EUROPEAN
SPALLATION
SOURCE

OVERVIEW OF THE

INTEGRATED CONTROL SYSTEM

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1. ICS IN 30 SECONDS

The Integrated Control System Division (ICS division) is an organisational unit responsible for the control systems within the ESS facility including control systems for accelerator, target, neutron scattering systems and conventional facilities. ICS' vision is to see ESS operated efficiently, reliably and safely, with a control system that everyone loves. The ICS division shall provide and maintain world-class and cost-efficient control, protection and safety systems and services for the ESS facility. The division shall develop competence and innovative solutions that can be shared in the community through open processes.

2. INTRODUCTION

Control Systems at the European Spallation Source

The neutron science experiments at ESS and the operation of neutron-producing facilities (accelerator, target) rely heavily on a controls and information technology infrastructure. Many complex physical processes have to be concerted, such as proton beam acceleration, neutron beam production, and the characterisation and conditioning of experimental material samples. These processes depend on other enabling processes, such as magnetic field generation, equipment cooling, motion control, supply of electrical power and highly sophisticated measurements for their characterisation. The related equipment (electromagnets, neutron detectors, cooling systems, etc.) needs to be controlled and monitored by operating staff, engineers and researchers. This is achieved through many different and distributed but interconnected control systems.

The physical processes and system behaviours throughout ESS, from the ion source to neutron scattering characterisation systems, are characterised by a high degree of interdependencies. The operating staff, engineers and scientists need tools for the comprehensive supervision, analysis and optimisation of all involved systems and processes. This is realised by a homogeneous data communication layer, *which integrates all technical systems that participate in neutron production and experiments at ESS*. This communication layer enables all involved systems to exchange data and provides the necessary tools for the analysis of information acquired from these systems. The ensemble of these control and communication systems is commonly referred to as the ESS's *Integrated Control System* (ICS).

The creation of the ESS Integrated Control System requires a team of specialists in many fields, such as industrial automation, software engineering, computer science, safety engineering, network infrastructure design, electrical engineering, accelerator technology, neutron scattering technology and even natural sciences domains. Within ESS, the ICS division is the organisational unit that is responsible for the development, operation and maintenance of the Integrated Control System over the ESS life time. The ICS division covers the core competencies required for this mission and establishes the required line organisation.

The ICS division develops a consistent and sustainable architecture for the control systems and related networks and services deployed in the ESS facility. For this, the ICS division engages in ESS in-house standardisation of controls and computing technologies, which range from commercial off-the-shelf products to highly customised devices or even novel developments. During the ESS construction phase, the ICS division executes the *ICS construction project*, which delivers the control system scope for the ESS greenfield facility.

Note: The abbreviation "ICS" is in practice often used for three different purposes:

- ***Technical: the control and communication systems at ESS,***
- ***Organisational: the ICS division,***
- ***Managerial: the scope of the time-limited ICS project during the ESS construction phase.***

The outline of involved parties, science and technical domains indicate the diversity of ESS internal and external stakeholders who the ICS division interacts with. "Figure 1: The ICS Division Stakeholder Overview" on page 5 gives an overview on the stakeholder groups that the ICS division often works with.

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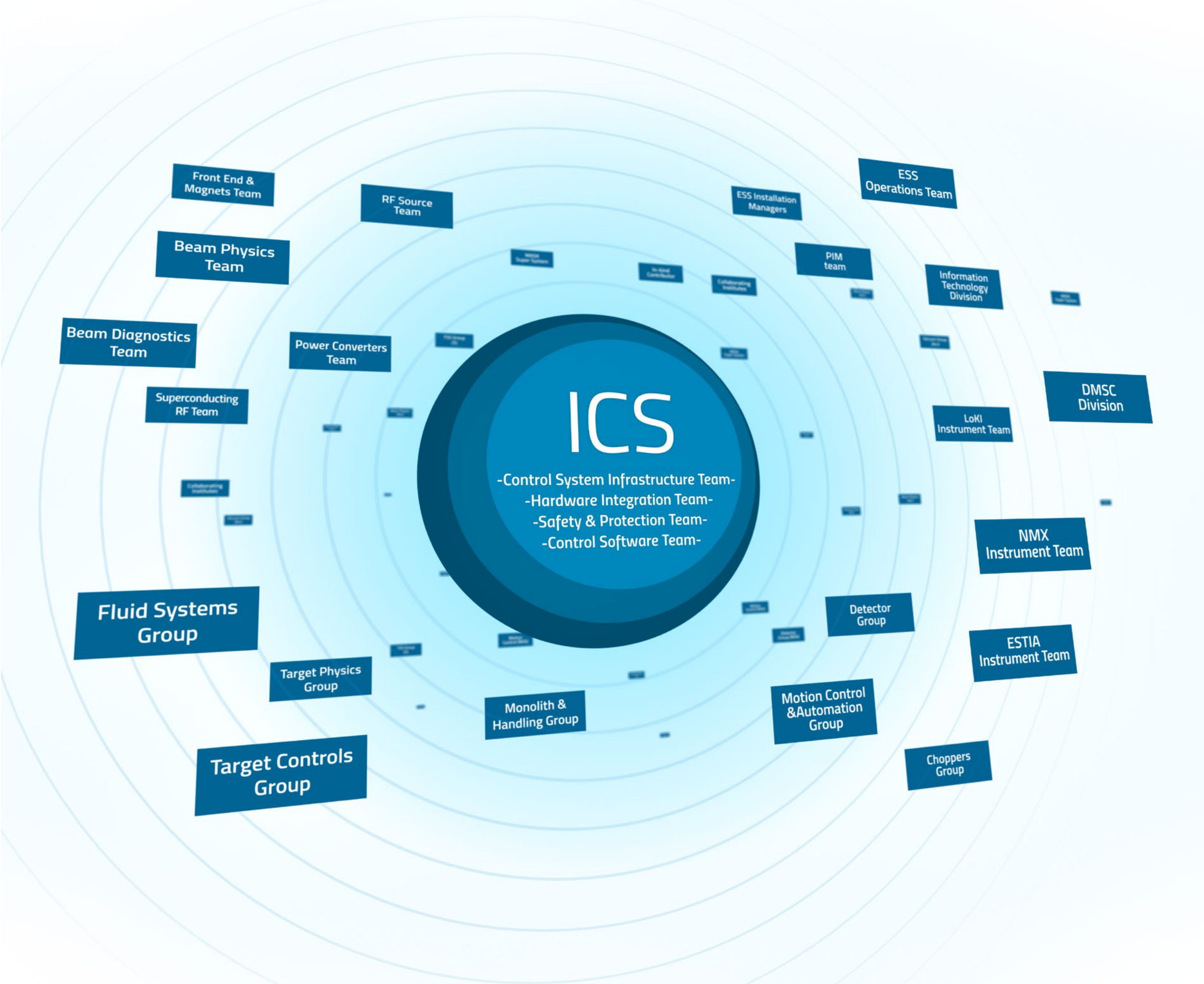

