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# Bridging open and proprietary control frameworks for fusion facilities: EPICS – Industrial SCADA integration in the CODAC system of IFMIF-DONES

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This paper presents an architectural approach for the Control, Data Access, and Communication (CODAC) system within the framework of the IFMIF-DONES (International Fusion Materials Irradiation Facility DEMO Oriented Neutron Source) control systems. This study focuses on the integration of the most widely adopted SCADA frameworks with state-of-the-art industrial automation standards in particle accelerator environments. The interoperability between EPICS and commercial control frameworks based on OPC UA is particularly emphasized, enabling a hybrid control ecosystem that leverages the strengths of both domains.The architecture enhances flexibility, scalability, and standardization across all systems and subsystems involved in supervision and control tasks. By facilitating seamless communication and modularity, it supports the use of both open-source and proprietary technologies while ensuring long-term maintainability and adaptability. The paper includes a review of comparable systems at other large-scale facilities, an evaluation of integration strategies, and a detailed discussion of the resulting CODAC architecture, highlighting its impact on the overall efficiency and interoperability of the IFMIF-DONES Central Instrumentation and Control Systems (CICS). This study aims to offer a complementary perspective on the control system architecture for IFMIF-DONES, exploring the potential integration of industrial SCADA frameworks alongside EPICS.

## 1. Introduction: IFMIF-DONES control systems

The International Fusion Materials Irradiation Facility - Demo Oriented Neutron Source (IFMIF-DONES) will serve as a research-material infrastructure to test, validate, and qualify materials for building future fusion power plants, such as the DEMO prototype reactor. Located in Escúzar (Granada), it is currently under construction [1,2] and will play a key role in the development of clean energy based in nuclear fusion reactors.

The operation of the facility will rely on the Central Instrumentation and Control System (CICS), a complex system that ensures the global supervision of IFMIF-DONES. The CICS will manage, monitor, and control all instrument parameters, as well as store and visualize data. It will maintain continuous, bidirectional communication with the Local Instrumentation and Control Systems (LICS), which will locally monitor and control individual subsystems to ensure that process variables remain within the required ranges [3–6]. Such control systems are critical for particle accelerators, guaranteeing precise operation, synchronization, and safety [7] while allowing the modularization of the different functions required to implement the complete operation of the facility.

The primary role of the CICS is to safely and reliably control the irradiation of samples while preventing damage. Its architecture is divided into three core systems, as shown in Fig. 1, they are:

1. Control, Data Access, and Communication (CODAC): It includes supervision, timing, data management, human-machine interface, and alarm systems. This proposal is based on these elements, which is the central one in charge of designing the machine's functional elements and operations.
2. Machine Protection System (MPS): It implements strategies to protect against failures in components, systems, or operations.

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3. Safety Control System (SCS): It comprises plant safety, personnel access safety, and radiation monitoring subsystems, ensuring compliance with safety standards.

Today complex control facilities are built on the top of Supervisory Control and Data Acquisition (SCADA) systems. They have traditionally been employed to control and manage industrial processes. These systems are widely implemented across diverse industrial sectors and, as outlined in [8], their primary functions typically include the following:

- Supervising installations and equipment.
- Monitoring and controlling plant operations.
- Managing the storage of plant variables.
- Processing data to support decision-making.
- Providing a Human-Machine Interface (HMI).
- Managing and recording alarm signals.
- Ensuring user management and access control at the plant level.

In the case of the IFMIF-DONES control system baseline [9], the CODAC technology is proposed to be based on the EPICS control framework [10]. EPICS is a technology designed and created in 1988 and has proven reliability and responsiveness in handling high-throughput data acquisition when controlling heterogeneous devices used in critical infrastructures, such as accelerators. This choice is mainly justified by the fact that EPICS is a free software (no license cost), it is also one of the common solutions used in the particle accelerator facility field [11], and in particular, in the Linear IFMIF Prototype Accelerator (LIPAc) -a prototype of the IFMIF-DONES built in Rokkasho (Japan) in 2010 [12] -, and its adoption in the most important nuclear fusion facility in the world, the International Thermonuclear Experimental Reactor (ITER) [13].

EPICS is a free software platform, that was first developed in 1994 and is maintained by a community of researchers located in different scientific facilities. It consists of a set of software tools and applications that provide a software infrastructure to be used as a distributed control framework. It is based on a common bus (channel) accessed by its own protocols: Channel Access (CA) and pvAccess (PVA), and it manages process variables (PVs) usually provided by Input-Output Controllers (IOCs).

In addition to its control bus protocols, this ecosystem of software also includes among others a graphical operator interface (CSS/Phoebus) [14], a data archiver [15,16], an alarm manager [17,18], etc. In the EPICS community there are also multiple contributions and customized developments for specific solutions, devices, and platforms. On the contrary, in the baseline design of IFMIF-DONES for the MPS and SCS it is proposed an industrial SCADA (such as Siemens WinCC OA [19]). This has been proposed for several reasons, especially for safety compliance but also considering that the physical implementation of these systems often uses industrial devices (such as PLCs), widely supported and integrated on those industrial control tools.

Given that the project is currently in its definition phase, design decisions remain open to refinement as technologies evolve or requirements change. As such, the IFMIF-DONES control system is conceived with versatility and adaptability at its core, ensuring that it can accommodate both current needs and future developments. This dynamic approach fosters the continuous evolution and enhancement of the system, beginning with the control framework itself, as illustrated in [20], where the latest advancements in the DONES Control System design are described.

