



Advancements in central control for IFMIF-DONES: Integrating CODAC, MPS, and SCS into a unified control framework

M. Cappelli^{a,*}, F. Ambi^b, E. Botta^b, J. Cruz^c, J. Diaz^c, Z. Chen^d, D. Dwojewski^e,
M. Giacchini^f, V. Gutierrez^g, R. Lorenzo^h, M. Montis^g, J. Sousaⁱ, A. Ibarra^h

^a ENEA, Frascati Research Center, Rome, Italy

^b Ansaldo Nucleare, Genova, Italy

^c University of Granada, Granada, Spain

^d University of Aalborg, Aalborg, Denmark

^e S2 Innovations, Krakow, Poland

^f INFN, Legnaro Research Center, Padova, Italy

^g CIEMAT, Madrid, Spain

^h IFMIF-DONES, Granada, Spain

ⁱ IPFN, Lisbon, Portugal

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ABSTRACT

The International Fusion Materials Irradiation Facility-DEMO—Oriented Neutron Source (IFMIF-DONES) represents a cutting-edge accelerator-based neutron source designed to produce high-energy neutrons for the irradiation of materials intended for use in DEMO, the future fusion reactor. Given the complexity of such a facility, a robust central control system is indispensable to ensure safe supervision and management of all operations. This paper provides an overview of recent advancements in the design of the Central Instrumentation and Control Systems (CICS) for IFMIF-DONES, focusing on the transition to the definition design phase. Employing a distributed approach, the architecture utilizes fast devices and dedicated networks for real-time communication among control units. This paper outlines the current status of the design for each CICS system and discusses existing and future plans for their integration into a unified control framework. The ongoing effort to integrate all CICS systems into a cohesive framework faces various challenges, such as data acquisition synchronization and interlock management. The integration of subsystems within CICS may be powerfully enhanced using artificial intelligence tools by enabling data-driven decision-making, proactive maintenance, adaptive control, and intelligent optimization.

1. Introduction

In future fusion power plants, the irradiation environment is primarily characterized by the presence of high-energy neutrons in the first-wall region [1]. For the DEMONstration Fusion Reactor (DEMO), in-vessel materials will face neutron fluxes reaching up to $5 \times 10^{18} \text{ m}^{-2} \text{ s}^{-1}$ at a peak energy of 14.1 MeV. This environment may result in displacement damage exceeding 10 dpa per year and a helium production rate of 10^{-13} appm/dpa, making the availability of a fusion-relevant neutron source a critical requirement for safe reactor design [2].

However, current neutron sources are incapable of replicating such conditions. An accelerator-based neutron source utilizing Dd-Li stripping processes (Li(d,nx)) has been widely recognized as the most

suitable option for delivering the required neutron flux and spectrum [3, 4]. To address this, the European Union has funded the development of a Li(d,nx) neutron source, IFMIF-DONES (International Fusion Materials Irradiation Facility-DEMO Oriented Neutron Source), under the EUROfusion Work Package Early Neutron Source (WPENS). This initiative aligns with the EU Roadmap [5].

The current design of the IFMIF-DONES facility is structured around five main systems: accelerator systems, lithium systems, test systems, plant systems, and central instrumentation and control systems [6–8]. The Accelerator Systems (AS) generate a 5 MW deuteron beam (125 mA, 40 MeV) with a rectangular cross-section of 100–200 mm x 50 mm. This beam is directed onto a free-surface liquid lithium target (25 mm thick, 260 mm wide) flowing at 15 m/s. The Lithium Systems (LS) handle

* Corresponding author.

E-mail address: mauro.cappelli@enea.it (M. Cappelli).

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lithium flow control, heat removal, and purification, supporting the High Flux Test Module (HFTM) of the Test Systems (TS), which houses material samples subjected to stripping reactions. The Instrumentation and Control (I&C) System, whose design evolution is extensively described in [9–12], manages all plant operations and integrates with general services classified as Plant Systems (PS).

This paper provides a comprehensive overview of the current design of the Central Instrumentation and Control Systems (CICS), emphasizing existing challenges and future plans for their integration into a unified control framework.

2. The central instrumentation and control systems (CICS): general architecture

The DONES I&C System follows a hierarchical architecture, extending from the top-level Central Instrumentation and Control Systems (CICS) down to the Local Instrumentation and Control Subsystems (LICS) [13], similar to the structures used in other experimental facilities, such as ITER [14–16] and other contemporary I&C designs for tokamaks [17].

Large-scale nuclear fusion facilities such as ITER, JET, and LIPAC have adopted varying strategies for their Instrumentation and Control (I&C) systems, each tailored to their specific technical and operational contexts. ITER has implemented a hierarchical architecture based on the CODAC Core System, which standardizes the use of EPICS for plant-wide control while promoting modularity and interoperability. JET, being one of the earliest large-scale fusion experiments, employs a more heterogeneous control environment, integrating legacy systems with modernized SCADA solutions and custom interfaces. LIPAC, on the other hand, relies heavily on EPICS for its distributed control needs, with extensive experience accumulated in the configuration of Input/Output Controllers (IOCs) and the integration of diagnostics and protection systems. Despite these advancements, challenges remain in achieving seamless integration, real-time performance, and scalable interoperability—particularly when extending functionalities toward AI-based

analytics, digital twins, or cloud integration. The architecture proposed in this paper aims to address these challenges by combining the robustness of industrial SCADA platforms with the proven flexibility of EPICS, interconnected through a dedicated OPC UA gateway.

The CICS comprise multiple subsystems, each capable of performing complex tasks autonomously. By employing a distributed control approach, the design ensures localized autonomy for individual subsystems while maintaining centralized oversight and coordination through the CICS. The CICS are responsible for the centralized management, monitoring, and control of all plant parameters and variables. Additionally, they handle data storage and visualization from a holistic system perspective.

To achieve this, the CICS leverage a suite of supervisory tools that enable continuous two-way communication with the LICS (Fig. 1). This design ensures seamless synchronization between local independence and centralized supervision.

It is important to note that "sensors" and "actuators" are used here as general terms, with their actual implementation varying depending on the system. These can include simple devices such as thermocouples, flow meters, pressure gauges, or radiation monitors, as well as more complex diagnostic tools. Typical actuators include electromagnetic pumps, valves, and motors. A detailed description of these instruments is outside the scope of this paper. The raw data collected from these devices are processed and converted into process variables, which are then made available throughout the entire plant. The Local Instrumentation and Control Systems (LICS) are responsible for managing every subsystem and component to ensure that process variables stay within the required range at the local level. I&C systems generally feature a Human-Machine Interface (HMI) and operational monitoring capabilities across different levels of the hierarchy.

