15 Control system

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15.1 Introduction

The control system refers to the hardware and software for the supervision, control, operation, protection, and data acquisition of the accelerators and beam lines. The main control system for the machine covers the linac, booster, storage ring (SR), and front ends (FEs) and includes the RF system, magnet power supplies, vacuum, diagnostics, insertion devices (IDs), etc. This distributed system uses several independent Ethernet networks, with dedicated servers in the computing room and particular databases. The term 'control system' also refers to independent (autonomous) hardware and software infrastructure for each beam line, including motion control, optics, diffractometers, sample environment, vacuum, etc.

The beam line control systems are independent from the logical point of view, having different databases and independent links with the central storage for data acquisition. At the same time they are very much interconnected with certain subsystems of the machine (control of IDs, FE diagnostics, etc.).

On the software side, building a system from scratch is no longer a cost-effective option and is not justified in most cases. A framework or toolkit and a middle layer are required. Tango[§] is a mature option, continuously growing and supported by other synchrotrons in the world. Tango is an object-oriented framework for building distributed control systems. The basic concept behind Tango is the device server model. A server is a program that manages one or several devices which are encapsulated in a piece of software (class).

This distributed control system runs on computers known as input/output controllers (IOCs) arranged around the technical areas in the accelerators and the controls racks in the beam lines. IOCs are typically compact PCI (cPCI) crates and are diskless, although industrial PCs (with disk) are also widely used. In modern designs, the number of IOCs can be reduced in favour of virtual servers in central data centres and extensive use of the Internet of Things (IoT), by means of pieces of equipment connected to the network. Figure 15.1 shows the generic architecture of a distributed control system like the one installed at ALBA [15.1, 15.2].

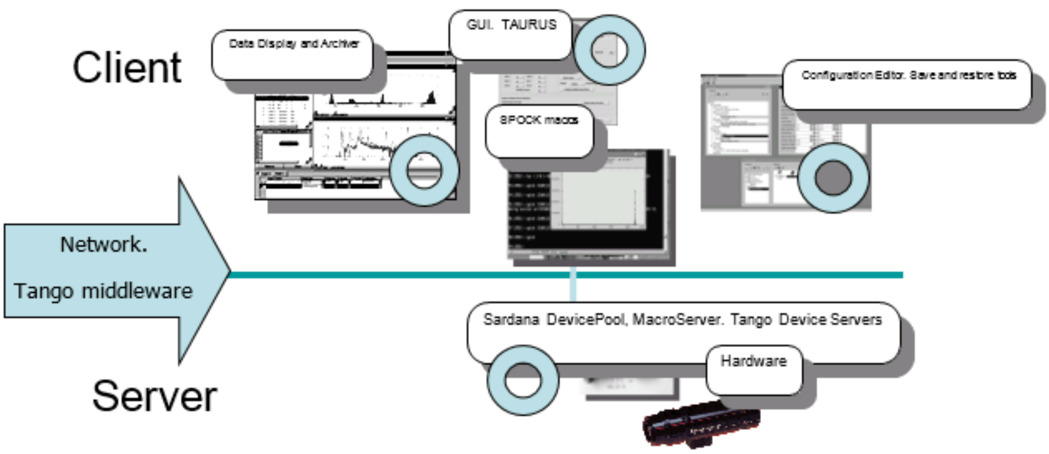


Fig. 15.1: Generic architecture of the software, similar to the control system at the ALBA synchrotron

15.2 Network

The overall architecture of the distributed control system is based on Ethernet. Ethernet is used for supervision and data communications and in most cases also as a fieldbus. There are two main reasons

[§]Tango Controls: http://www.tango-controls.org

https://doi.org/10.23731/CYRM-2020-001.139

for specifying Ethernet as the communications standard for both fieldbuses and supervision: cost and simplicity of maintenance.

All devices are by default required to have an Ethernet connection. But some of them, due to lack of availability in the market or other reasons (that is, convenience for other applications, since the control system must adapt to the market and customer needs), may specify different communication channels.

15.2.1 Ethernet connected

Ethernet is the preferred communication channel for:

- power supplies, except for eventually the correctors of the storage ring because of the very high bandwidth and short latencies that may be required for the fast-orbit feedback (FOFB), including power supplies of the booster and transfer lines, of the storage ring dipoles, quadrupoles, and sextupoles, and of the pulsed elements;
- oscilloscopes, spectrum analysers, and signal generators for diagnostics, which have an Ethernet link;
- Libera boxes for BPM controls, which communicate through Ethernet links;
- motor controllers;
- CCD cameras (gigabit Ethernet or GigE) for the fluorescence screens, optical transmission radiation monitors (OTRs)[**], and other diagnostic cameras;
- input/output controllers, servers, archivers, etc.;
- radiation monitors, which use the independent VLAN for safety, and also the programmable logic controllers for the personnel safety systems, which are linked through the Ethernet for user interface and diagnostics;
- some vacuum devices, such as rest gas analysis (RGAs), and other vacuum components which may be linked by Ethernet or other channels such as serial lines that might be more convenient from the installation cost point of view.

15.2.2 Not Ethernet connected

Exceptionally, some devices may require another type of communication channel.

- Correctors for the storage ring: if Ethernet is not fast enough (the latency of the switches can be too high), there are other options such as the PSI interface [15.3]. As an example, the ALBA synchrotron installed PSI interfaces and not Ethernet, in order to meet the needs of the FOFB, which requires a closed loop in the 10 kHz range.
- Programmable logic controllers (PLCs): the connection between CPUs and the remote periphery of the PLCs often has a separate link due to performance and cost reasons. A deterministic Ethernet (such as the Ethernet or PowerLink) is also frequently required. It will be separated from the general network hardware because of high traffic, specific latency requirements, and the need to avoid unwanted interactions with the standard switches. The safety PLCs for the personnel safety system use a dedicated communication channel (Pilz SafetyBus, for example) for design reasons and to satisfy legal constraints (IEC 61508 compliance). Other PLCs can use other links such as ProfiNET, RS485, etc.
- Vacuum devices: pump controllers and gauge controllers may still be sold with other cheaper interfaces such as serial lines. In this case, serial-to-Ethernet adapters would be needed to

[**] An optical transmission radiation monitor is a device that emits light by transmission of radiation, which is monitored by a CCD or CMOS-type camera.

interface with the control system, which in practical terms would add extra points of failure (the Ethernet-to-serial converters). Nowadays, the range of Ethernet vacuum controllers on offer is much wider than a few years ago, and the prices should fit the budget.

– Other devices such as beam loss monitors: these may use different independent networks, such as different flavours of RS485.

– Other specific devices and detectors for the beam lines with particular hardware: these can be interfaced through different technologies, such as GPIB, serial line, dedicated fibre optics, etc.