The current study contributes to an ongoing reassessment of the

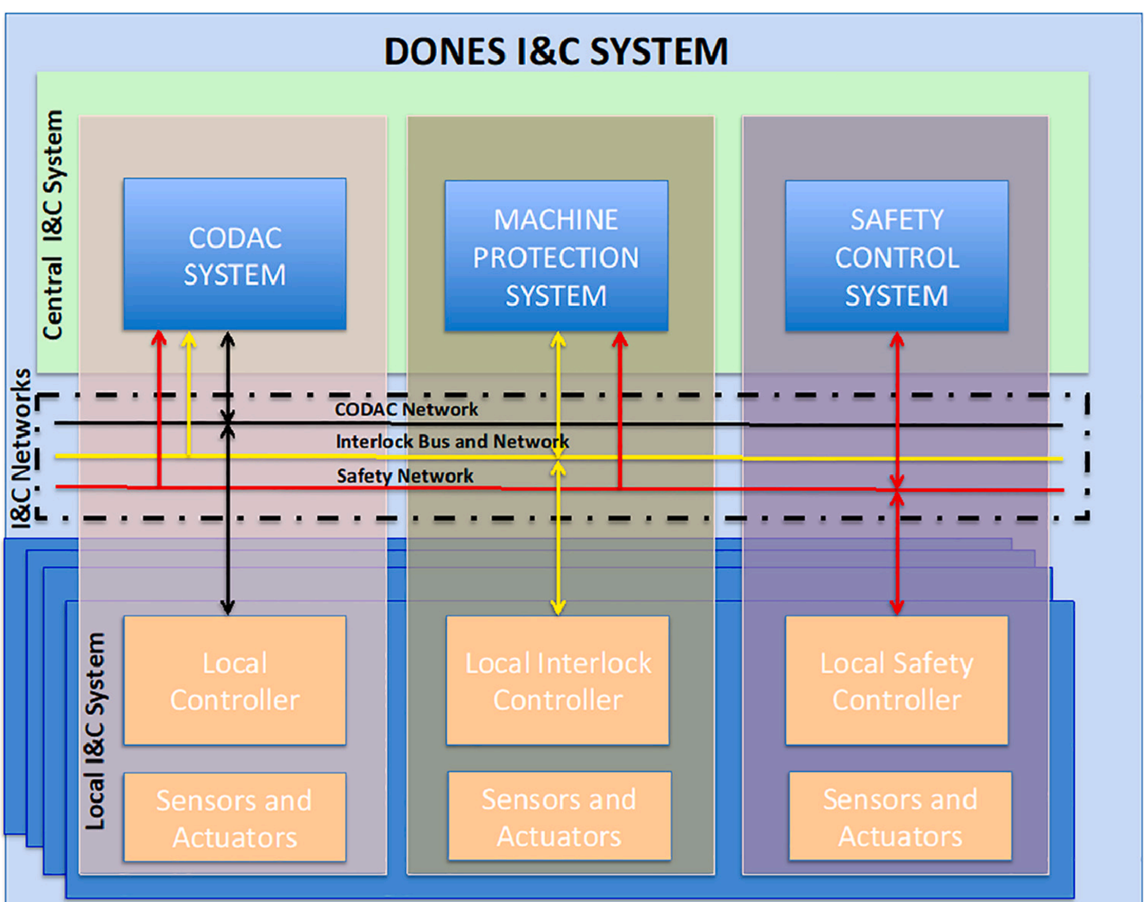


**Fig. 1.** DONES I&C Architecture. (Taken from [5]).

CODAC architecture, with the aim of enhancing its design through a more integrated and interoperable approach. One of the key directions under consideration is the adoption of a unified industrial SCADA framework across all CICS systems (CODAC, MPS, and SCS), with EPICS continuing to play a pivotal role in localized control within specific LICS. The revised architecture under evaluation streamlines the integration of additional LICS through industry-standard protocols, offering an alternative to EPICS where appropriate. To support this, several technologies enabling communication between EPICS and industrial SCADAs via a dedicated gateway are being explored, with a focus on benchmarking performance and assessing interoperability in practical scenarios.

Nowadays, modern industrial SCADA systems have evolved to integrate advanced technologies that enhance efficiency, communication, and security. They adopt standards such as OPC UA and HTML5 [21], incorporate IoT devices, and enable cloud connectivity and interoperability with other systems. Furthermore, these systems leverage artificial intelligence (AI) and machine learning (ML), either natively or through supplementary modules, to optimize control processes and improve operational accuracy. Enhanced security measures are also a key focus, using cryptographic methods and authentication protocols to safeguard both data and system integrity [22–26].

Finally, on the LICS side, it is expected that on the one hand some LICSs will be implemented with control and communication systems that inherently use market standard technologies and protocols (Non-EPICS); and on the other hand, other LICS (as the Accelerator System) could be better developed using open source frameworks like EPICS to make the most of the knowledge and experience gained in LIPAc and other accelerators. For this reason, a hybrid approach that makes it feasible to work with both ecosystems is desirable.

The main purpose of this work is to propose a complementary architecture design for the CODAC system in relation to the CICS and LICSs, where each technology can fit in the best way making the most of their features and strengths, and at the same time, facilitating the integration among the technologies and the standardization of the systems and protocols in use.

## 2. State of the art

There are a large number of reference particle accelerator facilities worldwide. Their control systems are custom developed to accommodate their unique features. Unfortunately, there is no public documentation summarizing all the implementation details, and this information remains internally on each of these infrastructures. For the sake of the reader's clarity, the information about the monitoring and control systems of some of the most relevant current particle accelerators and nuclear fusion facilities is reported in Table 1. The reported data include public information obtained from websites, conferences, journals and direct information gathered through informal discussions with relevant stakeholders.

This overview does not aim to exhaustively detail the specific implementations and custom developments of each facility, but rather to highlight the predominant or widely adopted control frameworks. Notably, large-scale facilities, such as CERN, often employ multiple frameworks in parallel, leveraging their distinct capabilities for different subsystems and operational scopes.

Note that PCS (Plasma Control System) [27,28] is a structured system architecture specific for plasma control, originally developed by General Atomic (GA) for the DIII-D facility and is used in several fusion plants.

The presented table shows that the control systems of major particle physics and nuclear fusion facilities have traditionally been based on two main open-source frameworks: EPICS and TANGO [29]. IFMIF-DONES has aligned itself with EPICS from the outset, primarily influenced by its adoption in ITER. However, TANGO also represents a significant and mature framework in this domain, with high-profile deployments such as the Square Kilometre Array Observatory (SKAO) [30]. A broader overview of EPICS-based projects can be found in [11], and further TANGO implementations are listed in [31].

Despite differing technological architectures and design philosophies, EPICS and TANGO offer comparable functionalities and maturity levels. EPICS adopts a decentralized architecture centered on PVs using lightweight communication protocols such as CA and PVA to enable high-performance data exchange. In contrast, TANGO is based on an object-oriented model that represents devices as classes with attributes, properties, and commands. It typically relies on CORBA or ZeroMQ for communication, making it suitable for modular systems requiring structured device interactions and advanced graphical interfaces.

Both frameworks are appropriate for large-scale, performance-intensive environments. A general deployment strategy might leverage EPICS for time-critical, low-latency control layers, while TANGO could be favored in scenarios where object-oriented abstraction and extensibility are priorities. In practice, institutional familiarity, community momentum within specific research areas, and the availability of skilled personnel proficient in the chosen technology often influence the selection of one framework over another [32]. In the case of IFMIF-DONES, EPICS remains the primary control framework, drawing on precedents set by ITER, the Linear IFMIF Prototype Accelerator (LIPAc), and the European Spallation Source (ESS) [33].

ITER, an internationally prominent fusion energy research facility located in Cadarache, France, shares strategic objectives with IFMIF-DONES, as both are integral components of the roadmap toward achieving clean energy through nuclear fusion. The organization of their Instrumentation and Control (I&C) systems exhibits a similar hierarchical structure [34,35]. Both facilities implement a two-layered architecture, comprising a Central I&C System and a local I&C System, each of which is subdivided into three core subsystems: CODAC (Control, Data Access, and Communication), Interlock, and Safety.

ITER's control architecture encompasses approximately 21 subsystems and 170 local control systems. Its primary control framework is EPICS, though other platforms, such as WinCC OA, are also employed, particularly for specific functions within protection and safety systems. The facility manages more than 300,000 plant signals and has already surpassed one million PVs, with projections indicating a future expansion to around five million PVs [36].

This modular and scalable design exemplifies the complexity and demands of large-scale fusion facilities, reinforcing EPICS as a capable and extensible solution, and illustrating the practical integration of complementary technologies.

LIPAc is an operative prototype of the IFMIF-DONES accelerator system located in Rokkasho, Japan. Its control systems [37] are organized in Central Control System (CSS), Machine Protection System (MPS), Personnel Protection System (PPS) and Timing System (TS). The central monitoring and control operations are mainly carried out by Operator Interfaces (OPIs) built in Control System Studio (CSS). Currently, they are managing about 40.000 PVs. As IFMIF-DONES pathfinder, it is a key reference for this contribution.