As shown in Fig. 2, the CICS consists of three functional systems: the Control Data Access and Communication (CODAC) System, the Machine Protection System (MPS), and the Safety Control System (SCS). Each of these systems, at the central level, is in continuous or discontinuous, monodirectional or bidirectional communication with the

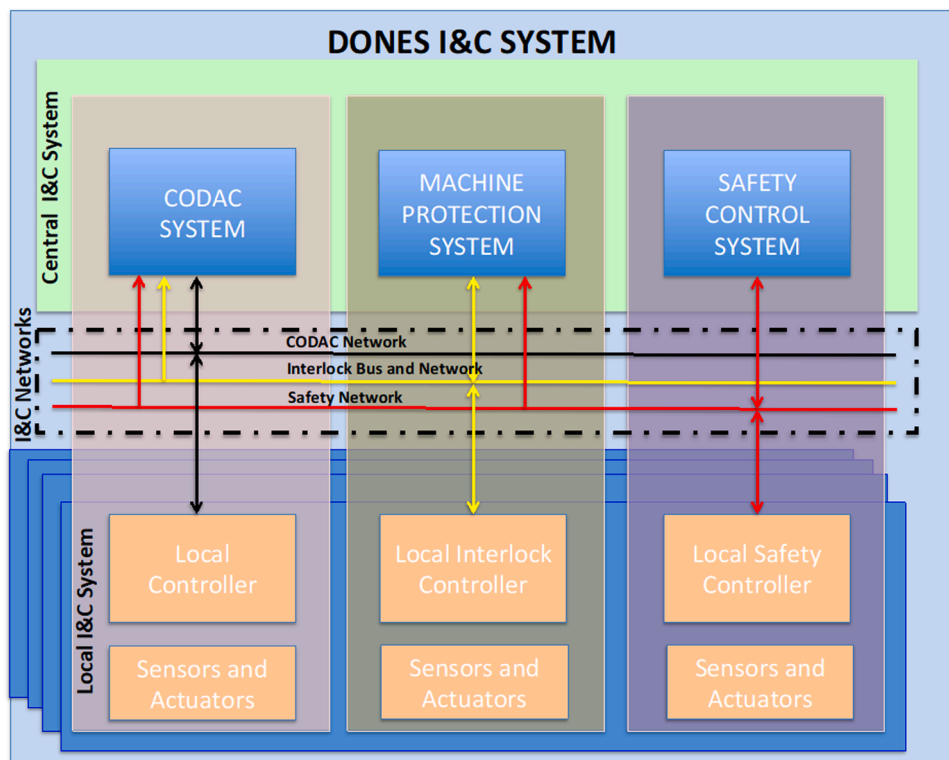


Fig. 1. DONES I&C systems: general top level architecture [12].

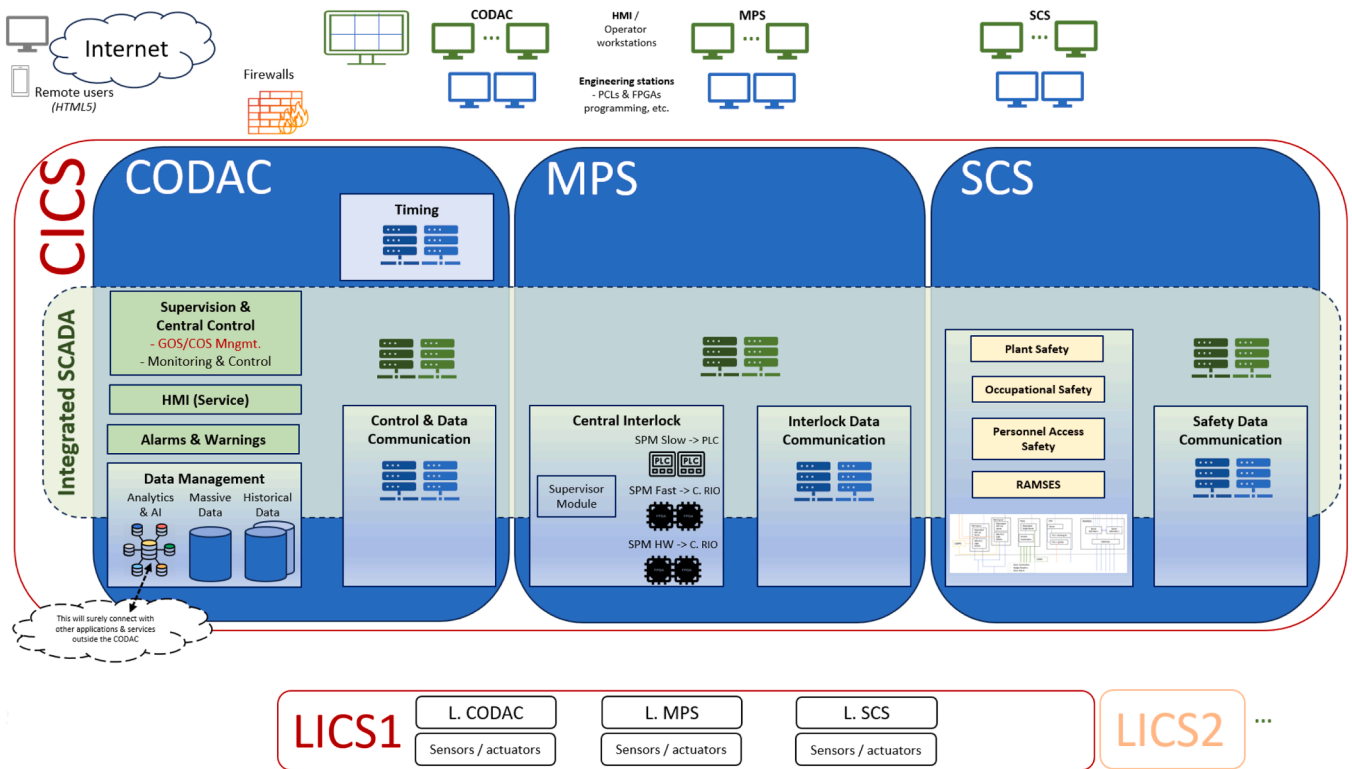


Fig. 2. DONES I&C systems: central and local architecture perspective as a base for the integration.

corresponding system at the local level through specific networks and buses. A comprehensive overview of the CODAC, MPS, and SCS can be found in references [9–12], while an extended, updated summary of the design of the entire DONES control system and its communication networks is described in [25].