The control networks must be separated from the offices and from the outside world by firewalls, specific network configurations, and demilitarized zones. The control system of the machine would need a number of different VLANs[††] with private IPs, as shown in Fig. 15.2. Beam lines, most computing services, and the office networks often have public IPs. The network should use modern services and implement up-to-date cyber-security policies, assigning IP addresses by dynamic host configuration protocol (DHCP), with appropriate authentication and authorization protocols. In order to maintain consistency across the whole system, the IPs and MAC addresses are assigned when possible during the pre-installation of the equipment and are centralized in the general corporative equipment and cabling database (asset configuration). Network configuration files such as RADIUS, DHCP, and DNS can be generated from this central corporative equipment and cabling database.

[††]VLAN stands for 'virtual local area network', defined by the standards IEEE 802.1D, 802.1p, 802.1Q, and 802.10.

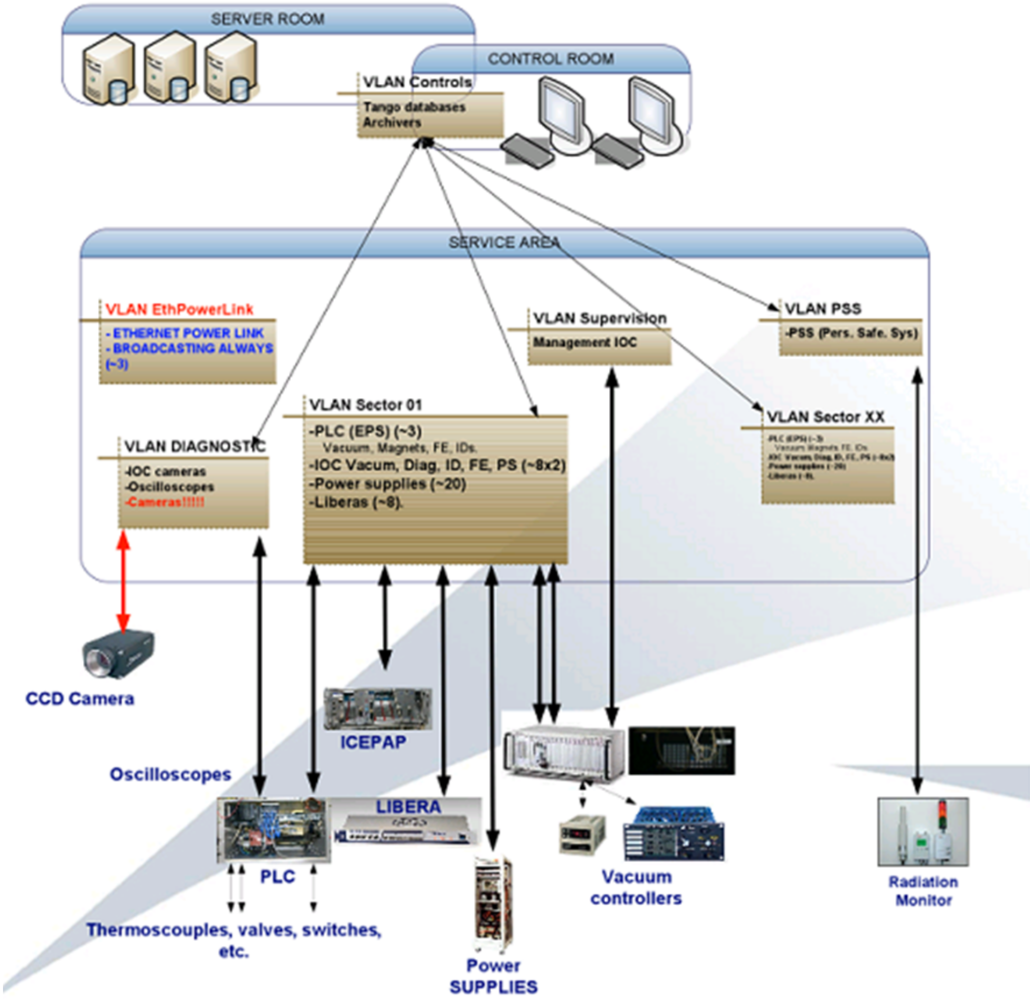


Fig. 15.2: Generic schema of the layout of the networks of a particle accelerator control system [15.1]

Several VLANs should be used for the machine controls: one general, one generic control network per sector, one for diagnostics, one for monitoring, one for protection and interlock systems, and one for safety systems, among others.

15.3 Controls administration

It is a common practice to have a generic control system account for administration. This has a few drawbacks from the security point of view but offers a number of advantages when organizing the installation and deploying software packages. The account has a predefined structure, in which packages, scripts, and configuration files are placed. This directory structure manages databases, servers, clients, graphical interfaces, scripts, remote booting, source files, and all the backups.

15.3.1 Development environment and collaborations

Version control tools need to be used. Subversion[‡‡] and Git[§§] are good choices, and both are well adapted to continuous integration/continuous delivery/continuous deployment tools and techniques. Keeping repositories in an external server enables collaborations between institutes, but for packaging and deployment an internal server would probably still be needed. On a second level, the Tango

‡‡Subversion or svn is a software version control tool: https://en.wikipedia.org/wiki/Apache_Subversion
§§Git is a version control system: https://en.wikipedia.org/wiki/Git

collaboration has a Git repository in Github***. Tango runs on both Microsoft Windows and Linux. The main operating system is often Linux, but Windows is used in some particular cases where specific hardware is required. Tango supports C++, Java, and Python for both client and server sides. Pycharm, Eclipse, and Qt Designer††† are tools commonly used by developers. Being multi-platform and compatible with multiple programming languages, Tango offers a lot of flexibility. In the particular case of ALBA, most computers run Linux although some devices run on Windows, such as the control system for DLLRF‡‡‡ and the interferometer for metrology measurements, and the preferred software programming language is Python [15.2]. In some facilities, such as the SOLEIL Synchrotron, use of Microsoft Windows operating systems and the Java programming language is more extensive.

A lot of work has already been done and is ready to be used free of charge. Other scientific installations—and in particular synchrotrons like the aforementioned ALBA, ESRF, SOLEIL, DESY, Max-IV, and Elettra—have actively contributed to the development of Tango, Sardana [15.4], and Taurus [15.5] on the software side, and the Electrometer [15.6] and IcePAP [15.7] motor controllers on the hardware side. Collaborations with these projects, though they would need to fulfil a few requirements and conditions depending on the project, are worth considering.

15.3.2 Standard tool for maintaining versions of software packages installed

A version control tool is not sufficient for keeping up-to-date an inventory of the versions installed in every machine. In addition, processes and tools for packaging, delivering, and deploying software are needed. The ESRF developed in the early 2000s a tool, blissinstaller, that was later used at the ALBA synchrotron as well. This tool keeps a central database with the software packages (RPM§§§) built and the version of each package installed in every machine (beam line, accelerators, etc.). Other more recent approaches use the native package management systems provided by the operating system (in either a local or a remote repository); this is more complicated to set up in the first place but may become easier to maintain in the longer term. Continuous integration/continuous delivery/continuous deployment and the modern concepts of DevOps are also reaching the control systems. Tools such as Jenkins**** are common nowadays and becoming crucial in the software deployment automation process.