ESS is a multi-disciplinary research facility located in Lund, Sweden and operates an accelerator-based neutron source, enabling research in the fields of materials, energy, health and environment, among others. Therefore, it presents important similarities with IFMIF-DONES. Their Integrated Control System (ICS) [38,39] considers the following main systems and infrastructures: Facility Supervision and Integration; Timing System; Process and device control systems; Personnel Safety Systems; Software Services; Control Room facilities; and Networks and infrastructure. Their primary control systems are based on EPICS, although they are also incorporating devices and solutions based on OPC UA, using this protocol to integrate the protection systems to their control systems and to other conventional facilities [38]. It is worth mentioning that ESS has created its own environment and toolkit to facilitate the development and management of all its EPICS infrastructure, called ESS EPICS Environment (e3) [40].

In parallel, advancements in technology and the growing alignment

**Table 1**
Particle accelerators and nuclear fusion related facilities and their main control frameworks. Note that in most cases, more than one control framework is used, but only the most relevant ones are highlighted here.

| Name | Main Research Purposes | Country | Approximate Construction / Commissioning Year | Main Control Framework |
|---|---|---|---|---|
| **Particle Accelerator Facilities** | | | | |
| ALBA Synchrotron (ALBA) (albasynchrotron.es) | High-brightness X-rays for materials science, structural biology, nanotechnology and environmental research | Spain | 2012 | TANGO |
| Advanced Photon Source (APS) (aps.anl.gov) | Applications of hard X-rays in condensed matter physics, chemistry and energy-storage research | USA | 1996 | EPICS |
| Australian Synchrotron (ansto.gov.au/australian-synchrotron) | Medical imaging, nanotechnology and environmental science | Australia | 2007 | EPICS |
| Canadian Light Source (CLS) (lightsource.ca) | Agricultural science, environmental remediation and health research | Canada | 2004 | EPICS |
| Italian National Center for Oncological Hadrontherapy (CNAO) (fondazionecnao.it) | Hadron therapy for oncological treatment | Italy | 2010 | WinCC, EPICS |
| European Organization for Nuclear Research (CERN) (home.cern) | Fundamental particle physics (Higgs boson, quark-gluon plasma) as well as different applied science applications | Switzerland | 1954 | WinCC OA, JCOP, UNICOS, Custom |
| Deutsches Elektronen Synchrotron (DESY) (desy.de) | Basic research in particle physics and research with synchrotron radiation | Germany | 1964 | TINE, DOOCS, EPICS, TANGO |
| Diamond Light Source (diamond.ac.uk) | Structural biology, engineering stress analysis and cultural-heritage preservation | UK | 2007 | EPICS |
| ELBE Center for High-Power Radiation Sources (www.hzdr.de/db/Cms?pOid=25496&pNid=1732) | Provide accelerator-driven photon and particle sources. Secondary radiations go from high-energy gamma rays, to infrared and THz radiation, to neutron, positron and electron beams | Germany | 2001 | WinCC, EPICS |
| ELI Beamlines Laser Centre (eli-beams.eu) | Fundamental research, operating four ultra-intense laser systems, used for diverse research fields, including biology, medicine, physics, chemistry, materials engineering, space research and nanotechnology | Czech Republic | 2018 | TANGO |
| European XFEL (xfel.eu) | X-ray laser research facility | Germany | 2017 | Custom |
| European Spallation Source (ESS) (europeanspallationsource.se) | Neutron scattering for soft matter, proteins and engineering materials | Sweden | 2014 | EPICS |
| European Synchrotron Radiation Facility (ESRF) (esrf.fr) | Analysis of the structure of proteins and macromolecules of biological interest, study of materials and study of the electronic structure and magnetic properties of matter. | France | 1994 | TANGO |
| Elettra Sincrotrone Trieste (elettra.eu) | Materials science | Italy | 1993 | TANGO |
| Fermilab (fnal.gov) | Neutrino physics (DUNE), dark matter, muon collider R&D | USA | 1967 | EPICS, Custom |
| FAIR / GSI (fair-center.eu) | Nuclear structure, antimatter, astrophysical nucleosynthesis | Germany | 2017 | WinCC OA, UNICOS |
| Karlsruher Research Accelerator (KARA) (ibpt.kit.edu/kara.php) | Accelerator physics and instrumentation | Germany | 2003 | WinCC OA, TANGO, EPICS |
| KEK (SuperKEKB) (kek.jp) | Electron-Positron collider. Luminosity and particle physics experiments. | Japan | 2018 | EPICS |
| IHEP / HEPS (english.ihep.cas.cn) | High-energy synchrotron radiation light source | China | 2019 | EPICS |
| Japan Proton Accelerator Research Complex (J-PARC) (j-parc.jp) | Materials and Life Sciences and Hadron Experiments | Japan | 2009 | EPICS |
| Linear IFMIF Prototype Accelerator (LIPAc) (ifmif.org) | IFMIF-DONES prototype. Deuteron Accelerator. | Japan | 2015 | EPICS |
| MAX IV Laboratory (maxiv.lu.se) | Nanoscale imaging, catalysis, soft X-ray spectroscopy and molecular dynamics | Sweden | 2016 | TANGO |
| National Synchrotron Light Source II (NSLS-II) (bnl.gov/ps/nsls2) | Nanoscale resolution materials. | USA | 2015 | EPICS |
| PSI – Swiss Light Source (SLS) (psi.ch/en/sls) | Synchrotron to produce electromagnetic radiation of high brightness | Switzerland | 2001 | EPICS |
| SLAC National Accelerator Laboratory (slac.stanford.edu) | Ultrashort X-ray pulses (LCLS), quantum materials | USA | 1962 | EPICS |
| Sirius (Brazilian 4th Gen Synchrotron) (lnls.cnpem.br/sirius-en) | Understand the atomic structure of molecules for the development of new drugs, materials, etc. | Brazil | 2020 | WinCC Unified, EPICS |
| Spallation Neutron Source (SNS) (neutrons.ornl.gov/sns) | Fundamental physics, structural biology, biotechnology, magnetism, superconductivity, chemical and engineering materials, nanotechnology, complex fluids, etc. | USA | 2006 | EPICS |

(continued on next page)