3. The central instrumentation and control systems (CICS): recent advancement of the main systems

In Fig. 2 the recent advancements of the CICS architecture with a detailed decomposition of the three systems is presented. In what follows the main results of the current design for the three main systems (CODAC, MPS, SCS) are reported.

3.1. Control data access and communication (CODAC) system

The CODAC System is a key component of the Central Instrumentation and Control System (CICS) for IFMIF-DONES, responsible for managing and synchronizing local control systems and collecting and archiving plant data. CODAC coordinates technical systems such as the Accelerator, Lithium, Target, and Plant Systems, ensuring configuration, synchronization, and data retrieval. Its functions include monitoring, data collection, system status display, automated tasks, alarm management, and connection with the Machine Protection and Safety Control Systems. Comprising six subsystems—Supervision and Central Control, Timing, Data Management, Central Control Room and Human-Machine Interface, Alarms and Warnings, and Control and Data Communication—CODAC acts as the central hub for integrated control, monitoring, and data management across IFMIF-DONES operations.

In Fig. 3a scheme of the main CODAC components and its interfaces with the local controllers is reported. It should be observed that two control frameworks are required by the current architecture for IFMIF-DONES systems: EPICS (Experimental Physics and Industrial Control System) [18] and an industrial SCADA.

Indeed, the primary control framework for the CODAC local control

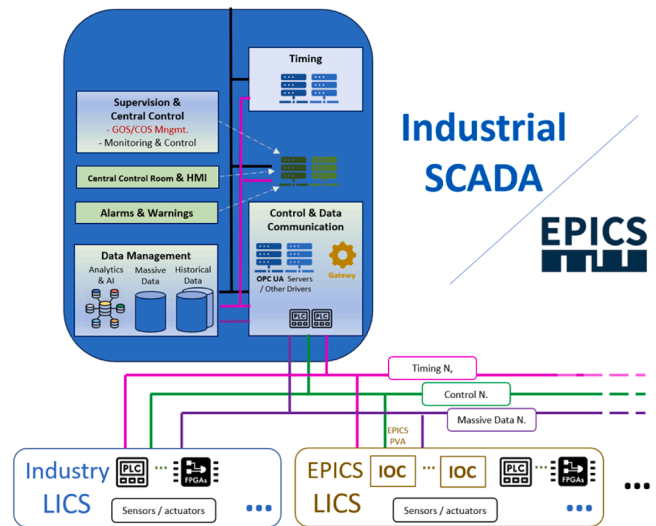


Fig. 3. CODAC system: central and local architecture and interfaces.

is the EPICS infrastructure, an open-source platform released in 1994 and made freely available in 2004. The choice to use EPICS stems from its widespread adoption in particle accelerator control systems, including successful implementation in the LIPAc prototype in Japan.

Industrial SCADA systems have evolved significantly, now integrating advanced technologies such as OPC UA, HTML5, IoT connectivity, cloud integration, and support for AI and machine learning tools. They also offer enhanced security features, native support for industrial communication protocols, and increased interoperability.

Given this evolution, integrating EPICS-based Local Instrumentation and Control Subsystems (LICS) with industrial SCADA solutions via standard protocols becomes a key design requirement. Simultaneously, for conventional control systems (e.g., HVAC, EPS), high-level safety

subsystems (such as SCS and MPS), and various CODAC services (including HMI, alarm management, and data handling), industrial SCADA may offer a more suitable solution. However, adopting such a hybrid control framework introduces notable integration challenges, as discussed in Section 4.

3.2. Machine protection system (MPS)

The Machine Protection System (MPS) safeguards the IFMIF-DONES plant against system and equipment failures, control system errors, and incorrect operations through dedicated sensors, actuators, and high-integrity logic solvers. Its role is strictly focused on investment protection, while safety measures for environmental, occupational, and human health are managed by the Safety Control System.

The MPS follows a two-tier architecture consisting of the Central Machine Protection System (CMPS) and Local Machine Protection Systems (LMPSs). The CMPS coordinates plant-wide protection actions, detecting, processing, and managing interlock events across systems. For example, it can rapidly shut down the beam to protect the Accelerator Systems and the Target Assembly. LMPSs handle subsystem-level failures and protection functions, communicating critical protection data with the CMPS to ensure system-wide integration and response to faults (Fig. 4).

The Central Machine Protection System (CMPS) is organized into three separated interlock subsystems based on the total time response requirements related to the importance of the equipment to be protected: slow interlocks (above 300 ms), fast interlocks (below 300 ms), and superfast interlocks (below 30 μs). The superfast interlock architecture enables rapid actuation of protection functions.

The CMPS is modular, comprising the Supervisor Module, System Protection Modules (SPMs), and the CODAC Interface Module. Additional LMPSs can be added with minimal changes to SPMs and modules can be modified or disconnected while maintaining other CMPS functions.

MPS technologies have been selected by applying fail-safe criteria according to industry 4.0 (or 5.0) guidelines, which emphasize robust cybersecurity measures, secure hardware and software configurations, and comprehensive risk assessments throughout the machine lifecycle.

While the CMPS's modular, fail-safe design and progressive integration capabilities provide significant advantages, careful attention is to be paid to the potential challenges in integrating diverse control frameworks and ensuring seamless operation across local and central systems.

The main integration considerations and challenges are:

1. Local-Central Integration:

Directly connecting local sensors and actuators to the CMPS FPGA within the superfast architecture can streamline protection functions, though it bypasses local controllers. Because such direct actions might overlap with independent and parallel safety mechanisms triggered by the SCS, they should be strictly limited to protection functions that have been demonstrably validated a priori to consistently transition the plant to a 'safe state'.

