules which offer 32 analog input channels for the RF power, 16 digital inputs for the alarms and 16 digital outputs for the enable. In addiction 4 digital inputs are used for a readback of the external interlocks. The actual interlock is performed by a solid state relay the custom PCB with the DB15 connectors.

SOFTWARE

The architecture of the software is based on the EPICS framework. This was chosen as a standard for the whole laboratory and offers many advantages over the previous software. In fact it supports a vast array of different field devices and protocols, with minimal custom code. Moreover, in EPICS all the Process Variables (PV) are shared over the network, so that even separate systems can be easily interconnected. Given the standard EPICS network protocol, the Channel Access (CA), it’s easy to script automatic procedures using simple bash scripts or python code thank to libraries like pyepics [4] and pysmlib [5]. All the PV can be archived with the EPICS Archiver Appliance and various tools are available to manage and visualize the alarms or to build graphical user interfaces (GUI) without writing custom code.

IOC Device Supports

An EPICS Input Output Controller (IOC) was developed with the device support for all the hardware. For the RF amplifier interface box the modbus module is used to map each MODBUS register to a PV, which then represents the

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA104

underlying value (eg: forward RF power). Another module (csm) has been used to apply conversion tables to the power values to convert them from voltages to watts.

The motor box instead implements a custom protocol on top of 6 MODBUS registers for each motor driver. Thus, a custom device support was developed in C++ to implement the record motor functions on top the MODBUS registers. This was split on two abstractions layers (asyn ports) on top of the modbus one: the first one implements the Beckhoff protocol to access the internal functions of the motor driver and the second one implements the EPICS motor interface by using the underlying port to access the Beckhoff functions. Since this device support is not specific for the RF control system but can be used by anyone using EPICS and the Beckhoff modules, it has been published as open source code on Github [6].

Finally, the legacy LLRF controller can be operated via a string-based protocol over the telnet port. Thus, EPICS streamdevice modules has been used to implement such protocol and make available all the controller settings as EPICS PVs.

Graphical User Interface

Figure 3: RF Control System console.

A graphical user interface has been developed with Control System Studio (CSS) (Figure 3). It was organized following the physical layout of the accelerator: a synoptic show the complete accelerator and lets the user open a window for each cryostat. This shows the status of the 4 cavities in the cryostat and present a button to open a detailed window for each cavity. Here it's possible to control all the parameters of such cavity, including the tuner and coupler motors, the LLRF controller setpoint and see the power amplifier readbacks. With this interface an operator can power on and lock the cavity, seeing the amplitude, phase and frequency errors of the feedback loop.

On top of those interfaces, which replicate the functionality of the previous control system, some useful new pages show the status of all the cavities on a single window. These are designed for the conditioning, exposing mainly the control over the quiescent power and the loop phase to power on a cavity, and for the beam transport exposing the reference phase and the accelerating field.

Furthermore, the new software allows the user to save the values of all the PVs at a certain point, and restore it later thanks to the *autosave* module. This is especially useful to test different configuration of the parameters of the control system being able to rollback to a know working status.

COMMISSIONING

The installation of the new hardware required minimal field work, since all the box were compatible with existing cables. The only new installations were the networking cables and the adapters from the Comtrol Devicemaster serial RJ45 ports to the legacy LLRF controller DB25.

Since all the hardware is now connected to the network all the IOCs were run on a virtual machine, improving the uptime and reducing the maintenance required compared to having dedicate computers. Given the modularity of the cryostats, the IOC startup script is designed to launch a generic cryostat, and all the specific details of each cryostat are loaded from an environment file. *manage-procs* is used to run multiple IOCs on a single host, and to start, stop and manage them. *epicsmng* [7] instead is used to build the IOC and the EPICS modules. The EPICS Archiver Appliance is used to retrieve the history of all the PVs and has proven especially useful during the test and debug of the system.

Some automatic procedures have been developed to replace the ones on the previous control system, including some procedures to perform power ramps or pulsing to condition the cavities. Another procedure, called *soft tuner* moves the tuner motors to reduce the frequency error when this approaches the bandwidth limit of the LLRF controller. The software is also integrated with the cryogenic system so that it knows when a certain cavity in powered on.

CONCLUSION

The new RF control system of the ALPI accelerator has now been installed on the low and medium beta lines, which include the first 10 cryostats out of 20. It has been working for a few accelerator runs, proving its robustness and easing the operation of the accelerator. The next phases of the upgrade will complete the transition to the new software on the whole accelerator and finally introduce incrementally the new LLRF controller, which will give finer control over the feedback loop. Still, the new EPICS-based software opens new possibilities on its own, since it's now possible to easily automate and script many manual operations. Furthermore, given the ability to store the history of all the Process Variables on the archiver, it's now possible to train Deep Learning models on this vast dataset with the aim of developing smart capabilities for the control system [8].

REFERENCES

[1] D. Bortolato *et al.*, "Upgrade of the LLRF Control System at LNL", in *Proc. ICALEPCS'17*, Barcelona, Spain, Oct. 2017, pp. 678–681. doi:10.18429/JACoW-ICALEPCS2017-TUPHA117

ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA104

[2] Dalesio, Leo R., A. J. Kozubal, and M. R. Kraimer, *EPICS architecture*, No. LA-UR-91-3543, CONF-911116-9, Los Alamos National Lab., NM (United States), 1991.

[3] G. Savarese *et al.*, "Design and Development of the New Diagnostics Control System for the SPES Project at INFN-LNL", in *Proc. ICALEPCS'21*, Shanghai, China, Oct. 2021, pp. 428–432. doi:10.18429/JACoW-ICALEPCS2021-TUPV016

[4] M. Newville *et al.*, "pyepics/pyepics:," Feb. 2022.

[5] D. Marcato *et al.*, "Pysmlib: A Python Finite State Machine Library for EPICS", in *Proc. ICALEPCS'21*, Shanghai, China, Oct. 2021, pp. 330–336. doi:10.18429/JACoW-ICALEPCS2021-TUBL05

[6] D. Marcato *et al.*, "beckmotor." https://github.com/darcato/beckMotor

[7] D. Marcato *et al.*, "epicsmng." https://github.com/darcato/epicsmng

[8] D. Marcato *et al.*, "Machine learning-based anomaly detection for particle accelerators," in *2021 IEEE Conference on Control Technology and Applications (CCTA)*, pp. 240–246, 2021. doi:10.1109/CCTA48906.2021.9658806