Figure 1: The ICS division stakeholder overview

The complexity of stakeholder involvement in the control systems can be illustrated by looking at a process control system as an example. Such a process control system may have all of the following stakeholders

- one or several groups from other technical ESS divisions as owners of the controlled equipment,
- ESS operations teams, with interests in the technical support for executing operational tasks and procedures (such as switching on the ion source),
- one or several ICS groups, as owners or providers of control systems or control system infrastructure,
- external partners,
- in-kind contributors,
- commercial suppliers,
- other central ESS functions such as the ESS Environment, Safety and Health division,
- ESS end-users, who conduct neutron science experiments.

3. ICS ARCHITECTURE

The 'Integrated Control System' of the ESS is an ensemble of interconnected, distributed control and computing systems for different control domains and purposes. Some of the most prominent systems and infrastructures are described in the following.

Facility Supervision and Integration

ESS uses the EPICS family of distributed control system software [22] to realise a *homogenous facility integration layer* for all ESS systems relevant to neutron production and usage. This communication layer enables all involved systems to exchange data, and provides operators, engineers, etc. with the necessary tools for supervising, analysing and controlling these systems. See section 4.1 and 4.4 for more information.

Timing System

The ESS has a timing system [14] that provides high-precision synchronisation of the distributed control systems in order to achieve coordinated operation of the accelerator, target and neutron instruments. The timing system is synchronised to the accelerator power sources. It broadcasts operational data, time stamps and trigger events to a large number of receivers simultaneously with a deterministic nano-second accuracy.

Machine Protection Systems

ESS machine protection supports the operational availability requirements for neutron production by preventing equipment damage through dedicated protection functions. In addition to protecting equipment and avoiding unnecessary downtime, information on root causes of errors can be collected for further analysis and continuous system improvements. Machine protection can be summarised as the P3 principle:

- Protect the equipment,
- Protect the beam,
- Provide the evidence.

See section 5.3 for more information.

Process and device control systems

Process control systems interact with equipment which enables or monitors physical processes. Examples of systems that require process control are cooling systems, electromagnet systems or ventilation systems, and the process control function is usually realised with industrial automation technology. Device control systems also control equipment and related physical phenomena, but usually in a more accelerator and research technology specific context, such as proton beam diagnostics, experimental sample conditioning and neutron detector systems. Device control systems are often realised as customised high performance control systems. See section 4.2 for more technology information.

Personnel Safety Systems

Providing and assuring safe conditions for personnel is required to operate ESS. The ICS division provides Personnel Safety Systems (PSS) to identify, analyse, and mitigate against the facility's prompt ionising radiation hazards, as well as other hazards such as high voltage, magnetic fields, lasers, motion controls and oxygen depletion. See section 5.5 for more information.

Software Services

The ICS division provides a set of software services to ESS developers, operators and users for operational and maintenance purposes. This software provides graphic user interfaces for operation, machine data analysis and archiving, equipment configuration, calibration and maintenance. See sections 4.1 and 4.4 for more information.

Control Room facilities

The ICS division provides the environment and equipment for ESS operators, scientists and engineers for interaction with the ESS systems. The most prominent example is the ESS main control room. The main control room is the ESS' central place where the proton and neutron beam production is controlled and supervised and related operational activities are executed. Additionally, the ICS division provides local control rooms for the cryogenic systems and console workplaces for the neutron instruments. See section 5.4 for more information.