**Table 1** (*continued*)

| Name | Main Research Purposes | Country | Approximate Construction / Commissioning Year | Main Control Framework |
|---|---|---|---|---|
| SOLARIS National Synchrotron Radiation Centre (synchrotron.uj.edu.pl) | Fundamental physics experiments | Poland | 2015 | TANGO |
| French National Synchrotron (SOLEIL) (synchrotron-soleil.fr) | Synchrotron that enables research in many fields, including physics, chemistry, environmental sciences, medicine and biology. | France | 2006 | TANGO |
| **Nuclear Fusion Related Facilities** | | | | |
| ASDEX Upgrade (https://www.ipp.mpg.de/16195/asdex) | To prepare the physics base for ITER and DEMO. | Germany | 1991 | Custom |
| DIII-D (https://d3dfusion.org/) | To identify and develop solutions that address key remaining fusion science and technology challenges | USA | 1986 | Custom |
| Experimental Advanced Superconducting Tokamak (EAST) (english.ipp.cas.cn) | Fusion plasma research | China | 2006 | EPICS |
| International Thermonuclear Experimental Reactor (ITER) (iter.org) | Demo of sustained fusion via tokamak | France | 2010 | EPICS. WinCC OA, Custom |
| Joint European Torus (JET) (euro-fusion.org/devices/jet) | Fusion plasma behavior and confinement | UK | 1983 | Custom, EPICS |
| JT-60SA (jt60sa.org) | Advanced research on tokamak fusion | Japan | 2020 | EPICS |
| Korea Superconducting Tokamak Advanced Research (KSTAR) (kstar.kfe.re.kr) | Fusion plasma studies | South Korea | 2008 | EPICS |
| MAST (Mega Amp Spherical Tokamak) Upgrade (https://ccfe.ukaea.uk/programmes/mast-upgrade/) | To investigate novel exhaust concepts, to advance the spherical tokamak design and to extend physics knowledge in fusion | UK | 2013 | Custom |
| National Ignition Facility (NIF) (lasers.llnl.gov) | Inertial confinement fusion, high-energy density physics | USA | 2009 | Custom |
| NSTX-U (National Spherical Torus Experiment - Upgrade) (https://sites.google.com/a/pppl.gov/nstx-u/) | Explore the spherical tokamak concept | USA | 1999 | Custom, EPICS |
| Wendelstein 7-X (W7X) (https://www.ipp.mpg.de/w7x) | To investigate the suitability of a stellarator type for a power plant | Germany | 2014 | Custom, WinCC |
| WEST (Tungsten (W) Environment Steady-state Tokamak) (https://irfm.cea.fr/en/presentation-of-west/) | To carry out a scientific programme relevant to ITER, specialized in tungsten divertors experiments | France | 2016 | Custom |

with contemporary industrial standards have led to the adoption of modern SCADA systems in several large-scale scientific facilities, including NASA [41], CERN [42,43], and the aforementioned ITER project [44].

The implementation of WinCC OA at CERN is probably the most illustrative example of an industrial SCADA in a large research facility. This SCADA platform underpins the supervisory and control system of their two main industrial frameworks: JCOP and UNICOS [45]. WinCC OA is employed across a broad range of systems, including the Electrical System, Cooling and Ventilation, Vacuum, Cryogenics, Gas Distribution, Radiation and Environment Monitoring, Handling and Equipment Monitoring, Geometry and Alignment System and Testbench system, among others. Currently, approximately 850 systems operate on WinCC OA at CERN. Some of them, like the PSEN (Electrical Supervision), manage 4 million DPEs (Data Point Elements ~ Variables) with a single server, in redundancy. The ATLAS experiment (one of the general-purpose detectors at the Large Hadron Collider, LHC) integrates about 130 systems and 12 million DPEs; WinCC OA also coordinates a common state machine across all the systems [46]. In other research facility as MIT Plasma Science and Fusion Center (PSFC), Ignition (from Inductive Automation) provides the Supervisory Control and Data Acquisition environment in their new superconducting magnet test facility for the SPARC Toroidal Field Model Coil (TFMC) program [47]. Another example of a particle accelerator research facility using an industrial SCADA is the ELBE Center for High-Power Radiation Sources, which uses commercial control systems based on WinCC as SCADA, PLCs, and fast data acquisition systems [48].

In many facilities that adopted open-source control frameworks such as EPICS, the decision was largely driven by the lack of viable industrial alternatives at the time of construction. Therefore, several of these research plants have also had to incorporate other solutions to satisfy all the new demanded functionalities apart from the proper local control [49], especially regarding data exploitation or fast monitoring needs, where the facilities must analyze and exploit the generated information from different systems in a rapid and consolidated way. For instance, Diamond Light Source beamlines use EPICS for low-level control, and the Java based Generic Data Acquisition (GDA) framework for the high-level user interface and data acquisition [50,51].

Similarly, the ESS has adopted an aggregation and streaming software architecture [52] based on Apache Kafka [53] to address the high-performance computing demands of neutron beam data processing. This architecture can cope with those high data rates and make them available to applications for data saving and live data reduction, while also providing feedback to the experiment control and visualization. On the other hand, slow metadata is obtained from devices using EPICS and sent to this framework by the Kafka bus. Complementary tools, such as InfluxDB [54] and Grafana [55], are employed to store and analyze data from radiation monitoring systems [56].

Other facilities have integrated other control frameworks. At DESY (Deutsches Elektronen-Synchrotron), integration efforts have focused on combining the TINE and DOOCS frameworks [57–60], the latter of which includes connectors for TANGO and EPICS. Similarly, the ALBA Synchrotron has promoted the deployment of the Taurus framework [61], a graphical user interface toolkit that is functionally analogous to

CSS/Phoebus [14] in the EPICS ecosystem, which can integrate and visualize information from TANGO and EPICS systems.

A noteworthy example of integration between a commercial SCADA and an open-source control framework is the initiative at ITER, where EPICS and WinCC OA have been integrated for connecting Intelligent Electronic Devices [62]. Additionally, ITER is developing the Integrated Modelling & Analysis Suite (IMAS) [63]. The Neutral Beam Test Facility (NBTF), specifically the SPIDER experiment focused on ion source development, also employs WinCC OA for its safety system [44].

At the Karlsruhe Research Accelerator, WinCC OA works as the overall SCADA for all beamlines, and allows the interconnection between different systems controlled by TANGO and EPICS respectively, providing a graphical user interface too [64].

Finally, it is also worth mentioning the case of Sirius, the Brazilian 4th generation synchrotron light source. In this facility, WinCC Unified is being adopted as the general supervisory system across scientific operations [65] to offer a simplified web visualization and concentrate the creation of alarms notifications. It will coordinate the data generated by different equipment, some controlled by EPICS and others using industrial protocols such as OPC UA provided by commercial automation systems. To facilitate interoperability, EPICS Process Variables (PVs) will be mapped and converted into OPC UA variables.

In summary, the current trends on the newest facilities show that the convergence of open-source frameworks with solutions coming from the automation industry is the most relevant approach in large and modern facilities. This study proposes an enhancement of the control architecture that maximizes scalability, interoperability, and standard compliance while reducing the complexity of the system design and infrastructure. This hybrid model seeks to maximize performance to address stringent demands for rapid signal processing and high-throughput data handling, while preserving the flexibility, modularity, and community-supported development characteristics of open-source platforms.

## 3. Control system alternatives for CICS and LICSs

Considering the possible combinations of technologies to implement the CICS and LICS systems, the following four main alternatives can be evaluated for the global architecture of the control systems:

### 3.1. EPICS as a unique control framework

In this option, the three CICS systems (CODAC, MPS and SCS) would be implemented using EPICS as well as all CODAC LICSs.

This alternative may conflict with the following assumptions:

- MPS and SCS are typically implemented using PLCs, fully supported by industrial SCADAs.
- Some LICSs could be implemented without using EPICS (especially on large facilities with in-kind contributions of different countries that complicated integration if a reference standard is not adopted).

### 3.2. Control framework functional division: the current DONES proposal

Regarding CICS, the current project design documents and specifications indicate that CODAC would be implemented in EPICS, but the MPS and SCS will use an industrial SCADA. Therefore, this would be a hybrid architecture. All LICSs would continue being implemented using EPICS. Fig. 2.1 shows an example of this configuration, where it can be noted the necessary inclusion of a new element that would act as a "gateway" for the communication between the two different technologies: EPICS for CODAC and an industrial SCADA for MPS and SCS.