15.3.3 Remote booting

The physical computers in the service area will be *diskless*; they get their operating system from an external server in the computing room. This has proven to be an excellent solution for maintaining and keeping versions up to date, but it is probably not yet suitable for beam lines where every beam line has an ‘independent control’, making the gains of such a configuration less significant. As an example, the control system of the machine at ALBA initially installed 120 compact PCIs for the interfaces with timing, 16 industrial PCs for vacuum control, 10 industrial PCs for front ends, and another 6 for insertion devices, as well as a few others related to LLRF and fan-outs for timing, making a total of more than 160 industrial computers. The central services for the control system also require virtual machines and physical bare-metal servers in the data centre, for central databases, archiving, etc. These can be of the order of 50–100 servers, depending on the size of the installation.

***Tango Git repository: https://github.com/tango-controls

†††Pycharm: https://www.jetbrains.com/pycharm; Eclipse: https://www.eclipse.org; QT Designer: https://en.wikipedia.org/wiki/Qt_Creator

‡‡‡DLLRF stands for ‘digital low-level radio frequency’ and provides fast regulation for the RF phase and amplitude [15.8].

§§§RPM is the Red Hat Package Manager: https://en.wikipedia.org/wiki/Rpm_(software)

****Jenkins is a leading open-source software for DevOps automation: https://jenkins.io/

15.4 The control system centralized sequencer and hardware access manager: the Sardana 'device pool'

The control systems of beam lines and accelerators might look very different, but they are actually not so distinct [15.1]. The control for the machine is closer to a commercial SCADA[††††], where the total number of elements to control is very large but the number of different types of elements remains constrained. The control for the beam lines, based on detectors data acquisition, sample environments, and synchronization with motor movements, is more 'ad hoc'. The key point is the need to be able to easily add and remove new hardware from one experiment to the next or in the middle of an experiment, and to be able to configure scans with multiple motors, experimental channels, and on-line plotting and data visualization.

In some cases the machine also needs such capabilities as cycling magnets or scanning power supplies during the commissioning. The aim of the Sardana device pool is to provide an abstraction of the hardware with a simple and easy-to-use configuration tool and with a complete interface for configuring and executing scans and managing different user interfaces (graphical user interfaces or command line interfaces) at the same time. Figure 15.3 shows a snapshot of the initial main graphical user interface (GUI) of BL22 at ALBA, developed in Taurus and running Sardana and Tango [15.4, 15.5].

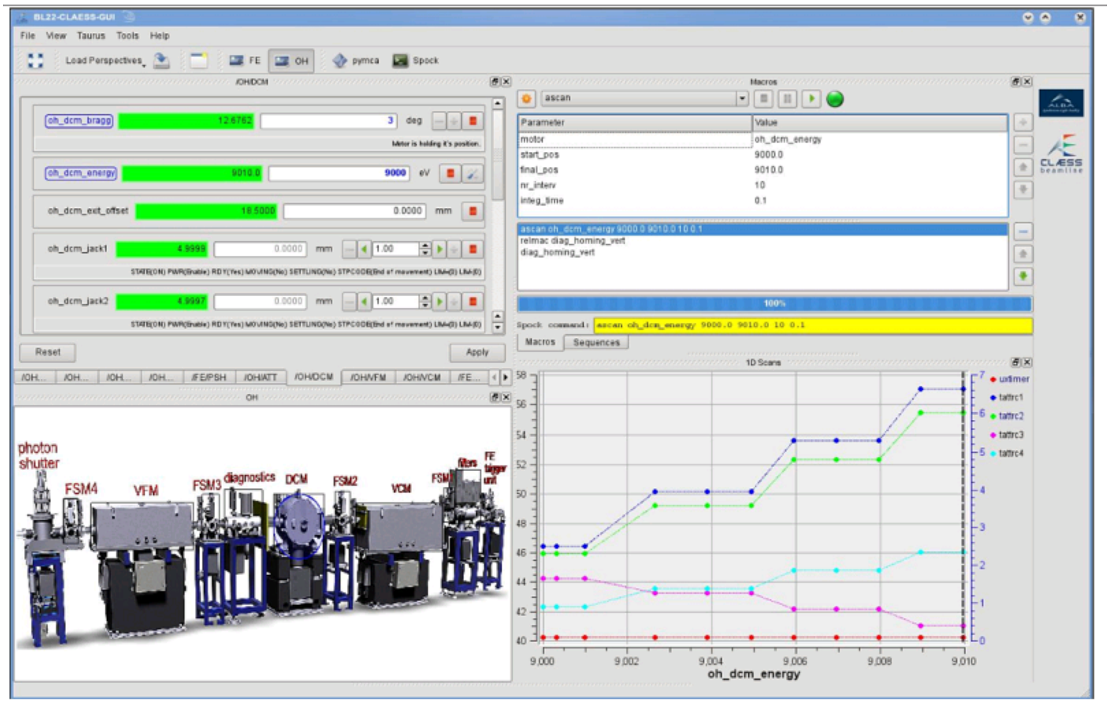


Fig. 15.3: Snapshot of a Sardana GUI based on Taurus at BL22 of ALBA

15.5 IT infrastructure: backups, storage, databases, central management information system, and system administration

There are a few areas of information technology (IT)[‡‡‡‡] that are not covered in depth in this report but which are very relevant and critical to the control system. These include communications and network design and maintenance, cyber-security, system administration, databases, central storage, backup and archive services, and server hosting. Financial applications, project management tools, and service management infrastructure are other key IT disciplines that are not covered in this document.

††††SCADA, Supervision Control and Data Acquisition: https://en.wikipedia.org/wiki/SCADA
‡‡‡‡Information technology (IT): https://en.wikipedia.org/wiki/Information_technology

15.6 Naming conventions

Defining a naming convention at an early stage is crucial. A naming convention must exist for the engineering drawings and documents and must be compatible with the naming convention for the control system. These naming conventions, together with the equipment and cabling database [15.8], must be ready at an early stage.

15.7 Equipment, controls, and archiving databases

Databases are mandatory for the control system. Some facilities, such as SOLEIL or the ESRF, implement commercial databases (mostly Oracle or Microsoft SQLServer). ALBA has defined three main categories of databases, all of them running MySQL[§§§§] (free of charge), which offer sufficient performance and features for most needs.

(1) The **corporative equipment and cabling database** [15.8]: this has been developed early and made available to the electrical and electronic engineers. It is essential for the cabling definition and is intensively used during the cabling specifications, call for tenders, and installation. It has proven to be an excellent tool, which during operation became crucial for the maintenance. This database is used for pre-installing software in the IOCs, defining the network configuration (DNS, DHCP and RADIUS files, PLC variable definitions, etc.), and generating code automatically. The equipment protection system relies on it for defining PLC variables, Tango dynamic attributes, and GUI configuration files [15.9].