Networks and infrastructure

The ICS division provides technical data communication networks called the ***Technical Network***, centralised computing resources and data storage facilities needed for the operation of the ESS systems. See section 4.3 for more information.

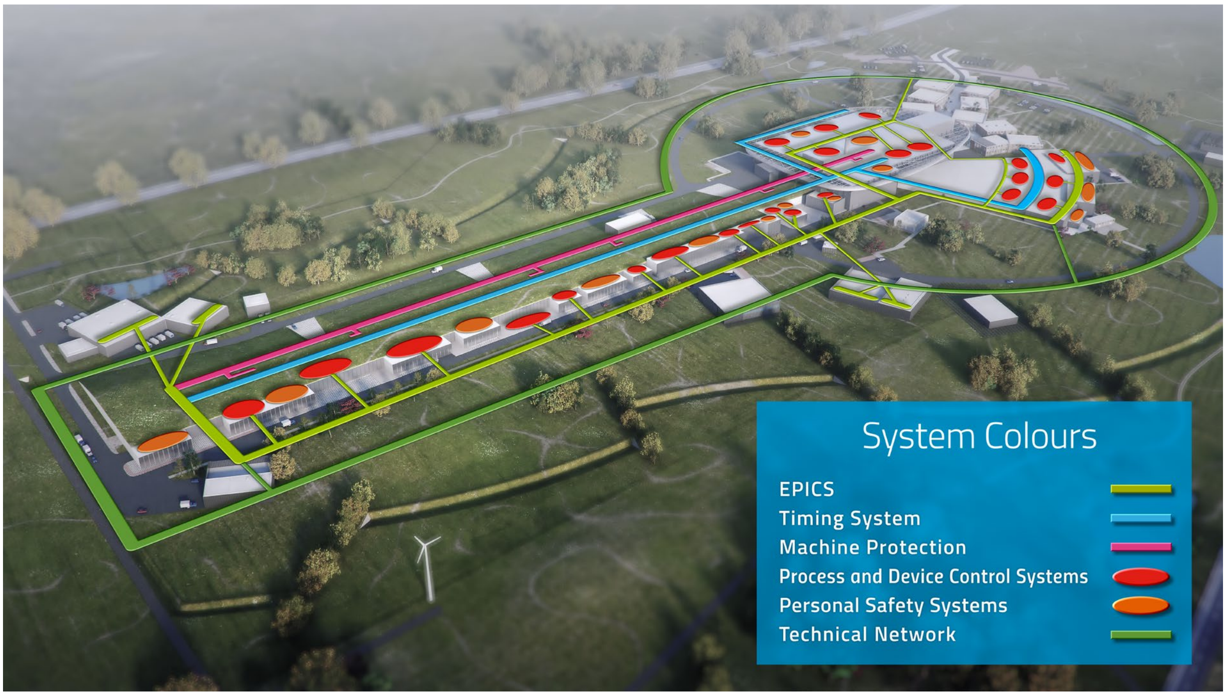

Figure 2: ICS system distribution overview. This schematic indicates roughly the facility-spanning character of the networks for EPICS, Machine Protection, the Timing System and the Technical Network backbone, contrasting the more confined character of process and devices control systems and Personnel Safety Systems.

Figure 2 indicates the on-site distribution of the various systems. While these systems are often independent, they are also interconnected.