2. Integration of Different Control Frameworks:

The CMPS relies on the CODAC Interface Module for interfacing with

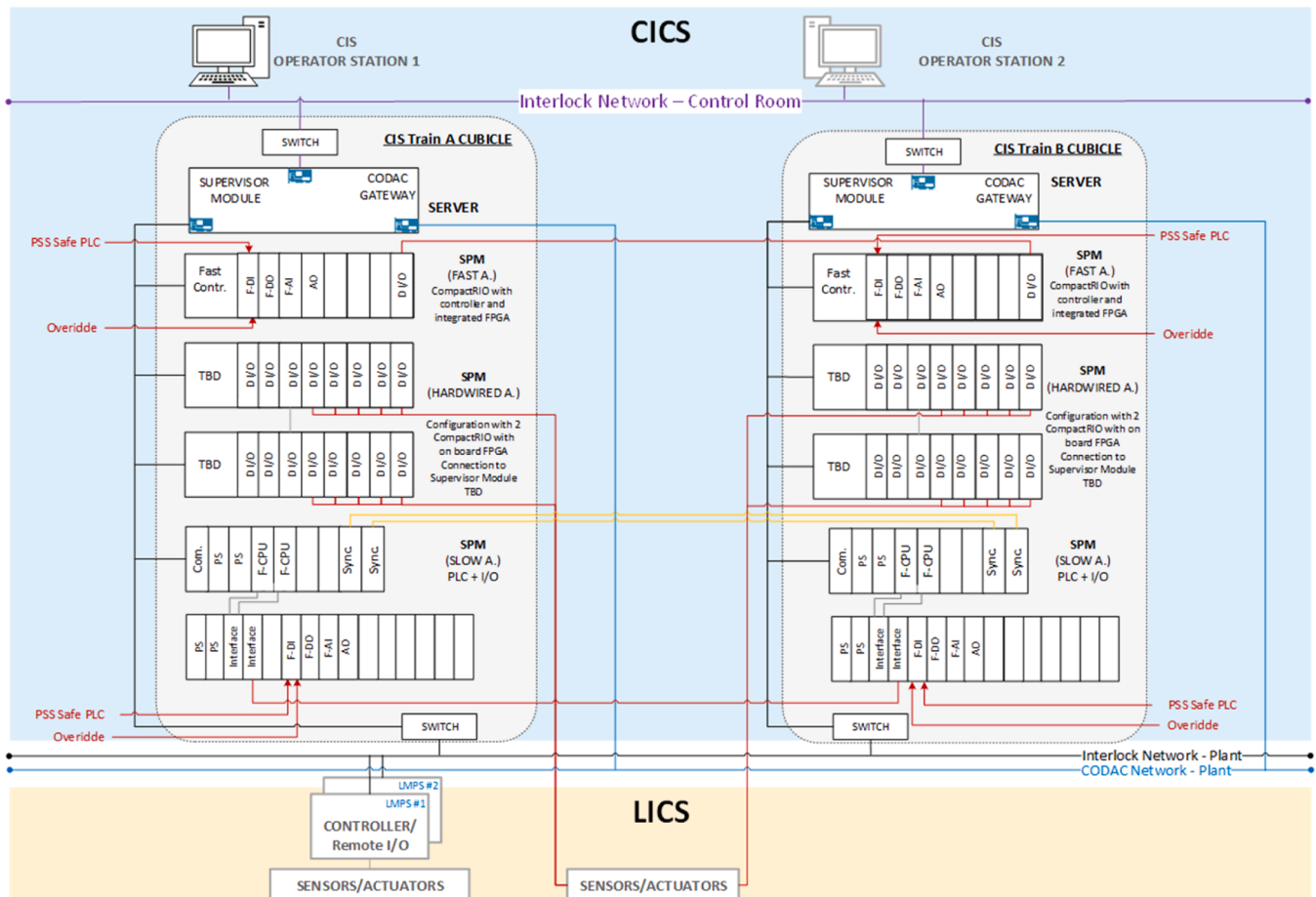


Fig. 4. Local versus central protection functions and redundancy.

CODAC, while some LMPSS may use industrial SCADA systems. This hybrid framework necessitates robust gateways to manage communication, which could introduce delays, protocol mismatches, or bottlenecks.

3. Modularity and Progressive Commissioning:

While the modular design supports incremental integration, adding new LMPSS or modules might require rigorous testing to ensure compatibility without affecting the existing system’s stability.

4. Fail-Safe Operations:

Ensuring fail-safe functionality across diverse subsystems, including those using different control frameworks, requires robust and redundant mechanisms. The fail-safe design must account for potential communication breakdowns or synchronization issues between LMPSS and the CMPS.

3.3. Safety control system (SCS)

The Safety Control System (SCS) is a safety-grade protection system designed to implement safety functions oriented to protect personnel and the environment. It shall operate in an independent architecture to minimize interaction with the conventional control system.

The SCS coordinates various protection functions, enables manual control by operators (if authorized by the safety procedures), and displays values associated to critical data for operator supervision. Each subsystem has a different Safety Important Classification (SIC) based on

the safety functions it performs or on the associated accident scenarios (see [19,20]). The architecture is divided into two main parts: an upper part, which consists of servers and gateways to make information available to CODAC and to monitor all system operation, and a lower part, which consists of separate systems with different performance, configurations, and physical components. The separation between network levels is ensured by dedicated servers, creating a layer of protection between operators and safety controllers, with an additional separation between the safety system and the CODAC system via the CODAC gateway (Fig. 5).

As shown in Fig. 5, the exchanged signals are of two distinct levels of priority: safety interlock signals (high priority) and diagnostic signals (low priority). The safety interlock signals, using a reference design with selected hardware, must be transmitted with maximum speed and reliability, whereas the low-priority diagnostic signals can be transmitted via Ethernet with adequate reliability. These design choices impact the application of relevant standards (IEC 61226, IEC 61513, IEC 61508) related to SIL classification, streamlining the SIL assessment by optimizing the use of COTS components and expediting both the qualification process and the network design.

The SCS architecture has been optimized by introducing the following subsystems, each functionally independent from the other and with different requirements and safety classification: Plant Safety Subsystem (PSS), Occupational Safety Subsystem (OSS), Personal Access Safety Subsystem (PASS), and Radiation Monitoring System for the Environment and Safety (RAMSES).