This option implies to have all the LICSs talking EPICS protocol natively. But apparently it is expected to have non-EPICS LICSs too (e.g. Remote Handling, etc.). So, this possibility should be optimized to improve the control system homogeneity.

### 3.3. Alternative hybrid architecture frameworks

In this option, LICS may be implemented in EPICS and also using industry standard technologies (Non-EPICS). There are two sub-options here:

A. Unified Industrial SCADA

The three CICS systems (CODAC, MPS, SCS) would use the same industrial SCADA.

Some LICSs could be implemented using EPICS (e.g. Accelerator System LICSs), and others could directly use standard market technologies (such as PLCs) or COTs. Fig. 2.2 illustrates this alternative. In this scenario, the three CICS systems will communicate directly between them.

Another kind of gateway would also be needed here, but only for communication between the CODAC and the LICS implemented in EPICS.

B. Mixed technologies in CICS

In this scenario, CODAC would keep the original idea of being implemented in EPICS, and the MPS and SCS with industrial SCADA. However, some LICSs could be implemented using EPICS (e.g. Accelerator System LICSs) and others could use standard industrial technologies. Fig. 2.3 shows an example of this configuration. It is worth mentioning that this option would require not one but two different kinds of gateways, in different positions: the first, inside the CICS, to communicate the Central CODAC (in EPICS) with the MPS and SCS (an Industrial SCADA); the second, to communicate the Central CODAC with the LICSs that do not implement EPICS.

It is important to highlight that this architecture would request two different gateways in different positions. For that reason, this doesn't seem to be a very good option either.

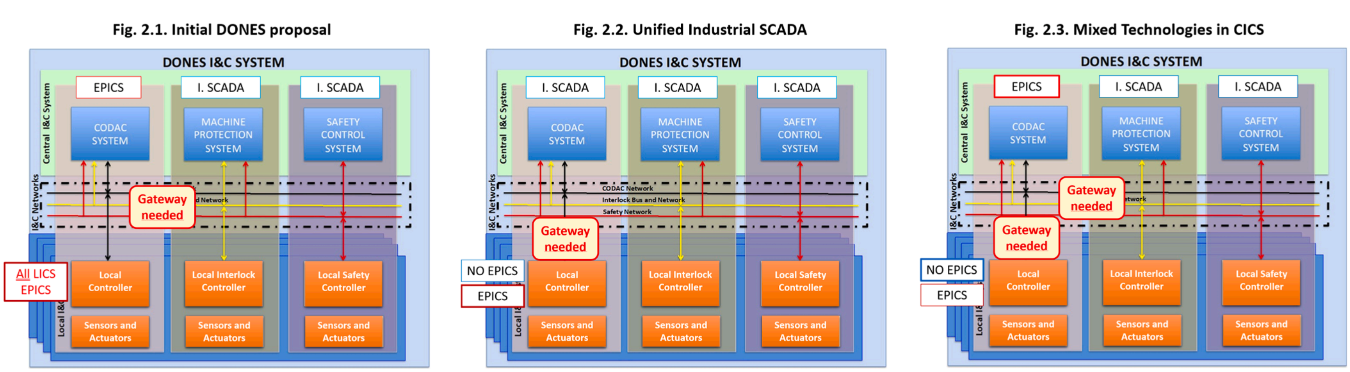


**Fig. 2.** Different required gateway positions in each hybrid scenario.

### 3.4. Everything using industrial frameworks (Non-EPICS solutions)

In this last option, CICS would also use a unified SCADA (CODAC, MPS, SCS), but no LICSs would implement EPICS (so EPICS would not be used at any place).

In the same line as option 1, this alternative also cannot be considered. Keeping flexibility for the facility's custom instruments is a key target, and this may require using open-source solutions like EPICS. Some feasibility studies should be performed to treat it as a viable option.

At this point it looks clear that the control systems of IFMIF-DONES should require a hybrid scenario. Since it will be requested to keep and connect two different control frameworks (EPICS and an industrial SCADA), any kind of gateway or tool able to talk and communicate with both "worlds" will be needed.

Fig. 2 illustrates the three feasible options indicated here, which show the different locations where the gateway would be needed in each hybrid option described.

## 4. Technology considerations for the IFMIF-DONES CODAC system

A comparative study was conducted to investigate the feasibility of using EPICS and other industrial SCADAs in IFMIF-DONES, especially in the CODAC framework. The study includes: (1) a list of desirable IT requirements for the IFMIF-DONES control systems; (2) how well the evaluated control platforms comply with these requirements; and (3) an economic assessment of the deployment cost of those different solutions, considering the entire system lifecycle and not only the license cost.

**The main findings of the study can be summarized as follows:**

1) It is strongly recommended to unify the SCADA framework by adopting an industrial SCADA solution for CODAC, MPS, and SCS. This would enhance practicality, operability, and functionality, while also avoiding potential bottlenecks in the CICS. Based on the analysis of various options, the results indicate that adopting one of the evaluated industrial SCADA platforms, such as WinCC OA, System Platform/Wonderware, Ignition or Atvise, to unify the management of CODAC, MPS and SCS would be more appropriate.
2) The license cost should not be taken as the only key decision factor. Although open-source software such as EPICS does not incur license costs, long-term economic assessments suggest that it may prove even more costly than commercial industrial solutions when factors such as implementation complexity, documentation accessibility, required management resources and potential risks are considered. Naturally, this conclusion is closely linked to the size and capacity of the engineering control team: large facilities may afford bigger teams and benefit from greater customization, whereas this is not always feasible for medium or small-scale facilities. If an industrial SCADA is already selected for MPS and SCS, extending its use to CODAC would result in only a marginal increase in overall cost, primarily due to the addition of more tags. In any case, the study showed that its adoption would be more cost-effective than EPICS in this context, even when considering the full scope of system deployment and lifecycle costs.
3) If meeting SIL3-like safety certification is a strong requirement for MPS and/or SCS, only some industrial SCADAs meet that requirement. It is important to note that several manufacturers indicate that SIL3 framework qualification should apply not to the SCADA system itself, but rather to the connected field devices. Their products are designed to support and interface with such certified devices. This proposal aligns that perspective. In particular, the requirement for SIL3 qualification has been deemed unnecessary for the CODAC system, provided that safety functions are correctly implemented and wired to certified low-level devices. This approach broadens the range of viable industrial SCADA solutions for the remaining systems.

In addition, other considerations must be taken into account for the selection of technologies in the architecture design for CODAC (and in general for CICS):

- Central CODAC must coordinate the LICS at a high level and communicate with MPS and SCS. Additionally, it may interface with advanced analytical tools, artificial intelligence systems, modeling platforms, and real-time digital twins. This represents a strong argument in favor of adopting widely accepted technologies and standard communication protocols for CODAC, in order to facilitate integration, enhance interoperability, and minimize potential communication bottlenecks.
- Within the EPICS framework, the main CODAC subsystems (such as HMI, Alarm & Warning, and Data Management) are primarily provided and managed through CSS/Phoebus (Phoebus being the latest version of CSS). This is a Java-based framework and toolset designed to be installed on operator PCs to monitor and operate EPICS control systems. Although Phoebus is a powerful tool within the EPICS environment, it is tightly bound to EPICS-specific protocols (CA/PVA) and is not designed to operate as a high-availability service for multiple concurrent users. Moreover, it lacks adaptation to modern HMI platforms, such as tablets, smartphones, or fully native web interfaces, as indicated in [66] and [67]. In contrast, contemporary industrial SCADA systems offer significantly higher performance, interoperability, and functionality. They also provide better scalability, enhanced security management capabilities, and broader support for standardization and integration with other tools, protocols, and system features that are increasingly essential for fulfilling CODAC's evolving requirements.