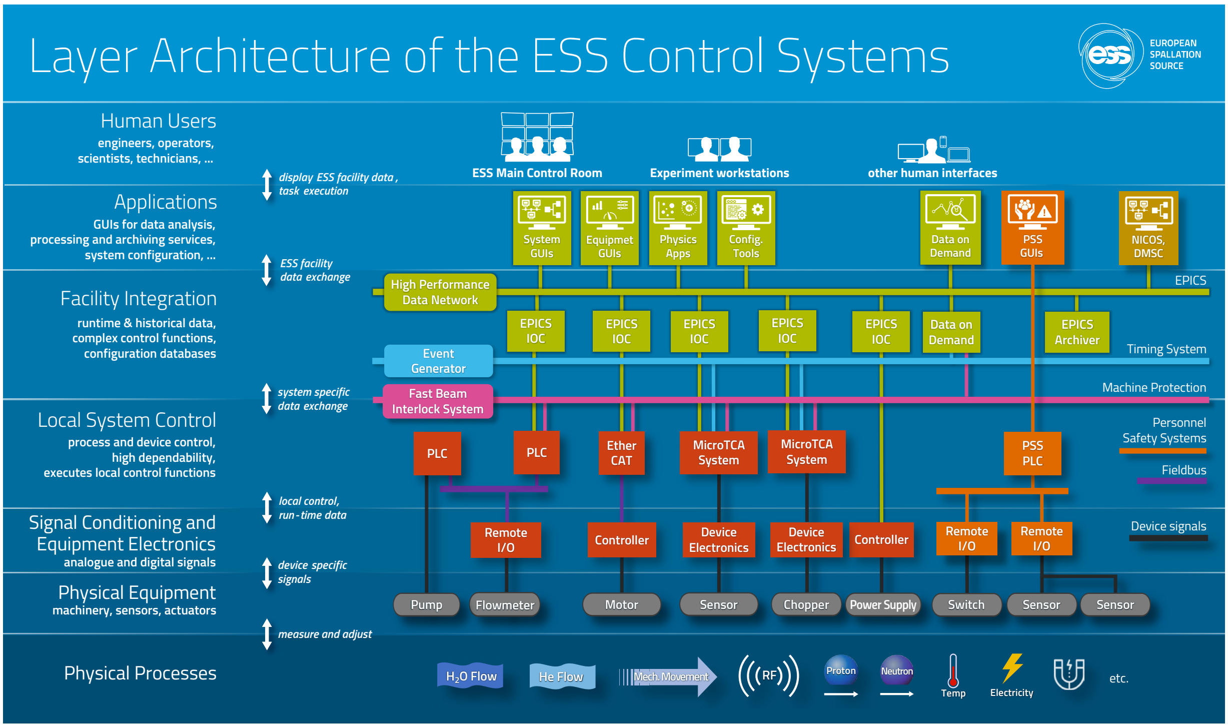

Figure 3: Layer architecture of the ESS control systems

Figure 3 is a schematic overview of control system layers and the relationships between physical processes, equipment, control, communication and supervision systems and human users. Control systems in the layer architecture view are presented in section 5.1.

4. ICS TECHNOLOGIES

The role of technical standards for the ESS control systems.

The control systems have to perform according to the ESS goals for enabling neutron science, but also provide the flexibility to cope with modifications over the ESS life time. The need for enhancements, upgrades and modifications have to be expected during commissioning and as experience is accumulated in operation. Among the drivers for upgrades and modifications are general advancements in technology, and new research interests that require novel experiment or instrument designs.

For the ESS control systems this means that their design goals are system specific trade-offs between function, performance, cost-efficiency, safety, reliability and maintainability. A central principle for achieving overall optimised control systems is to apply a limited, but versatile and powerful well-defined set of system technologies. The ICS division defines, customises and maintains this technology portfolio, which is called the "ICS standards". Maintaining these standards is more than simply defining technologies – it also includes providing the means to apply the ICS standards efficiently. Therefore, the ICS division also provides the needed staff competences, enabling systems such as for code management or testing, work procedures, and maintains good relationships with suppliers and collaborations with other external organisations. The ICS standard portfolio is continuously evaluated and adjusted, based on evolving ESS needs as well as trends in the related research and industry domains. In the following sections, an overview of the core technologies used by ICS is given. An extensive description can be found in the ICS Handbook [13].

4.1. Software

ESS uses the EPICS family of distributed control system software for the creation of a facility-wide data communication layer, which integrates all technical systems that participate in neutron production and experiments.

EPICS

A set of EPICS-based software technologies and services form the core of the EPICS environment. Communication between the various process and device control systems, databases, etc. are realised by the "EPICS base". The EPICS base consists of the EPICS protocol, programming libraries and configuration conventions for a variety of operating systems, programming languages and hardware platforms. These are used to implement EPICS Input-Output-Controllers (IOC), which connect to equipment distributed over the ESS site. ESS operators, engineers and scientists can use various graphical user interfaces (GUI), including synoptic system overviews, engineering screens for devices, and machine settings management applications. Applications help users to manage the system configurations, which is important for repeatable and efficient configuration of layered machine settings and sequences. Configuration management applications can also help users to incrementally develop complex system configurations through working with 'snapshots' of previous parameter configurations.

In addition to the EPICS base for equipment integration and management, the ICS division deploys the following software components and services which are essential to the operation of the facility.

Archiving Service

The *EPICS archiving service* is the time-stamped machine history archive, which collects and stores data from the IOCs, and provides tools for retrieving and analysing the collected data. The archiver application provides analysis functions for the visualisation, correlation and export of the collected machine history. The EPICS archiving service is primarily aimed at troubleshooting, machine performance analysis, operations and maintenance support. Neutron experiment data acquisition is realised with dedicated systems tailored to the individual instruments.

Alarm System

The EPICS based *Alarm System* informs users about conditions that may interrupt, or have already stopped, neutron production or can otherwise be harmful to the facility or its components. The alarms help personnel to diagnose causes of such conditions, and to take appropriate actions to prevent or mitigate their effects. The alarm system is essential for reducing downtime and maximising availability of the ESS services.

Control System Studio

ESS uses *Control System Studio* as the standard tool for run-time interaction with the ESS control systems. CS-Studio is closely associated with the EPICS family of open-source software and included in the ESS standard software distribution. The ICS staff has a high level of expertise in using this tool and can create feature-rich graphical user interfaces. System owners and engineers can also create customised GUI applications for their systems easily through drag-and-drop functionality.

Electronic Logbook

Users can document decisions, actions and notable events and observations during operation in an *electronic logbook*, which is also required by regulatory authorities. Integrated into the ESS control application suite, the logbook is used to document operation events in various media formats, including text, pictures, screenshots and hyperlinks, including links to ESS information systems.

Accelerator Machine Model

ESS uses the OpenXAL development environment as the framework for high level physics applications which are needed to simulate beam trajectories of the proton beam. A machine model of the ESS accelerator allows to translate the simulation results to machine settings and apply these to the equipment during operation.

Control Configuration Data Base

For management of the control systems, the ICS division uses the *Control Configuration Data Base (CCDB) environment*, which includes closely related services and guidelines such as for ESS Naming [18]. The CCDB environment is explained in more detail in section 5.2.