The PSS ensures the application of the defense-in-depth principle by incorporating technological safeguards designed to prevent or mitigate the consequences of postulated accidents, thereby protecting workers,

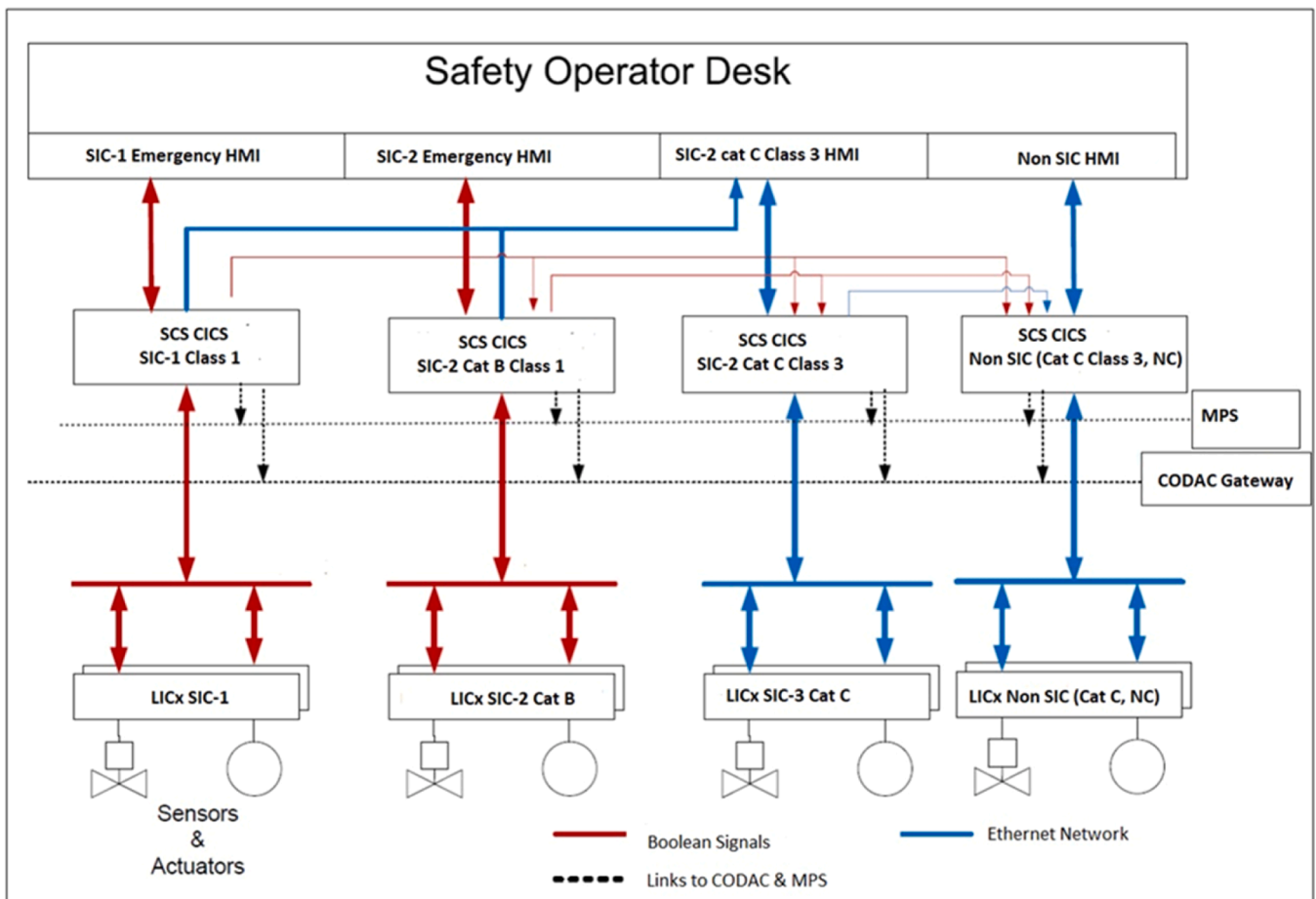


Fig. 5. Safety Control System (SCS) architecture: local versus central functions and redundancy.

the public, and the environment.

A fundamental feature of the PSS is its architecture based on two independent and parallel signal acquisition, processing, and actuation trains (cubicles), each equipped with certified safety controllers or logic solvers.

The requirement for this dual-train design stems from the safety analysis report, which mandates the implementation of two separate defense layers—each with a probability of failure on demand (PFD) of less than 1×10^{-3} . In the case of each Reference Accident Scenario (RAS), the combined PFD target is even more stringent, typically less than 1×10^{-6} .

For reliability and functional safety assessments, the recommended methodology to conduct a RAMI (Reliability, Availability, Maintainability, and Inspectability) analysis is based on IEC 61508.

The remaining subsystems of the SCS focus on direct protection for personnel and the environment, which are handled separately.

The OSS is responsible to support people (workers and the public) protection from non-radiological hazards (toxicological, physical, electrical, cryogenic, etc.) within the plant during both normal and abnormal conditions. OSS is closely integrated with the PASS and the PSS, but it does not perform active actuations.

The Personnel Access Safety Subsystem (PASS) is responsible for ensuring the safety of individuals (workers and the public) in areas with potential prompt risks, both radiological and non-radiological. PASS controls access to specific areas and enclosures within the plant, particularly where mechanical means are insufficient to mitigate safety hazards. Its main functions include stopping hazardous equipment in case of intrusion, banning access when a risk is detected, controlling access to safety airlocks, and interlocking safety access with other safety subsystems.

A key function of PASS is to guarantee the emergency shutdown of the AS if people are verified to be present in forbidden areas and the possibility to exit. PASS is built on Commercial Off-the-Shelf (COTS) platforms with proven reliability in similar applications. It uses independent sensors (mechanical position switches) for door access and communicates with other safety subsystems (PSS, OSS, RAMSES) to actuate safety logics in real-time.

The Radiation Monitoring Subsystem for the Environment and Safety (RAMSES) is designed to support the protection of people by continuously monitoring radiation dose rates and dose in areas at risk of exposure to ionizing radiation and contamination. If measured dose levels exceed predefined alarm thresholds, RAMSES triggers alarms that are communicated to the Personnel Access Safety Subsystem (PASS). RAMSES only monitors areas with expected dangerous radiation levels and is structured in three levels:

1. Instrumentation, distributed throughout the plant, primarily using COTS components.
2. Radiological Synthesis Units (RSUs), managing localized alarms and route data to a centralized server.
3. Centralized Servers and HMI for monitoring and supervision.

Each monitoring device in RAMSES is connected to the dedicated servers for routine tasks, such as configuration and data acquisition. Safety-critical devices are equipped with redundant digital outputs connected directly to PSS. RAMSES features include: single sensors for non-safety functions, duplicated sensors for safety-related functions, COTS detectors for monitoring, Radiological Synthesis Units (RSU-1 and RSU-2) to collect and process data from detectors and actuate area alarms, Area Alarm Units to manage and alert radiation levels in real time.

4. The challenge of integration: local versus central control and commercial versus open-source scada

The current design phase includes a strong integration approach

involving each CICS component to realize a unified control framework. The integration process is a critical aspect of ensuring the seamless operation of the IFMIF-DONES facility, but it is fraught with technical and operational challenges.