(2) The **Tango database**: this is used, among other purposes, as a name service for Tango. It is the central point of the control system.

(3) The **archiving database**: this is also a MySQL database running in separate hardware (much more powerful and adapted to the high workload of registering and making available to several clients of the order of 13,000 values last accessed in a few seconds). This archiving database records temperatures, setpoints, pressures, and many other process variables. The sampling rate can be further increased, up to the range of a few milliseconds, by using temporary archivers with dedicated databases.

Fast data loggers are purpose-specific systems that, depending on the requirements and on the hardware, can reach the micro/nanosecond or even faster ranges.

Signals can be visualized online in trending graphs and can also be recovered from the historical database. Data will typically be kept for few months and then removed and stored in permanent storage media.

The regular archivers define different triggering modes:

- regular intervals (user defined);
- on change (interval user defined);
- thresholds (greater/lower than a certain value);
- statistics, e.g. computation of minimum, maximum, average, r.m.s., full width half maximum (FWHM), etc. of the last X (user defined) samples.

15.8 Fast data logger

Although the fast data logger could be considered part of the archiver, the two are actually very different. The archiver is generic for any variable in the control system (in the case of Tango it can be considered part of the core services); this means that it collects data from device servers and saves the data to a database. The archiver provides tools for configuring the data to be archived, the signals, the

[§§§§]MySQL is an open-source relational database management system (RDBMS): https://en.wikipedia.org/wiki/MySQL frequency, and so on, as well as visualization tools for making trending graphs with on-line data and with historical data retrieved from the database.

The fast data logger is actually a set of subsystems, with independent hardware adapted to a particular purpose. There can be several fast data loggers for different applications and with different hardware. A fast data logger reads a reduced number of signals, which have to be stored in the microsecond/nanosecond range or faster. The aim is to have a record of the last few milliseconds for diagnostics and post-mortem analysis. Studying an arbitrary event means having a trace of relevant signals before and after the event. This is accomplished by means of one or several ring buffers, which can be configured with different sampling rates for different signals. In the ALBA synchrotron, for example, this is achieved by fast ADC cards (ADLINK2005; four ADC channels, 16 bits, simultaneous) running on cPCI crates or, in some cases, using specific hardware of a particular subsystem such as the Lyrtech hardware in the DLLRF system [15.10].

15.9 Equipment protection system

The equipment protection system (EPS) concerns the so-called interlocks and operation of components such as fluorescent screens, shutters, etc. It comprises the vacuum system, magnets, RF system, insertion devices, front ends, and beam lines. It is implemented using PLC technology. In the ALBA synchrotron the EPS is implemented with B&R PLCs that have the CPUs (around 50) in the service area and the remote peripherals (around 100) inside the tunnel interconnected by a X2S bus. PLC CPUs are connected by a deterministic network (Ethernet power link [15.11]). Every beam line has its independent EPS installation, with an independent CPU and dedicated peripherals. The PLC technology offers the reliability needed for the machine protection. Software interlocks managed by Tango with a potential risk of damaging components of the machine should be avoided.

Figure 15.4 shows the hardware layout of the vacuum system and the EPS. Racks with PLC CPUs are represented in red. The EPS of the machine manages thousands of signals that need to be processed and displayed in a comprehensive way. Figure 15.5 shows the main GUI of the EPS of the control system for the machine at ALBA.