4.2. Hardware

The ICS division has adopted three standardised hardware technologies for implementing the ESS control systems based on performance [13].

These three hardware technologies are MicroTCA, EtherCAT and common industrial automation technology. A specialised technology is used for the ESS Timing System. All systems based on these technologies are integrated using EPICS.

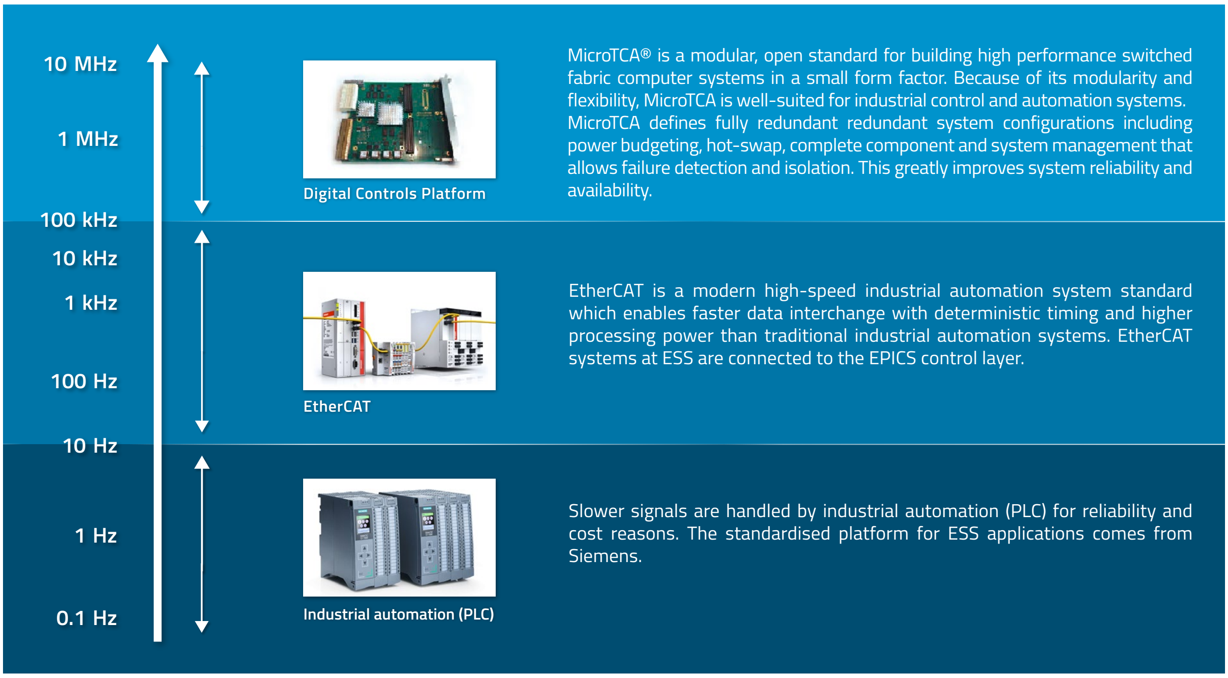

Figure 4: Control technologies and performance

With these three levels of technology performance, the full range of required signal speed can be covered while complying to the strict reliability and availability demands at ESS. The standardisation of these technologies makes the implementation cost-efficient and maintenance relatively simple. A standard technology overview is given in Figure 4.

MicroTCA

High performance signal processing and data acquisition functions are implemented on a custom-made platform based on the modular MicroTCA standard. Typical systems in this category contain computers in the MicroTCA form factor that can run EPICS environments. This is complemented by flexible and powerful data acquisition and processing engines typically implemented in high density FPGA technology. The physical front end to these systems is also modular, typically using the FMC form factor for interfacing electronics.

EtherCAT

For mid-range performance, industry standard EtherCAT systems are used to implement real time fieldbus applications with a good price/performance ratio. The pulsed character of the ESS beam production requires synchronisation and event-specific information in a significant number of use cases where EtherCAT technology can be applied and full custom platform solutions would be too costly.

Industrial Automation Systems

The low end of the performance spectrum is handled with commercially available industrial automation systems supplied by Siemens. This cost-effective solution also addresses ESS reliability and maintainability needs and integrates well into EPICS.

Timing system technology

The ESS Timing System is based on technology from Micro Research Finland (MRF) who specialises in developing precision timing systems for accelerators or similar large-scale scientific applications [14].

Facility integration using EPICS

The presented technologies are used to realise control systems and equipment integration as shown in the “Local System Control” layer in Figure 3. To enable data exchange with the rest of the facility and centralised software services such as the EPICS archiver, each of these local control systems is controlled by an EPICS Input/Output Controller (IOC), shown the “Facility Integration” layer in Figure 3. These EPICS IOCs can be realised through standard Industrial PCs, but the majority of IOCs are handled with virtualisation technology as described in section 4.3.

4.3. Networks and Infrastructure

All sub-systems and components of the distributed ESS control systems, human workplaces and data processing facilities are interconnected by a set of data networks.