On the other hand, EPICS is a solution that has been commonly used in the field of accelerators and scientific facilities, including LIPAc (i.e. the main reference for the IFMIF-DONES accelerator). Therefore, some LICS systems are expected to be deployed using this technology (e.g. the Accelerator Systems).

For these reasons, the current study proposes a hybrid architecture that preserves interoperability with EPICS modules, enabling researchers to access and manage EPICS PVs or OPIs from those LICSs that implement EPICS.

## 5. Proposed enhanced CODAC architecture design in relation to CICS and LICS

In this work a unified control framework for IFMIF-DONES is presented, with the capability of seamlessly integrating source modules from EPICS with industrial blocks. This is possible because of the development of an architecture strongly supported by interoperability standards (such as OPC UA) that are widely supported by all industrial tools. In addition, the EPICS / Industrial SCADA bidirectional gateway is a unique component. This new element integrates into the architecture, enabling interoperability between both frameworks.

The impact of this approach could be significant. On the one hand, it brings all the benefits of the open-source tools (today EPICS, but TANGO may be addressed in the future too) to the industrial ecosystem. It leverages all the advantages of EPICS as described in [68] and contributes strongly to integrate all the previous experience of the fusion and particle accelerator community with this technology. This enables code reuse where possible and simplifies the development of fully customized subsystems.

On the other hand, EPICS can now be supported by many other monitoring, visualization, database or data analysis tools that are included in modern SCADAs. AI tools can also be integrated into this proposed architecture without the need to develop custom tools for such processes. Thus, the integration of open-source frameworks and industrial SCADAs brings together the best of both worlds, reducing costs, time to market, and enabling a level of modularity and integration previously unattainable.

The bases of the proposed architecture are as follows:

- Use a unified industrial SCADA for CODAC, MPS and SCS.
- Allow the LICS to be implemented in EPICS or by means of other standard technologies and protocols.
- Only use standard-based gateways if they are strictly necessary.
- Improve time responses and provide high availability whenever possible.

This aligns with what was described in Section 3 Option 3.A (Unified Industrial SCADA). Fig. 3 illustrates the proposed new architecture for CODAC within the CICS/LICS scope of IFMIF-DONES.

### 5.1. Description and details of the proposed architecture

The EPICS / Industrial SCADA gateway is a key element of the presented architecture. In Fig. 3, it is placed within the Control and Data Communication module in the CODAC system. Any communication between an EPICS component and the central CODAC system should pass through this gateway; however, different options are available for its use and scaling. A more detailed explanation of this gateway is provided in the next section.

This gateway will not be required for communication between Central CODAC and Non-EPICS LICS. These interactions can be performed using the OPC UA protocol or any other driver/protocol supported by both the SCADA and LICS devices involved (for instance, S7 for communication with Siemens PLCs). For each case, the fastest and most efficient option should be selected.

Regarding the other components, it should be clarified that the schema implicitly assumes internal communication and processing among the local components within a LICS, especially for Timing signals. Conversely, there will be no direct communication among different LICSs (all communication among LICSs must pass by the CICS).

Another important point to emphasize is that this proposal includes a field bus (such as EtherCAT or Profinet) connecting the LICS and the internal CICS system (CODAC, MPS and SCS). The architecture also represents connections for slow, fast and superfast (hardwired) signals from LICSs to MPS and SCS systems. Redundancy is considered where required in each case. Note that network devices, VLANs, subnetting, etc., are not included in the architecture (only the required types of connections are specified). Three different network connections to the LICSs are planned for the CODAC:

- One (shared) for everything related to Supervision and Central Control Subsystem, Alarm and Warning Subsystem, Human Machine Interface and common information to be stored by the Data Management Subsystem.
- One for the Timing Subsystem.
- One for special and massive data (raw data from fast controllers, internal sensor variables or any other kind of information not managed at CICS level but useful for optimization and prediction maintenance) to the Data Management Subsystem too.

A key objective of this architecture is to be "AI-ready" (prepared to incorporate Artificial Intelligence components). The massive data network would facilitate the transmission of heavy volumes of data and simultaneously allow the on-line updating of intelligent controllers and the edge-computing [69].

Finally, regarding EPICS, it should be noted that the essence of this architecture is to replace the use of CSS/Phoebus in Central CODAC services with an industrial SCADA. This will allow each LICS to be implemented using the most suitable technology (EPICS or another industrial standard). In the future, common rules and specifications for LICS design and technology could be established differently, but the architecture itself does not impose any technology constraints.