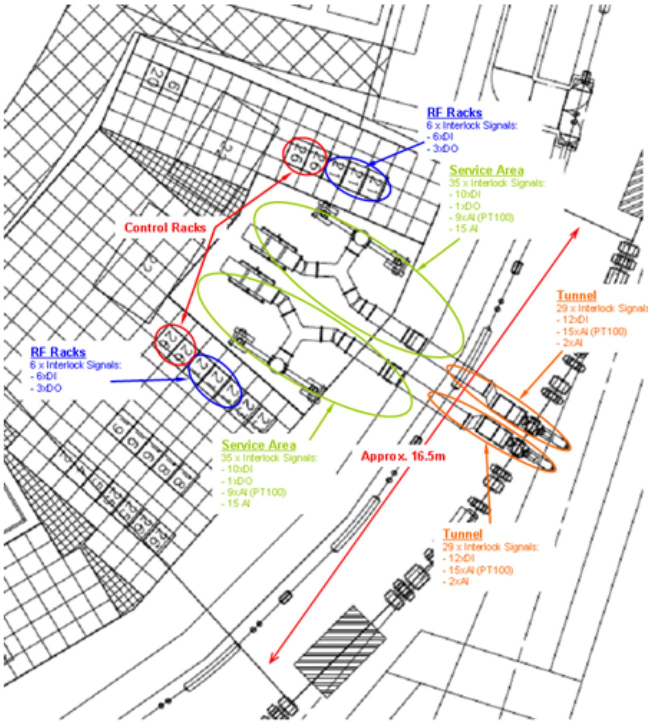


Fig. 15.4: Layout of the equipment protection system of an RF plant at ALBA

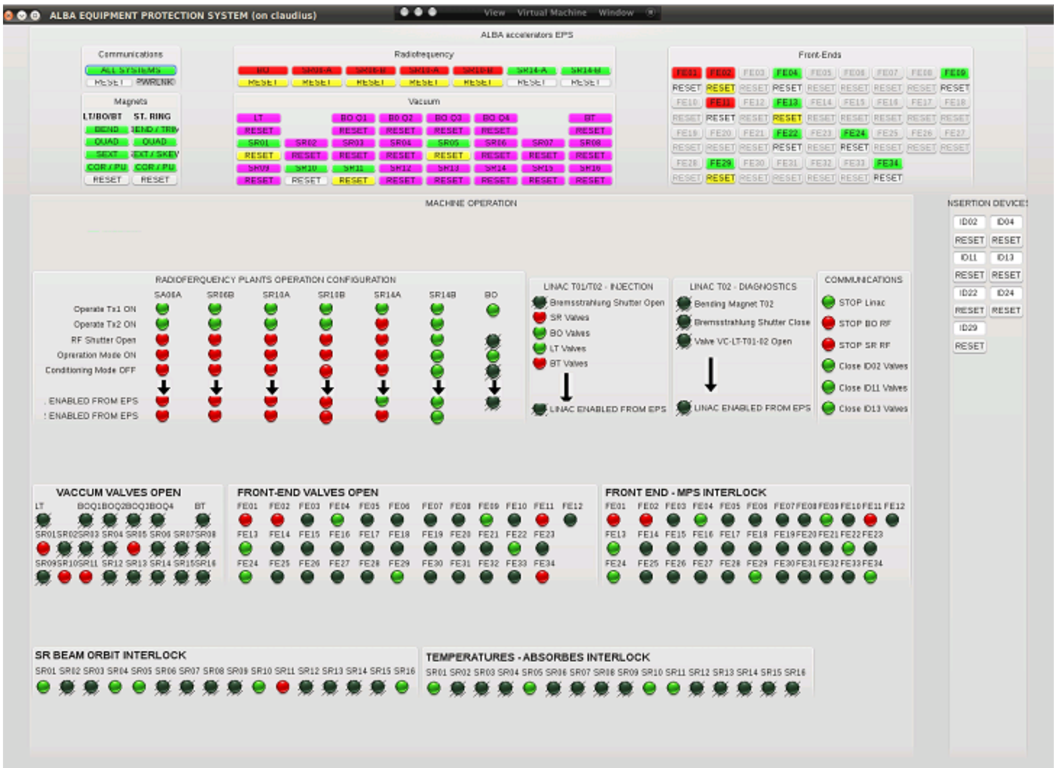


Fig. 15.5: Main GUI of the equipment protection system at ALBA

15.10 Machine controls

The software architecture is distributed. In a Tango-based control system, servers run in IOCs (Linux machines, PCI/cPCI computers), and human interfaces run on so-called workstations installed in the control room. IOCs and PLCs access field devices. Links between workstations, IOCs, and PLCs are based on Ethernet TCP/IP.

All software for the operation of the machine, user interfaces, device servers, archiving/restoring utilities, etc. communicate through Tango. User interfaces include those for monitoring settings and also archive/restore tools, tools for making trend graphs, etc. Two levels are defined:

(1) the **server level**, which manages the hardware, runs on industrial PCs or cPCI racks, and comprises analogue input/output (AI/AO) cards, digital input/output (DI/DO) cards, connections to PLCs, and so on;

(2) the **client level**, which includes user interfaces for monitoring, control, and setting values as well as recipes, archivers, etc. Fig. 15.6 shows the first version of the top-level synoptic of the booster synchrotron control system at ALBA.

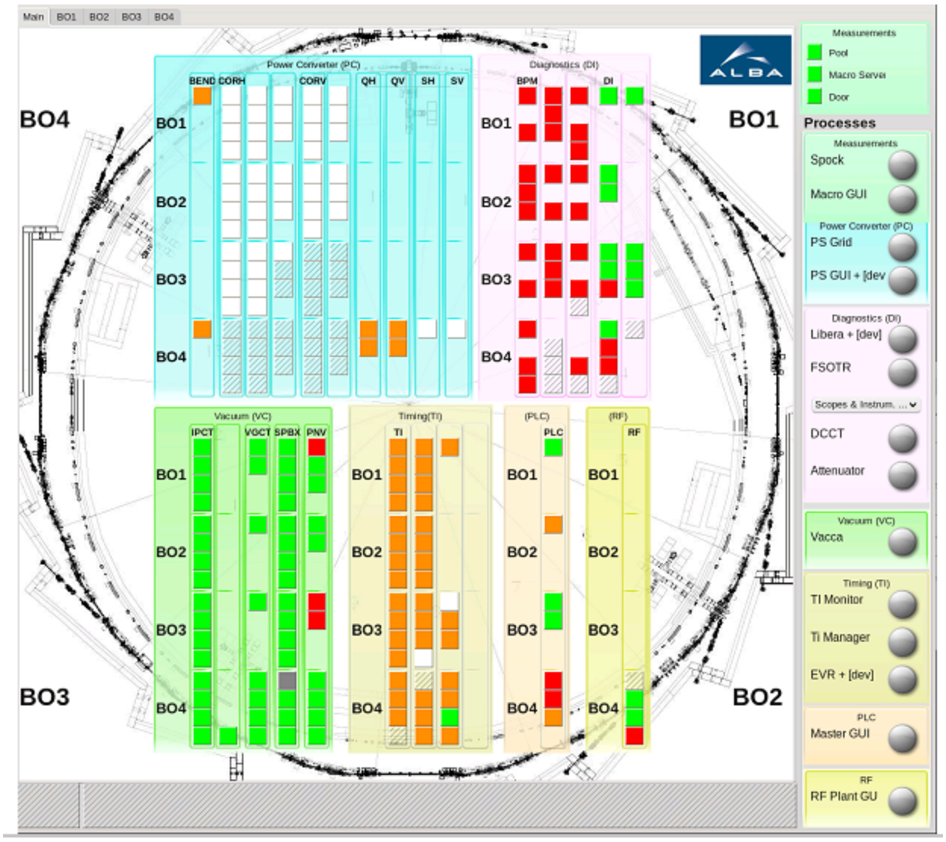


Fig. 15.6: Main GUI used for the booster control system at ALBA; it summarizes in a single view the state of all elements.

15.10.1 Subsystems

From the functional point of view, the control system can be divided into five parts (other divisions are possible, depending on the aim).

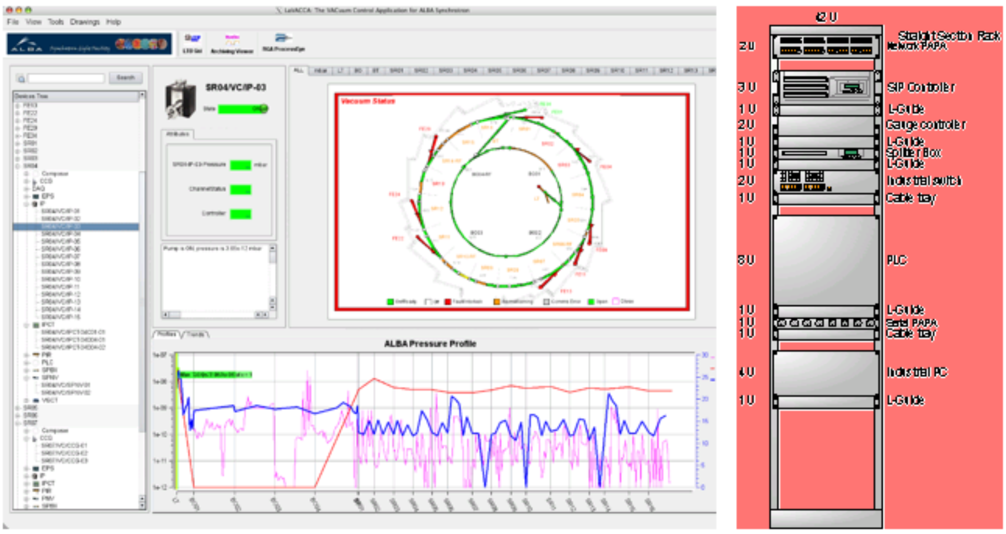
- **Supervisory control system** (Tango), including:
  - device servers, which control and get data from pieces of hardware called devices;
  - servers, which group low-level devices and implement sequences (e.g. Sardana device pool, macroserver);
  - generic graphical interfaces for monitoring, configuring, and operating the machine, which are used by operators, machine physicists, and beam line scientists; these interfaces are provided by Tango;
  - archiving tools for configuring signals to be stored long-term in the central databases and for archiving and restoring these signals;
  - alarm handling tools, which manage the configuration and operation of alarms and provide means of acknowledging and archiving alarms sorted by category, severity, and so on;
  - save/restore utilities, which save and restore the huge number of distributed parameters and set points of such complex machines as accelerators and beam lines, resulting in a sort of catalogue of recipes which are then available for restoring, consulting, comparing, etc.
- **Fast data logger** used to trace interlocks and problems in case of trips; typically it will run in the μs range.
- **Timing and fast interlock system** used for synchronization of the machine and for propagation of fast interlocks along the accelerator.