The Technical Network

The *Technical Network* is the major backbone data carrier for control system information exchange. It enables all EPICS based information exchange between local control systems, local devices, operator consoles, control system computing and data storage facilities. The technical network is built with approximately 300 network switches, routers and firewalls, and about 235 km of copper and optical fibre cables. A site-wide, high performance, bi-directional optical fibre backbone connects the various buildings, sections and experiments, where local copper networks branch out to local connection points. The Technical Network is built with high availability, reliability and security in mind.

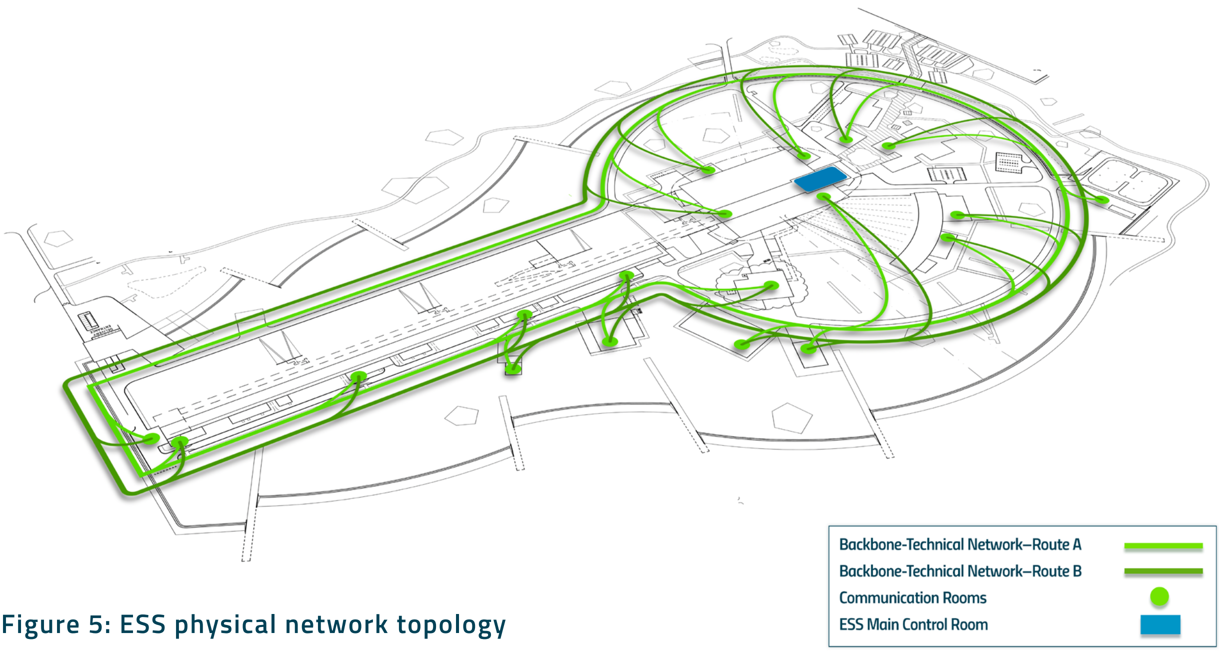

Figure 5: ESS physical network topology

Virtualisation and Container Technology

The ESS control systems demand a significant amount of computing resources for running EPICS and other software services. A key strategy for realising high availability of these computing services is a heavy deployment of virtualisation and container technology. This means that many of the EPICS IOCs and other software services are deployed on virtual computing systems or isolated software processes, which are physically realised on high-availability, managed computer clusters in centralised server rooms. This strategy allows for high availability by flexible resource allocation, load balancing, a tightly controlled and protected environment and cost-efficient resource utilisation.

Timing System Network

The Timing System Network distributes timestamps, event triggers and selected operational data to all systems which need high-performance synchronisation. It connects the central ESS timing system event generator with many local event receivers using fibre optics technology [14].

4.4. EPICS 7

ICS engages in the development of the next generation of the EPICS technology; EPICS 7. While this is primarily motivated by the technical benefits for the equipment integration at ESS, this engagement is also a contribution to the community which made EPICS available.

EPICS is open source.

EPICS is an open-source software technology, widely used at accelerator and other large-scale research facilities. It has been developed in this type of environment as a community effort for almost three decades. This community effort includes the provision of the core libraries, hardware and operating-specific drivers, modules and development tools. But equally important, the EPICS community engages in open sharing of experiences (for example in workshops, conferences, email lists), practical help and staff visits for reviews and training. In short, EPICS as technology and community lives and thrives on active engagement in its community. By contributing to the development of EPICS 7, ESS can participate and strengthen the community and influence the EPICS development roadmap.

3 + 4 =7

EPICS version 3 is the most widely deployed version today. To accommodate for the increasing demands of new research facilities, some fundamental improvements were introduced in EPICS 4, including a new communication protocol, new libraries and data types. However, EPICS 4 is not straightforward compatible with existing EPICS 3 control systems and software. EPICS 7 (from the combination of '3+4') extends EPICS 3 with EPICS 4 functionality, without breaking backward compatibility, and hence allows for full utilisation of the existing EPICS base.