The main key challenges in CICS Integration are listed herein:

1. **Data Acquisition Synchronization:** The CICS involves numerous subsystems, each with its own data acquisition rates, formats, and interfaces. Synchronizing real-time data streams from disparate sources such as the AS, LS, and HFTM is essential to ensure consistent performance and accurate system monitoring. Discrepancies in timing or delays in data processing could lead to inaccurate system responses or misalignment between subsystems, compromising safety and efficiency.
2. **Interlock Management:** The integration of interlock systems, which ensure the safety and protection of personnel and equipment, adds another layer of complexity. These systems must communicate effectively across various subsystems while adhering to strict latency and reliability requirements. Balancing the need for quick responses with the scalability of the interlock framework poses significant design and operational challenges.
3. **Heterogeneous Subsystems:** Each subsystem within the CICS (e.g., plant control, safety systems, and monitoring frameworks) relies on distinct architectures, protocols, and standards. Harmonizing these technologies into a cohesive, interoperable framework requires significant engineering effort, particularly in defining unified communication protocols and interfaces.
4. **Scalability and Future-Proofing:** As new requirements emerge during the operational lifecycle of IFMIF-DONES, the CICS framework must remain flexible to accommodate upgrades and expansions. Ensuring modularity and scalability in design is essential but challenging when integrating subsystems designed independently.

To address these issues, the integration effort can also leverage artificial intelligence (AI) tools that provide innovative solutions for optimizing control, decision-making, and system operations (see [21]):

1. **Data-Driven Decision-Making through Machine Learning:** AI algorithms can analyze vast amounts of real-time data from the subsystems, identifying patterns and correlations that may not be immediately apparent. This capability enhances the accuracy of decision-making processes and enables proactive responses to anomalies.
2. **Proactive Maintenance:** Predictive maintenance algorithms powered by AI can identify potential issues in hardware or software before they lead to failures. This reduces downtime and maintenance costs while ensuring the reliability of critical systems such as the Accelerator Systems and Lithium Systems.
3. **Adaptive Control:** AI can enable dynamic adjustments to system parameters based on changing operating conditions. For example, machine learning models can optimize the control of the lithium flow system or the operation of the test module in real time, improving overall system efficiency.
4. **Intelligent Optimization:** AI-based optimization tools can fine-tune system performance by continuously evaluating operational data and adjusting control strategies to maximize output and minimize energy consumption.

It should be observed that the use of AI does not represent a solution for the integration of LICS and CICS: it may be considered as a service above the architecture and integrations between systems. Instead of AI being deeply embedded within the core architecture of LICS and CICS integration, it's positioned as an *overarching service layer*. This means AI algorithms and models operate on data collected from both systems, providing advanced functionalities without fundamentally altering how LICS and CICS communicate or exchange data (i.e. an "intelligence

layer" on top of the existing infrastructure).

Successfully integrating CICS into a unified control framework requires a combination of technical innovation, cross-disciplinary collaboration, and rigorous testing. Ongoing and future work may include:

1. Developing a "Unified Data Architecture": Establishing standardized data formats and protocols to streamline communication across subsystems (this could give a solution of the double control framework, as discussed later). This point is still under study and evaluation, and it is not mandatory as multiple protocols may be used and coexist to manage different tasks as well.
2. Building Redundant and Secure Interlock Systems: Designing robust interlocks that can operate seamlessly across the integrated framework while adhering to stringent safety standards without causing an unnecessary frequent beam shutdown.
3. Implementing AI-Driven Control Algorithms: Gradually integrating AI tools into non-critical systems, followed by their deployment in safety-critical and performance-critical areas.
4. Creating a Digital Twin for System Simulation: Developing a digital twin of the entire CICS framework to simulate integration scenarios, test interoperability, and identify potential issues in a virtual environment.
5. Enhanced Testing and Quality Assurance: Establishing a comprehensive testing protocol to validate the integration of subsystems under various operational conditions.

4.1. Integration CICS-LICS

The interface between local and central control systems (i.e. between LICS and CICS) is critical for reliable, efficient, and safe system operation. In fact, in IFMIF-DONES plant where a hadron accelerator system at medium energy is coupled with a metal liquid circuit to cool a steel target where hadrons are impinging to originate high energy neutrons for components irradiation, there is a need for interfaces with a high level of integration to ensure smooth information flow and optimal system performance. In [22] an overview of a possible integration strategy for diagnostics and instrumentation in order to better define constraints and requirements has been proposed. Here, the focus is on the technological characteristics of local and central interfaces, which form a crucial junction, enabling correct data exchange and coordinated actions.

In fact, complex systems usually require a hierarchical architecture:

1. local controllers manage individual components or processes;
2. local controllers communicate with a central control system;
3. the central control system is responsible for overall system coordination, monitoring, and decision-making.

An effective interface between local control systems and central control system contributes significantly to achieving the following key objectives:

- **Reliable Operation:** Ensuring that data flow reliably and accurately between the local and central systems is crucial for timely decision-making and system stability.
- **Efficiency:** Efficient communication protocols and data structures minimize communication overhead, optimizing bandwidth utilization and system performance.
- **Security:** The interface needs to be robust and secure to prevent unauthorized access.
- **Reliability:** The interface shall prevent data corruption during transmission by ensuring reliable system operation.
- **Scalability:** The design should accommodate the addition of new local controllers and sub-systems in the future, allowing the system to grow and adapt.

- **Flexibility:** The interface should be adaptable to different types of local controllers and communication protocols, enabling integration with diverse technologies.

The activity of designing an effective interface between local control systems and central control system requires careful consideration of four factors at least:

- **Data Exchange Requirements:** The data volumes between the field and the control center must be appropriately sized to identify the architectural requirements. Thus, identifying the type and volume of data to be exchanged between the local and central systems is critical. Data can be associated to measuring data, warning and alarms, control commands, configuration information, and status updates. Data types can be textual or Boolean and associated to different events.
- **Communication Protocols:** Selecting appropriate communication protocols ensures reliable and efficient data transmission. Communication protocols must be defined as standards to avoid the proliferation of "exotic" solutions in the implementation phase. For example, OPC UA is used for the communication of CODAC towards SCADA systems, whereas MPS and SCS use PROFINET, ProfiSAFE, EtherCAT (FSOE), TwinCAT. Also, OPC UA is considered as an option towards the supervision module on TCP/IP.
- **Real-time Communication:** Depending on the application, real-time communication may be necessary for time-critical control actions. Protocols like EtherCAT and Time-Sensitive Networking (TSN) offer deterministic real-time communication capabilities.
- **Network Security:** Implementing robust security measures to protect the interface from cyberattacks is crucial. Firewalls, encryption, and authentication protocols are essential for securing data exchange.