- **Equipment protection system** responsible for the protection of all the equipment of the machine.
- **Personnel safety system** (PSS), responsible for ensuring that any operation is done in safe conditions and sending any system to a safe state in case of failure.

Other subdivisions of the control system could be done by subsystems, such as vacuum system, radio-frequency system, timing system, diagnostic system, magnets and power supplies, insertion devices, and front ends.

15.11 Vacuum system

The vacuum control system is highly distributed as well. It deals with control, interlocks, and data acquisition. As an example, the machine at ALBA initially required around 170 ion pumps, 70 cold cathode gauges, 35 Pirani gauges, 45 gate valves, and more than 500 thermocouples—just for the vacuum subsystem. These numbers tend to increase after the commissioning to cover specific needs in different locations. Other devices, such as RGA and NEG pumps, may also be required (at ALBA, 16 were needed initially, one per sector). Figure 15.7(a) shows the main synoptic of the vacuum control system, VACCA, of the machine at ALBA [15.9]. Figure 15.7(b) shows an example of the definition and configuration of the instrumentation racks in the early stages of the project. These configurations of racks can be required at early stages during the hardware pre-installation.



(a) (b)

Fig. 15.7: (a) Synoptic of VACCA, the vacuum control system at ALBA [15.9, 15.1]; (b) first layout definition of a straight section instrumentation rack for the vacuum system.

15.12 Power supplies

All power supplies are interfaced by an Ethernet link, with the exception of those for the storage ring correctors, which may need a more deterministic interface. Figure 15.8 shows the generic electronic interface for monitoring and controlling setpoints and current measurements in all power supplies of the machine at ALBA.

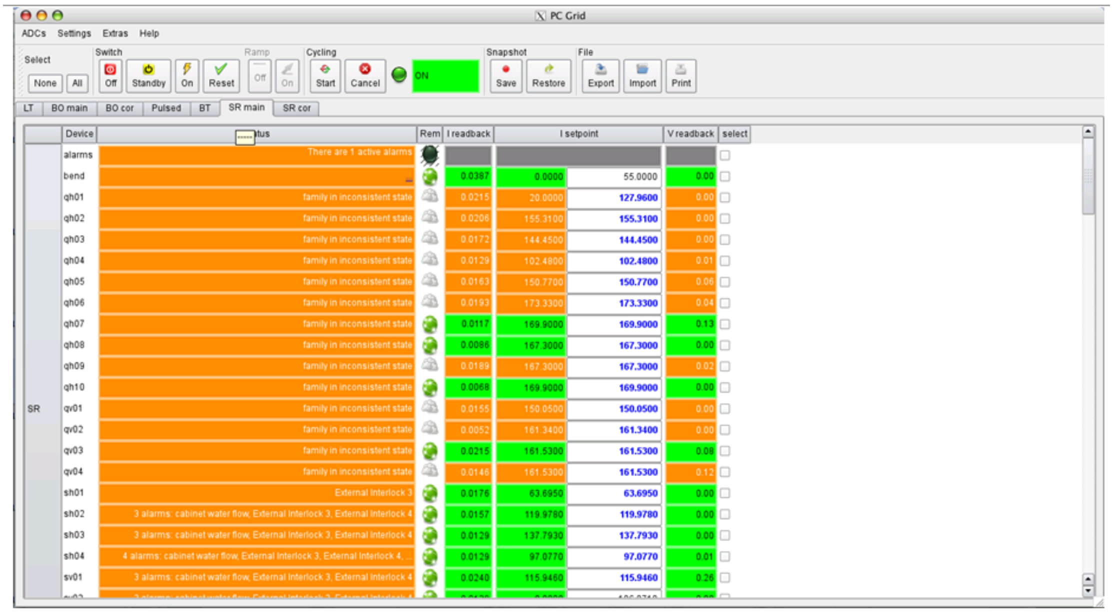


Fig. 15.8: Graphical interface for the power supplies at ALBA

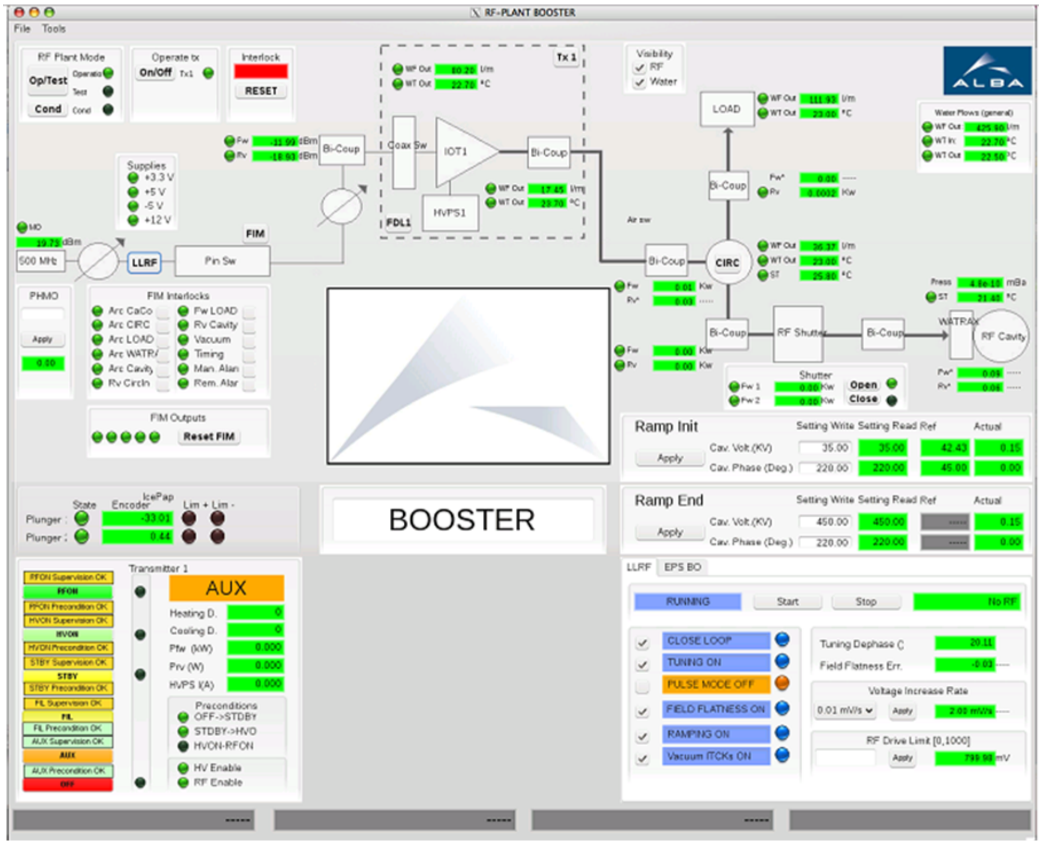


Fig. 15.9: Main synoptic of the GUI for the control system of the RF plant at ALBA