The Experimental Physics and Industrial Control System

Main motivations for using EPICS 7 over EPICS 3 include:

- Data handling and data types: Increasing relevance of 2-dimensional data, such as from area detectors, cameras etc. motivates the support for more complex control data constructs.
- Data transfer performance: Ever-increasing amounts of data drives optimisations of data transfer performance. EPICS 7 implements several technology advancements for increased performance
- Remote Procedure Calls: EPICS 7 introduces so called remote procedure calls which can use dynamic data structures. This feature adds additional flexibility for IOC and application development and performance optimisation.

EPICS 7 is already in limited use for operation at some accelerator facilities

5. ICS FUNCTIONS

5.1. Overall control system function

The low energy beam transport section (LEBT) is one of the first sections in the ESS accelerator. It requires a representative variety of control system functions and is used to illustrate the application of ICS technologies as presented in chapter 4.

Figure 6 shows a schematic view of some of the control systems for the LEBT section. Operators in the main control room and other users such as technicians use a set of GUIs to control, operate and maintain the LEBT. GUIs and tools exchanging information with the ESS facility are shown on the "Applications" layer.

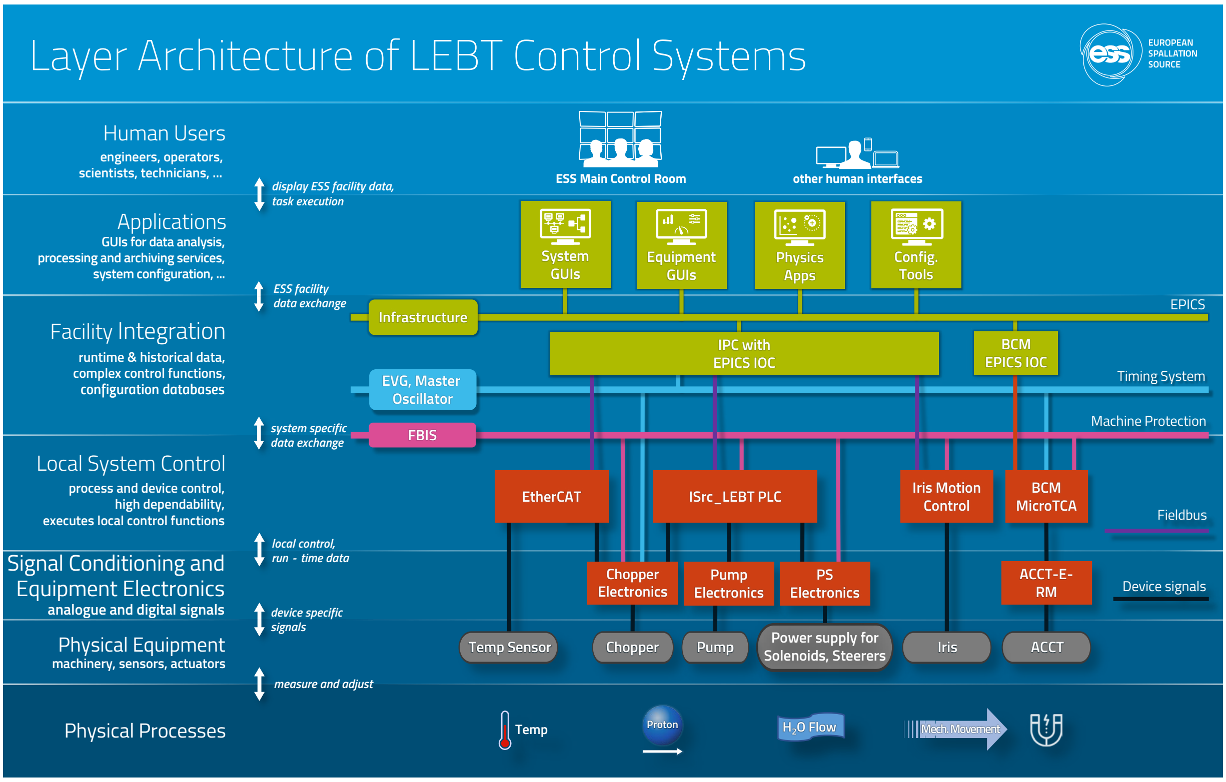

Figure 6: Layer architecture of control systems in the LEBT section

The LEBT contains different kinds of equipment such as power supplies, pumps, and beam instrumentation systems, forming the "Physical Equipment" layer. This equipment is connected to either equipment specific electronics on the "Signal Conditioning and Equipment Electronics" layer, or directly to local control systems, such as PLCs on the "Local System Control" layer. In any case, local system control is realised with the ESS technology standards (MicroTCA, EtherCAT or Siemens PLC systems - see section 4.2). On the "Facility Integration" layer, an Industrial PC (IPC) runs the EPICS IOC which handles all local control systems and makes them accessible to the operator GUIs and databases through the EPICS protocol.

The beam current monitoring system shown in Figure 6 consists of the following:

- The AC Current Transformer (ACCT) measures the beam current at the end of LEBT.
- A signal condition board (ACCT-E-RM) converts the signal from the ACCT to a signal that can be handled by a data acquisition device.
- The MicroTCA controller digitises the signal and propagates it to the EPICS layer.
- The IOC processes the signal data and makes it available for all other IOCs and services on the Facility Integration layer. This means, the signal data becomes available for users for monitoring, analysing, displaying or storing in the control system archive.

The MicroTCA controller is also connected to the fast beam interlock system, which is part of the machine protection function. Based on the information received from the beam current monitoring system, the fast beam interlock system can inhibit proton beam production.