Several communication technologies facilitate data exchange between local and central control systems:

1. **Wired Communication:** Technologies transmitting data over a wire-based communication technology (telecommunication cables)
2. **Fieldbuses:** Communication networks that connect industrial devices at the field level with controllers.
3. **Industrial Ethernet:** High-speed Ethernet networks providing reliable and scalable connections for industrial control systems.
4. **Hardwired:** Dedicated communication connections transmitting Boolean information by changing the DC voltage status of the line.
5. **Wireless Communication:** Technologies like Wi-Fi and cellular networks can be in principle used for remote control or data acquisition from geographically dispersed locations. Of course, like in similar complex plants, the realistic application of wireless devices may be limited by licensing issues or by an insufficient reliability.

A possible approach to improve the CICS-LICS integration could be aimed at:

- A. **Minimizing LICs:** By having multiple LICs within a single LICS (cabinet) communicating with different subsystems of central control system, the following objectives can be reached: save the overall number of cabinets required, save space, save resources (i.e. cable trays, power plugs, etc.), provided that this does not affect the foreseen safety procedures. Naturally, such an approach can be done easily for industrial/standard LICS, but it is very difficult to do for accelerator system where different in-kind systems are involved. This point may impact the other points.
- B. **Avoiding duplicate functionalities:** Each LIC focuses on a specific subsystem of the central control system, eliminating the need for redundant functions across multiple cabinets.

Essentially, designing LICS as a cabinet containing various LIC

modules or controllers for different control systems aligns well with avoiding unnecessary hardware proliferation and duplicated functionalities.

In particular, it allows for:

1. **Standardize Terminology:** ensure everyone on the project adopts this consistent terminology to eliminate confusion.
2. **Define LIC Interface Capabilities:** clearly define the interface capabilities for each LIC type (e.g., MPS-specific LIC, CODAC-specific LIC, SCS-specific LIC). This will guide decisions on how many LICs are needed within a single LICS cabinet.

By adopting this clarified terminology and establishing clear guidelines for LIC functionalities, it can be optimized the overall control system design and achieve better project efficiency.

4.2. Integration between two different SCADAs

The hybrid nature of the control system architecture introduces significant challenges. While EPICS is the primary framework for many LICS, an industrial SCADA solution has been proposed for the MPS and SCS. This industrial solution was chosen to meet strict reliability and safety standards. The coexistence of these two distinct control technologies creates a fragmented control environment and requires the development of gateways to enable intercommunication between the EPICS-based systems and the industrial SCADA framework.

The integration of EPICS with the industrial SCADA introduces several technical and operational challenges:

1. **Protocol Compatibility:** EPICS and industrial SCADA systems often rely on different communication protocols, which may not natively support seamless interaction. Developing a gateway that translates between these protocols introduces additional layers of complexity and potential points of failure.
2. **Performance Bottlenecks:** The protocol translation process between EPICS and SCADA frameworks can lead to communication delays or bottlenecks, particularly in scenarios involving high-frequency or high-volume signal exchanges. These delays can impact the real-time performance requirements of critical subsystems such as the MPS and SCS. MPS and SCS should have a degree of independence from "standard" controls, and the latter should only access information by reading, not writing. The "standard" control requires only to be updated with the status of MPS and SCS, without the need (nor permission) to control these system.
3. **System Homogeneity:** The coexistence of two distinct frameworks leads to a lack of uniformity across the control system. This heterogeneity complicates system-wide monitoring, diagnostics, and maintenance, requiring operators and engineers to be proficient in both frameworks. The limitation of the read-only rules between MPS/SCS and standard control should mitigate the complexity of the entire environment.
4. **Resource Allocation:** The effort to maintain and optimize two separate control infrastructures can result in increased resource consumption, both in terms of personnel expertise and financial cost. The duplication of development, testing, and validation efforts for separate frameworks adds to the overall workload. However, it is worth noting that in an approach where EPICS is used for the implementation of LICS and the three CICS subsystems are based on a unified industrial SCADA, the required expertise can be effectively organized and focused according to the specific scope of each subsystem.
5. **Commercial Strategy:** Cost balancing is clearly a key factor. The proposed hybrid approach can significantly enhance the overall capabilities of the control systems. A well-designed hybrid architecture supports long-term sustainability by providing the flexibility to integrate future technologies and adapt to evolving requirements. As

a result, the initial investment in the control systems is safeguarded, ensuring that the facility remains at the forefront of research and innovation.

To address these challenges, several strategies have been proposed and are currently under development:

1. **Optimized Gateways:** Developing high-performance, low-latency gateways that ensure reliable communication between EPICS and SCADA systems. These gateways need to handle large data volumes efficiently while maintaining real-time performance. In the case where MPS and SCS offer read-only data to the standard control, gateways management should be simplified.
2. **Simulations and Testing:** Using simulators to evaluate the potential delays and bottlenecks arising from protocol translations and signal exchanges. This helps identify critical points of improvement and ensures that the hybrid framework can meet the plant's operational requirements.
3. **System Standardization:** Exploring opportunities for greater system homogeneity by harmonizing communication standards across the frameworks where possible. For example, aligning protocols used by the industrial SCADA with EPICS-compatible standards could reduce translation overhead. The use of EPICS modules with industrial protocols (i.e. OPC UA, ModBus, EtherCAT, etc.), widely employed in similar facilities, allows for guaranteeing protocol standardization.
4. **Signal Prioritization:** Analyzing the volume and criticality of signals exchanged between EPICS Input/Output Controllers (IOCs) and SCADA components. This analysis helps allocate resources effectively, focusing on optimizing communication for the most critical signals.
5. **Enhanced Monitoring Tools:** Developing unified monitoring and diagnostic tools that can operate across both frameworks. Such tools would provide operators with a single interface to oversee the entire system, reducing complexity and the potential for errors.
6. **Long-Term System Evolution:** Establishing a roadmap for the potential convergence of the two systems over time. For example, as EPICS evolves, efforts could be made to adapt industrial SCADA components to leverage more EPICS-compatible technologies or vice versa.

A well-conceived hybrid solution would enable IFMIF-DONES to leverage the strengths of both EPICS and industrial SCADA systems. On one hand, it capitalizes on the extensive knowledge, community expertise, and proven success of EPICS in local control applications. On the other hand, it benefits from the robustness, efficiency, security, and modern capabilities provided by industrial SCADA solutions. Adopting industry standards enhances interoperability and promotes system standardization. This not only streamlines internal integration across diverse subsystems but also facilitates collaboration with other research facilities and technology providers, potentially unlocking new commercial and scientific opportunities.