### 5.2. The EPICS / industrial SCADA gateway

As already mentioned, a hybrid architecture is being implemented,

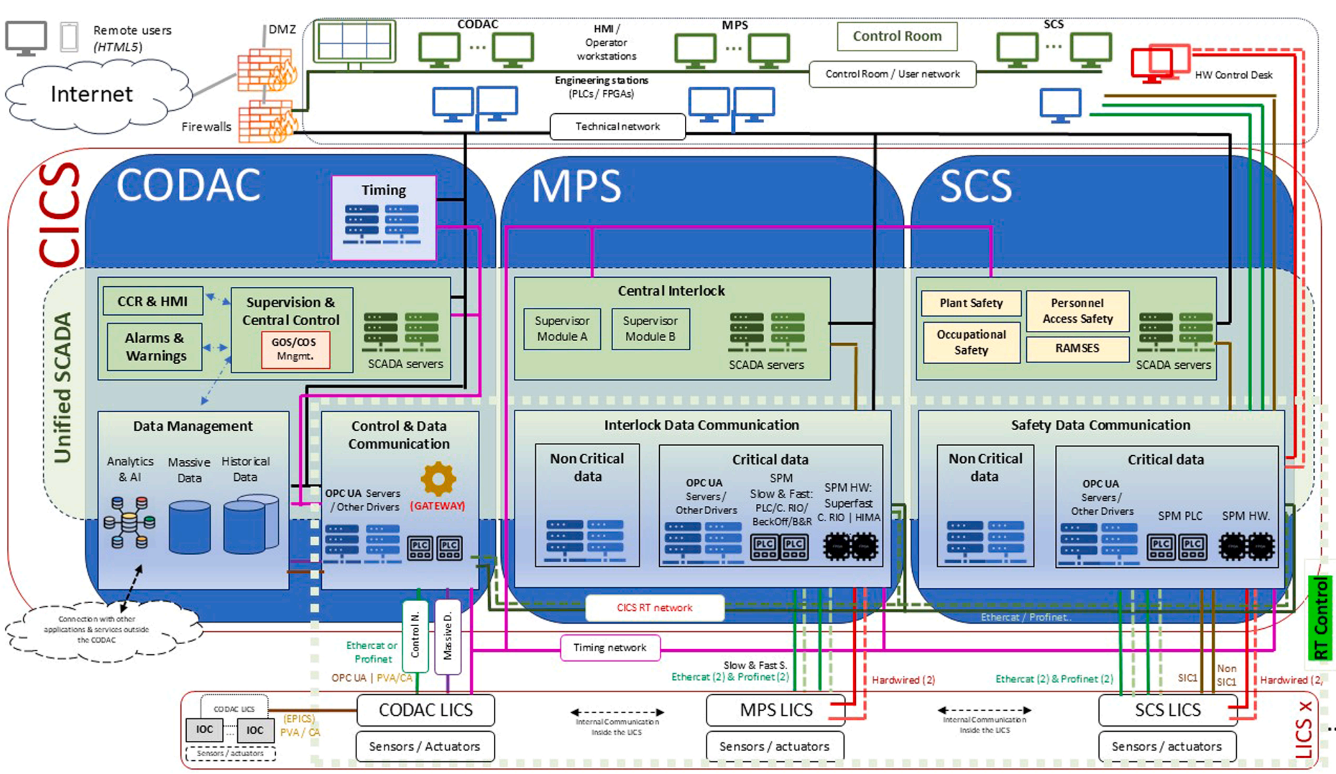


**Fig. 3.** Schema of the general new hybrid architecture proposed for the IFMIF-DONES control systems.

so a solution is required to enable communication between both frameworks: an industrial SCADA and EPICS.

Different options for this type of gateway could be explored within this scope:

- Develop an OPC UA Server capable of communicating with the EPICS PVA (PV Access) protocol.
- Develop a specific EPICS driver for the selected SCADA.
- Deploy a Kafka bus (or alternatively other message protocols like MQTT).
- Use the existing EPICS device support for OPC UA module [70,71].

The existing EPICS device support for OPC UA module is certainly a very useful tool; however, it is important to clarify that it principally acts as an OPC UA client. In general terms, it facilitates connecting devices that use the OPC UA protocol to the EPICS channel. In contrast, the proposed architecture requires connecting all EPICS systems and devices operating in PVA (channel bus, IOCs, etc.) to the rest of the control systems via one or more gateways (which would function as OPC UA servers if that is the case) to enable bidirectional interaction: this is the core requirement.

Apache Kafka is another promising technology suitable for this scope, particularly for the fast processing of events. It could even coexist with OPC UA servers for different purposes. Alternatively, developing a specific driver will depend on the selected SCADA and its available APIs, but a very good performance would be foreseen in each case because of the direct connection. Further research is recommended to test and compare these alternatives.

Although it is suggested that future works analyze all these alternatives, with the best one chosen based on performance and functionality for the IFMIF-DONES control system, this study needs to consider the use of one of them as the key component to communicate both frameworks. Following this line, the development of an OPC UA Server for the EPICS protocol (PVA) has been identified, as it offers two main advantages that can be anticipated:

- OPC UA is an industry standard (IEC62541).
- It would greatly expand EPICS's communication capabilities with other OPC UA frameworks and systems (not just a specified SCADA). For instance, most modern industrial SCADAs support OPC UA, as do many other systems capable of acting as OPC UA clients, such as Remote Handling, Virtual Reality tools, Enterprise Resource Planning (ERP) systems, cloud service providers and many more. Therefore, this gateway's functional scope would be broader because it will actually be an EPICS / OPC UA gateway.

The main components of this OPC UA server for PVA EPICS protocol could be a base OPC UA server SDK working as template (as the Open 62541 [72] or the one from Unified Automation) [73], the EPICS API PVXS (Gen 2) [74], and the proper custom developments to tailor the desired functionalities. Fig. 4 shows a basic schema of its components.

Among other benefits, the following key features could be expected:

- Bidirectional communication between OPC UA and EPICS PVs.
- Adaptability to filter and manage traffic based on networks, LICS, or other IP criteria.
- Automatic discovering of PVs.
- Hierarchical PV tree structure that enables plant modeling by system/subsystem, IOC IPs, or other logical groupings.

Performance, interoperability and scalability will be key properties for its suitability to the IFMIF-DONES environment.

Finally, regarding the position of the gateway, the two different approaches are equally valid: one or more centralized OPC UA servers deployed within the central CODAC or, alternatively, a separate gateway for each LICS or system using EPICS.

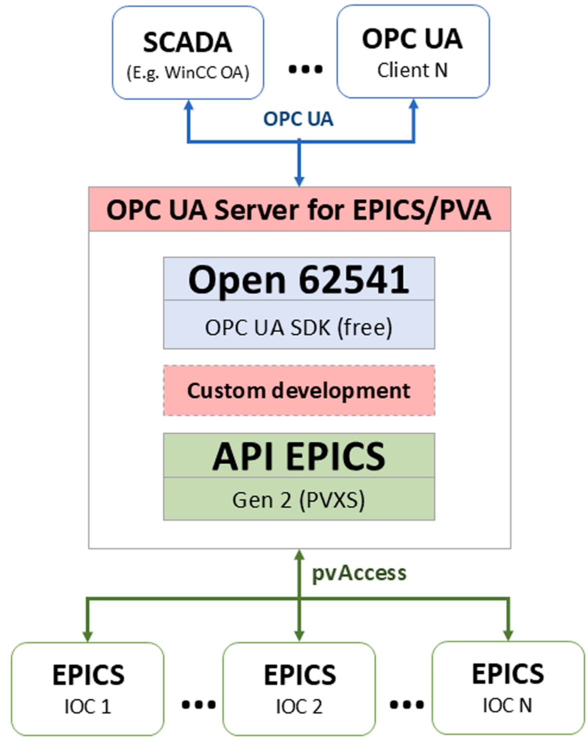


**Fig. 4.** Brief schema of the proposed OPC UA Server for EPICS PVA.

### *5.3. Advantages of the proposed architecture*

The proposed general architecture enables the CODAC system to benefit from a modern control framework while avoiding bottlenecks within the CICS. Simultaneously, it still allows the use of EPICS where it excels, namely, in local control; leveraging its proven efficiency and extensive experience gained through LIPAc and in other facilities.

Additionally, using a unified technology in the CODAC simplifies infrastructure and management tasks related to storage systems, databases, backup systems, interface designs, data analysis integration and AI tools. The project can achieve significant cost savings by avoiding the need to duplicate systems and effort. Notably, while some facilities have extended EPICS capabilities by layering custom developments, this proposal emphasizes maximizing the use of modern industrial products and open standards.

Modern SCADAs offer a great variety of protocols, drivers and ways of connection, and all LICSs should be able to communicate with the central CODAC using one of the available alternatives. For every connected device, the fastest or most efficient communication method should be selected. Nevertheless, for compatibility and standardization reasons, it is recommended that, whenever possible, LICSs support OPC UA at a minimum, as it is a consolidated industry standard nowadays.

Additionally, the proposed architecture opens the door to new proposals, developments and improvements within EPICS, such as the previously mentioned e3 framework. This type of framework could be used for the IOC (Input/Output Controllers) management in LICSs implementing EPICS (Accelerator Systems or others).