15.13 Radio-frequency (RF) system

The control system of the RF system has two levels. Most signals are managed by PLCs and the device servers running on dedicated IOCs. The fast control loops are performed on digital LLRF subsystems [15.10]. Slow loops, archiving, and control servers run on cPCI crates. The plungers are controlled by an IcePAP motor controller, the standard, configured in slave mode and receiving pulse and direction from the LLRF system. Figure 15.9 shows the graphical user interface of the control system of the RF plant of the booster synchrotron at ALBA.

15.14 Diagnostic system

Beam position monitors and beam loss monitors are distributed along the ring. Other diagnostic devices may be concentrated in certain sectors. Remote desktops connected to oscilloscopes are widely used for readouts of fast current transformers, direct current–current transformers, etc.

15.14.1 Beam position monitors

The beam position monitors (BPMs) are managed by Libera[*****] boxes, which have dominated the market for the past 15 years and have evolved to adapt to newer needs. They need several timing signals: system clock (10 MHz), machine clock (which is the revolution clock, 1.1 MHz for the storage ring or 1.2 MHz for the booster), trigger (which is the injection trigger. 3 Hz), and post-mortem signal (a trigger signal generated by the interlock system).

15.14.2 Beam loss monitors

A number of BLMs need to be distributed across the storage ring (depending on the size of the machine). For example, the ALBA machine used 80–100 Bergoz detectors with a V2F converter handled by Cosylab signal conditioners daisy-chained by RS485 links. Four modules (reading eight beam loss monitors) are chained and read by an IOC.

15.14.3 Fluorescent screens

The fluorescent screens and OTRs can be implemented with CCD cameras, which need to be standardized for cost-efficiency reasons. At ALBA, the standardized model was the Basler SCA1000 30GM (readout by GigE Ethernet connection), although later other gigabit Ethernet models from Basler were also validated. They are usually triggered by the timing system and inserted and removed by the standard PLCs of the EPS.

15.14.4 Scrapers and other motions in the machine

Again, it is important to focus on the standardization of hardware and software in order to minimize installation costs and simplify the operation and maintenance. The scrapers of the machine are very similar to slits in the beam lines and movable masks in the front ends. All these are movable elements comprising motors, pseudo-motors (gap and offset), and graphical components. The hardware equipment and software should be reused and shared where possible to save on development costs and time.

15.14.5 Oscilloscopes

There are many signals for which the best interface is still an oscilloscope or a spectrum analyser. Providing an Ethernet connection to these devices (remote desktop for Windows-based devices) is cost-effective and solves quite a few problems. It also simplifies the cabling in the control room (i.e. only Ethernet connections). Special attention should be paid to Windows and other standard operating systems that may be vulnerable to cyber-attacks if not regularly updated and patched, which is not always possible and in any case a challenge in the case of oscilloscopes installed in the accelerators and beam line control networks.

[*****]Instrumentation Technologies: https://www.i-tech.si

15.15 Insertion devices

In order to carry out state-of-the-art experiments and be prepared for future evolution, there needs to be flexible hardware synchronization between insertion devices and the beam line monochromator.

The standardization of the motor controllers can be extended to insertion devices. ALBA has successfully specified two-phase stepper motors for use with the standard IcePAP motor controller. These all have encoders configured in a closed loop, achieving precision better than a micron. Encoders typically have a precision of 0.1 micron, and the stepper motors move in closed loop with the encoders. Such configurations are also valid for big devices with large magnetic movement of the order of 1 mm/sec or more. Interlocks for the deviation of the tapper (maximum 2 mm in 1 m length) with dedicated sensors, cables, hardware, and PLCs should be installed.

15.16 Orbit correction

The closed orbit correction involves two types of logical feedback loops that can be merged in the same system with the same hardware and software. The slow loop runs at speeds in the Hz range, stabilizes the static orbit, and also deals with energy drifts and radio frequencies. The fast loop (known as fast-orbit feedback, or FOFB) corrects for small deviations, reads at kHz frequencies, and acts on low frequencies below 100 Hz.

In the case of ALBA, the orbit feedback integrates up to 120 BPMs (the total number can be changed by enabling/disabling selected units) controlled by Libera boxes and 88 horizontal and 88 vertical corrector magnets along with their power supplies [15.12]. This system is very much dependent on the BPM electronics and on the interfaces of the correctors' power supplies with the control system (which must be fast and have a low enough latency to allow setpoints to be delivered to all correctors at deterministic rates of 5–10 kHz).

15.17 Motor controllers

A motor controller is a key hardware component in a synchrotron. It is very relevant for the beam lines; however, it turns out to be optimal to standardize motor controllers in the same way as for the machine. The ESRF developed the IcePAP motor controller in the 2000s and in 2006 commenced a collaboration with ALBA, joined a few years later by MAX IV. Both ALBA and MAX IV attained a high level of standardization on the motor controllers, with more than 95% of the axes, most of them in the beam lines, controlled by IcePAPs [15.7]. The IcePAP is a very cost-effective option to consider for future projects.

15.18 Timing system

The timing system provides all the trigger signals for synchronizing the process of injection of electrons from the linac to the booster and storage ring. The operations in this process include firing the linac (gun) and triggering the necessary injection kickers and septa in the booster transfer lines and storage ring, as well as all the diagnostic events, RF system, etc.

The timing system of the ALBA synchrotron is based on events and uses the hardware sold by Micro-Research Finland, which is used very extensively among recently constructed synchrotrons. The system has been extended and converted to be bi-directional in order to manage fast interlocks (in the μs range) as well [15.13].

Micro-Research Finland's system works as follows. The synchronization signals are distributed by events. Those events (132 user defined) and 8-bit distributed bus signals are generated by internal counters, triggers, or software. Events are distributed by fibre optics (multimode 850 nm). The aggregated jitter of the system is reduced to 25 ps r.m.s. Both transmitter and receivers are flexible enough to perform the final fine-tuning. Receivers have a time-stamp to use with each event. Figure 15.10 shows the schematic of the timing system, with the add-on feature of the fast interlocks, achieved by making the fibre-optic links bi-directional so that they can pass messages from any receiver back to the transmitter and out again to the receivers. This timing system was first installed at ALBA and is now a standard feature of the control system.