The significance of the hybrid framework will ultimately depend on the scope and scale of its implementation, particularly the volume of signals exchanged and the number of EPICS Input/Output Controllers (IOCs) integrated into the system. These factors remain under active discussion and are subject to ongoing development efforts. Addressing the integration challenges outlined here will not only ensure the success of IFMIF-DONES but will also provide valuable insights for future fusion research facilities that face similar control system complexities. Further exploration of this topic will be presented in dedicated studies, as it exceeds the scope of this paper.

In developing the IFMIF-DONES control system design, the selection of the control framework plays a pivotal role in addressing the extensive complexities and challenges posed by the facility's diverse requirements. With numerous frameworks available, the decision requires careful consideration of factors such as adaptability, scalability,

maintainability, and resource efficiency. A comprehensive analysis of available options reveals that the E3 (ESS EPICS ENVIRONMENT [23]) framework stands out as a very promising choice for managing the EPICS-based platform for the DONES Control System, owing to its unique combination of flexibility, efficiency, and compatibility with the project's specific needs.

E3 is a highly adaptable control framework that has the ability to handle source code changes from various teams and subsystems, making it ideal for complex projects like the DONES plant. Its integrability with different subsystems and third-party developments reduces compatibility issues and supports continuous system evolution. E3's multiple versioning schemes and support for various Linux distributions, along with integration into the standard EPICS environment, enhances its versatility in collaborative settings.

E3 may be strategically chosen as the control framework for IFMIF-DONES due to its ability to efficiently manage versioning, and enable resource-efficient updates. The framework ensures scalability for large-scale projects like DONES by optimizing disk and network resource usage.

E3's compatibility with the standard EPICS build system might simplify adoption for EPICS developers, while its flexible architecture can support custom module integration and future technological advancements. The framework's emphasis on continuous integration and quantized deployment ensures efficient updates with minimal impact on operations.

By addressing the challenges of a hybrid and evolving control architecture, E3 may align with the strategic requirements of the ongoing IFMIF-DONES project.

5. Conclusions and future directions

This paper has outlined the advancements in the architectural design of the primary DONES CICS components. The development of an I&C system demands a comprehensive, transversal approach to ensure its successful implementation and alignment with the evolving plant design. Consequently, design decisions must be closely integrated with the concurrent development of all associated systems and subsystems to ensure compatibility and operational coherence.

The design activities presented in this work emphasize several key aspects: completing and integrating control and operational tasks, enhancing the interaction between the CICS and LICS, and ensuring holistic integration of the software and hardware components of the control system. By adopting these priorities, the CICS framework strives to create a robust, adaptable, and efficient control system for the IFMIF-DONES plant.

To further enhance integration and address potential challenges, several areas of improvement can be suggested:

1. **AI-Driven Optimization:** Leveraging artificial intelligence and machine learning algorithms could optimize data processing, anomaly detection, and predictive maintenance. AI tools can be used to predict failures, improve fault tolerance, and enhance the efficiency of supervisory tasks within the CICS. Positioning AI as a service above LICS/CICS integration offers significant advantages in terms of flexibility, modularity, and scalability. However, it's crucial to carefully consider potential drawbacks like latency, data bottlenecks, and security concerns. Only by addressing these challenges through careful design and implementation, the "AI as a service" approach can be a powerful way to enhance the capabilities of integrated control systems.
2. **Modular Design for Scalability:** Implementing a modular design in both hardware and software can allow for greater scalability and adaptability to future upgrades or changes in plant requirements. A modular approach will also simplify testing and validation processes.
3. **Advanced Communication Protocols:** Adopting high-performance communication protocols (e.g., Time-Sensitive Networking, TSN)

could improve the real-time data exchange between the CICS and LICS, ensuring more reliable and deterministic system behavior. This topic has been investigated by some of the authors in [24]. Enhanced communication layers would also improve synchronization across systems.

4. **Cybersecurity Integration:** Ensuring the cybersecurity of the I&C systems is critical, especially given the interconnected nature of the CICS and LICS. Robust encryption methods, intrusion detection systems, and regular security audits should be integrated into the system design to safeguard operations.
5. **Simulation and Testing Framework:** Developing advanced simulation tools and digital twins of the I&C architecture could improve design validation and performance testing during the early stages of development. These tools could simulate operational scenarios and help in optimizing both control logic and system interactions.
6. **User-Centric HMI Design:** Enhancing the HMI to incorporate intuitive visualizations, real-time dashboards, and user-friendly controls could improve operator efficiency and reduce the likelihood of errors. Designing interfaces tailored to different operator roles could further streamline workflows.
7. **Cross-Disciplinary Collaboration:** Establishing stronger collaboration between I&C developers, plant design engineers, and subsystem specialists is crucial for aligning control system requirements with the physical and operational constraints of the plant. Frequent design reviews and iterative feedback loops could strengthen integration efforts.
8. **Lifecycle Management and Maintenance Planning:** Incorporating lifecycle management tools and automated maintenance schedules into the CICS framework would ensure sustained performance over the facility's operational lifespan. These tools could also facilitate easy updates and upgrades as new technologies emerge.

By addressing these areas and fostering innovation through AI, automation and remote handling, and interdisciplinary collaboration, the integration efforts for the CICS can achieve their goal of providing a cohesive, reliable, and adaptive control system for the IFMIF-DONES plant. This integration not only enhances the operational efficiency and safety of the plant but also establishes a foundational model for future fusion research facilities, setting new standards in control system design and implementation.

CRedit authorship contribution statement

M. Cappelli: Writing – original draft, Conceptualization, Methodology, Writing – review & editing, Supervision, Investigation. **F. Ambì:** Investigation. **E. Botta:** Investigation, Data curation, Writing – review & editing. **J. Cruz:** Data curation, Writing – review & editing, Investigation. **J. Diaz:** Writing – review & editing, Investigation. **Z. Chen:** Writing – review & editing, Investigation. **D. Dwojewski:** Software, Investigation. **M. Giacchini:** Software, Investigation. **V. Gutierrez:** Investigation. **R. Lorenzo:** Investigation. **M. Montis:** Software, Writing – review & editing. **J. Sousa:** Investigation. **A. Ibarra:** Supervision.

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.

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Data availability

The data that has been used is confidential.

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