Regarding the CODAC subsystems, these are the main advantages of modern SCADAs that can be outlined in each case:

1) Alarms & Warnings Subsystem (AWS): Industrial SCADAs incorporate complete, flexible and powerful alarm management systems, such as WinCC OA, that is compliance with alarm industry standards, such as VDI 3699, DIN 19235 or OPC UA alarms and conditions [68].
2) Data Management Subsystem (DMS): Modern SCADAs offer a variety of integrated tools for historical data management, advanced

analytics, and so on. Apart from being compatible with most of the standard databases in the market (the exact list depends on each solution, but for instance, WinCC OA can support Oracle, PostgreSQL, InfluxDB, Microsoft SQL or others via API). In addition, they can be easily connected to other systems, cloud solutions, etc. [19]. On the other hand, regarding the storage of historical data, especially for fast signal processing, generating data archives directly to disk should be considered. Therefore, to be able to work with that data in the future, the need to parse those files and pass the data to tables where it can be exploited by standard tools is forecasted.

3) Central Control Room Equipment and Human-Machine Interface Subsystem (CRS): Industrial SCADAs incorporate stronger solutions for the graphic user interface, HTML interfaces, support for tablets, smartphones, and modern devices, a more robust security management and access permissions [8,22–26]. This subsystem will also be responsible for presenting the HMI of MPS and SCS, which are recommended to be implemented using an industrial SCADA as well.
4) Supervision & Central Control Subsystem (SCC): In this subsystem, the Global Operation States management of the plant must be taken into consideration, which will be in coordination with the Local Operation States from LICS. That will imply managing a high-level workflow, considering tasks, recipes, etc. interacting with global and local states and variables. Most modern SCADA can easily connect this kind of tools (for instance, the newest version of WinCC OA incorporates Node.js, Node-RED [75], and other additional modules). In any case, it is recommended that strict control functions be delegated to appropriate devices (such as central PLCs or NI Compact Rio, etc.), which can be configured using engineering stations or specific tools (as TIA Portal [76] of Siemens PLCs).
5) Control and Data Communication Subsystem (CDCS): Modern SCADA solutions offer a wide range of protocols and drivers, not only for connecting various types of devices, including PLCs and FPGAs, but also for integrating with other systems through industry-standard protocols, such as OPC UA [77]. This facilitates the interconnection with data analysis and artificial intelligence tools, remote handling and virtual reality applications, modeling and digital twin systems, cloud solutions, etc., as it is expected to incorporate to this facility.
6) Timing Subsystem (TS): This subsystem is planned to be implemented separately using its own technology. However, under the proposed architecture, Time Sensitive Networking (TSN) is a technology that could be suggested and studied in the future as a promising way to unify the control, timing and interlock networks [78]. The use of this technology would simplify the network design with the implied cost savings and ensuring of deterministic communications.

Finally, a key advantage of this architecture is its support for real-time control within a unified framework. This is made possible by the proposed common fieldbus connecting the LICS to the inner CICS components, namely, the CODAC, MPS, and SCS. This shared fieldbus enables deterministic signal transmission across the three subsystems. In such cases, control functions should be handled by appropriate real-time capable devices (e.g., central PLCs or NI CompactRIO systems).

However, it should be noted that LICSs implemented using EPICS would not be capable of real-time operation in this context due to the nature of the PVA protocol, which is based on TCP/UDP and not suitable for deterministic timing. Nonetheless, these systems would still be integrated into the overall architecture via the proposed EPICS / Industrial SCADA gateway.

## 6. Conclusions

This study was developed within the framework of the ambitious IFMIF-DONES project. First, a comprehensive analysis of the control frameworks used for different facilities has been carried out. A detailed overview of the current landscape, highlighting the key challenges faced by different approaches and identifying common constraints that hinder the implementation of more advanced features, has been presented. Although the study was initially focused on the IFMIF-DONES plant, the findings and proposed solutions may be generalized to offer potential value to a broader range of facilities.

As a solution, an enhanced architecture for the CODAC system in relation to the CICS and LICS is proposed. This architecture enables the effective coexistence of an industrial SCADA and EPICS, leveraging each's unique strengths while facilitating seamless integration, interoperability, and system standardization. The main recommendation of this study is to adopt a unified industrial SCADA for the CICS (CODAC, MPS and SCS) and to use EPICS for local control in the determined LICS whereas other LICS could also be implemented using other standard technologies. CODAC would no longer be limited to EPICS-native protocols (CA/PVA) nor constrained by the performance of intermediary communication bridges with this approach. Instead, it could offer high availability, support simultaneous multi-user access, and enable connectivity through various devices and interfaces. The trade-off for this flexibility is the need to develop an EPICS / Industrial SCADA gateway. However, this is a well-defined engineering task that can realistically be achieved within a limited timeframe and with reasonable resource investment.

This architecture might maximize the respective strengths of both frameworks by integrating an industrial SCADA at the CODAC level and using EPICS at the local control level. Industrial SCADA systems have modern features such as standardized protocols, interoperability, high availability, security, advanced data management, and compatibility with AI and cloud-based tools. Meanwhile, EPICS provides a robust, field-proven platform with deep community expertise, that is particularly suited for controlling scientific instruments. As discussed, the key to enable integration between these frameworks is the EPICS / Industrial SCADA gateway. Specifically, the proposed OPC UA Server for the EPICS PVA protocol, introduced in this study is a promising solution.

This alternative architecture also offers the potential to integrate EPICS with other control frameworks and systems. The main advantages of this proposal can be summarized as follows:

- Industrial SCADA and EPICS can effectively coexist, by leveraging their respective strengths and features while facilitating the integration of diverse technologies and standardizing systems and protocols.
- The architecture simplifies the system design and reduces the number of components, resulting in cost savings.
- Bottlenecks are removed from the CICS, improving system efficiency.
- Real-time control is enabled in both the CICS and LICSs, ensuring deterministic operation.
- The system supports modern devices and interfaces, thereby improving user interaction and accessibility.
- The proposed architecture is interoperable with several data analysis tools and databases and is ready to integrate AI-driven capabilities.

Finally, it must be underlined that the approach presented here primary focuses on technical considerations. However, the control systems to be developed for IFMIF-DONES may require additional considerations based on the available resources and the team's expertise in the future development and integration of the control framework.

This study provides a complementary perspective on the control system architecture for IFMIF-DONES, exploring the potential integration of industrial SCADA frameworks alongside EPICS. This does not exclude the possibility of adopting an all-EPICS control architecture, which remains a viable option. The final decision regarding the control system implementation will be taken by the responsible agency at the appropriate stage of the project, when the facility is ready for deployment. By that time, further technological advancements and validated results may offer new insights and justify alternative design choices.

Future work will focus on setting up an experimental reference design based on this architecture, taking the EPICS / Industrial SCADA gateways as key elements. This validation will involve many development actions to numerically estimate the performance of the proposed solution. For example, alternative communication methods between industrial SCADA and EPICS, such as specific EPICS driver for the selected SCADA, may be investigated. Alternatively, a Kafka bus may be implemented, or the EPICS device support module for OPC UA may be further tested.

Another interesting element to be further studied is TSN. This technology could simplify network design, leading to cost savings and it would be worthwhile to investigate its benefits for deterministic communication. Experimental work will be required to demonstrate the advantages of these networks. Lastly, all these actions could be validated through a proof of concept applied to LIPAc, where the selected industrial SCADA may be combined with the existing EPICS modules.

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## CRediT authorship contribution statement

**Javier Cruz-Miranda:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Miguel Damas:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Eusebio N. Al-Soliman:** Visualization, Validation, Software, Resources. **Javier Díaz:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Mauro Cappelli:** Writing – review & editing, Supervision, Project administration.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data that has been used is confidential.

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