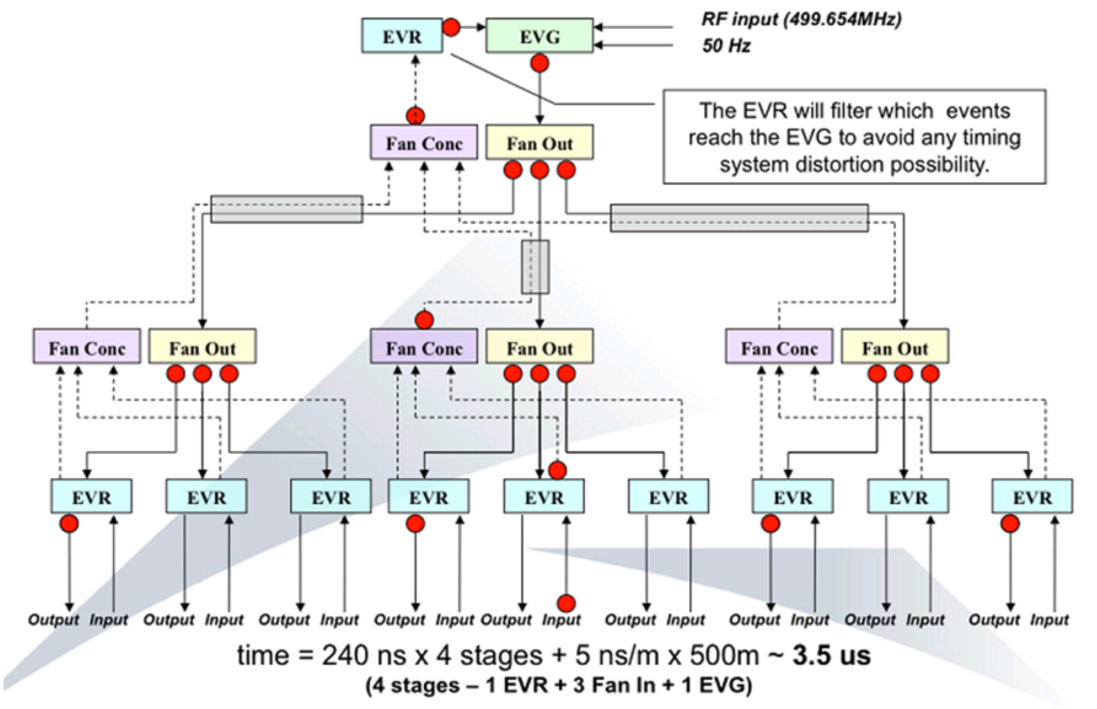


Fig. 15.10: Hardware layout of the timing system [15.13]

The most recent machines (the ESRF's being installed in December 2018) explored distributing the signals over PTP on deterministic networks, adapting the White Rabbit project[†††††] to this purpose. This approach is a good alternative to the Micro-Research Finland system for future installations.

15.19 Personnel safety system

The personnel safety system (PSS) monitors radiation levels and controls access to all the accelerator tunnels (linac, booster synchrotron, and storage ring) and beam line hutches. It prevents people from being exposed to a radiation dose higher than the limits established and specified by the competent authorities, ensuring that restricted areas are clear of personnel during machine operation and monitoring radiation levels outside the restricted areas (bunkers, tunnels, cabins, and hutches). It must be reliable and fail-safe.

Radiation hazards prevention involves technical aspects strictly regulated by different laws and always following the ALARA[‡‡‡‡‡] principle. It is subject to ionizing radiation regulations and the authorities of the individual countries. It has to be independent from any other system. For example, ALBA's PSS was reviewed, validated and approved by the Spanish Nuclear Safety Council.

The system has a number of inputs and produces outputs. Outputs should be redundant and diverse. The whole design must follow norms such as the IEC 61508 [15.11].

- **Redundancy** is achieved by having two independent channels for every signal.
- **Diversity** means that any action is applied to two different components of the system; for example, disabling the RF system means dumping the RF driver and dumping the HV power

[†††††]The White Rabbit project at the open hardware repository: https://www.ohwr.org/projects/white-rabbit
[‡‡‡‡‡]ALARA stands for 'as low as reasonably achievable'.

supplies. In other words, each individual action results in two redundant outputs (four signals in total).

Light panels that signal the state and show alarms or other major events must be installed in the relevant and appropriate places. The most cost-effective way of building the PSS is using safety PLCs. This has proven to be a good choice; it is very flexible and cost-effective.

15.20 Alarm handling

A generic alarm-handling system that is flexible, configurable, and transversal and which covers the whole control system is necessary from the initial phases of the project. The system provides mechanisms to configure the behaviour of the alarms, notifications, and databases for historical values; to monitor alarm activation, deactivation, severity, and traces; and to perform automatic actions and root cause analyses. The system should have adequate human–machine interfaces to correctly manage the large quantity of data [15.14].

15.21 Organization and economic aspects

The control system is critical for accelerators and beam lines. Its design needs to be considered from the beginning of the project and play a role in all phases of the development. The initial design and strategy for the installation must be ready at the early stages. Calls for tenders for the different components should include specifications for the interfaces with the control system. This includes specifications for standard hardware and software interfaces which can be applied generally to the many tenders involving the control system: linac, power supplies, diagnostics, motors, mechanical components, RF elements, insertion devices, monochromators, benders, mirrors, detectors, etc.

A project management system must be established from the beginning to share data between different subsystems and integrate the schedules for deliveries and installation of components. The goal is to have a central management system for the whole project, covering schedules, resources, risks, and the coordination of all sub-projects into the master baseline of the facility. The different sub-projects establish plans, organize resources, and define the delivery, installation, and commissioning of the different components. A model for project management could be Prince2, for example, which is the method followed at ALBA. It is well adapted to the needs of accelerators and beam lines, is easy to adapt to the scope of different projects, and can be combined with Agile methodologies for software development [15.15].

During the construction phase, different services will be built and some of them—such as vacuum chamber bake-outs, archivers, and other parts of the control system—will be turned on for operation during the installation. A system for tracking user requests and a central point of contact for the service desk would be required. ITIL best practices provide important guidelines for implementing service operation and support. This is particularly critical during the operation phase of the facility but would start already during the construction.

From the economic point of view, a good approach is to reserve a budget of 10% of the total project cost for the control system and computing services. This might vary depending on the strategy adopted in terms of software and hardware development and use of commercial off-the-shelf instrumentation. Writing software from scratch is money- and time-consuming. The right balance of in-house development and reuse of existing software (preferably free and open source or imported from existing institutes) is key to success. There will inevitably be some software to develop from scratch (e.g. for new hardware, new features, or new requirements), but there are many parts for which existing (and in some cases industrial) solutions are functional and fit to purpose. The use of industrial solutions (PLCs) and regular computers (industrial PCs) has worked very well in other synchrotrons, ALBA being a good example; it is cost-effective and reliable. Finally the manpower is very much dependent on the institute itself.

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