The timing system time stamps the readings of the beam current monitoring system. This allows to correlate them with readings of other systems in the facility. In addition, the timing system enables facility-synchronous event triggers with deterministic timing. The timing system also broadcasts real-time information such as accelerator operation modes which is used for on-the-fly configuration adjustments.

5.2. Controls Configuration Management

The ESS control systems consist of thousands of local control systems and their interfaces, connecting to a wide range of physical equipment. Achieving reliable, repeatable, flexible and efficient configuration management for all ESS control systems is a significant challenge in itself.

The ICS division has developed advanced automated processes and tools for managing the configuration and deployment of EPICS IOCs, PLC code and other devices. The following software components, based loosely on concepts developed in association with the EPICS community, are involved in the process.

The Configuration Controls Data Base

To manage the very complex configuration of the ESS control systems, operators and engineers work with an abstracted model of the facility and the control systems. By modelling the control systems, operators and engineers can efficiently configure the local control systems in detail and then automatically replicate that configuration to be applied on other identical systems with a few simple commands.

The Controls Configuration Data Base (CCDB) contains configuration information relevant for controlling physical and logical devices such as cameras, power supplies, pumps, valves, etc. This information is aggregated in the CCDB in *one model* of the ESS. The information in this model is complemented by supporting software products such as the ESS Naming Service for unique identification of devices and the ESS Cable Database which tracks all connectivity in the facility.

ESS EPICS Environment “E3”

An important delivery from ICS is a standardised EPICS development environment that is distributed to stakeholders, in-kind partners and commercial suppliers.

The development environment - the ESS EPICS Environment, or E3 - is a full software development environment for developing and deploying EPICS EOCs. E3 contains the correct EPICS base, device support modules, etc. for the ICS-standardised hardware platforms and operating systems.

With E3, contributing developers around the world can make sure that their software contributions are fully compatible with the ICS deployment environment.

Configuration Management and Deployment

The E3 code base and facility information from the CCDB is used by a set of tools that assist engineers and operators to quickly and consistently deploy complex configuration to the ESS control systems.

Engineers and operators first create or edit the system configuration in the CCDB to model the control system. A service called IOC Factory enhances the engineering efficiency by translating information in the CCDB to deployable configuration. Here, configurations can be efficiently managed through replicating or sequencing commands.

Operators can extract configuration information from the CCDB and apply adjustments to selected parts of the control system with a few commands. Proper versioning and auditing of changes in control system configurations are also possible through the IOC factory tool.

A similar tool specialised for industrial automation systems, called PLC factory, helps engineers reduce time consuming tasks by automatically generating I/O lists and standardised function blocks from information in CCDB.

Channel Finder

Another important product is the EPICS channel finder application. It implements a directory service for control system data, which allows users easier browsing and aggregation of entities in the control system. An estimate is that the full production ICS will contain 1.6 million values that are tracked by ICS. The channel finder helps users navigate and customise groups of interest.

5.3. Machine Protection

The Role of Machine Protection at the ESS.

ESS, being a user facility for neutron science, is facing high neutron beam availability requirements and is largely relying on custom made, specialised, and expensive equipment for its operation. Damage to this equipment could cause long shutdown periods, induce high financial losses and, as a main point, interfere with international scientific research programs relying on ESS operation and related beam production. Implementing a fit-for-purpose machine protection concept is one of the key challenges in order to mitigate these risks.

Achieving High Operational Availability of the ESS

The availability of the ESS facility an important parameter measuring the average neutron production compared to the planned production for a certain time period. Availability characteristics for a system can be determined by its reliability, availability, maintainability and inspectability. The ESS equipment relevant for neutron beam production, in this context called "the Machine", is in the scope of Machine Protection engineering. The Safety and Protection Group is taking the leading role in the engineering management of ESS-wide Machine Protection, and in the design and implementation of dedicated Machine Protection Systems (MPS).

The goals for machine protection are formulated as follows:

Goal 1:

Machine protection shall, in that order, prevent and mitigate damage to the machine, be it beam-induced or from any other source, in any operating condition and lifecycle phase, in accordance with beam and facility related availability requirements.

Goal 2:

Machine protection shall protect the machine from unnecessary beam-induced activation having a potential to cause long-term damage to the machine or increase maintenance times, in accordance with beam and facility related availability requirements.

Means to achieve Machine Protection

The availability goals will be achieved through:

- Designing the systems relevant for neutron beam production with high inherent reliability and overall low damage potential,
- Minimisation of the mean down time of these systems by introducing dedicated technical systems preventing and mitigating damage, called Beam Interlock Systems and Machine Protection Systems,
- Minimisation of the mean down time of the ESS systems by introducing dedicated operational and preventive maintenance procedures reducing the probability for unscheduled corrective maintenance.
- Supporting systems dedicated to reducing mean down time. These include analysis, management and recovery tools addressing operational activities related to machine protection (such as for customised for "post-mortem" event analysis).

The right strategy to achieve the availability goals will involve a mix of the above measures. The ESS approach for achieving the operational availability goals using the aforementioned measures is presented in more detail in the ESS Machine Protection Concept [15].

5.4. Main Control Room and Experiment Operation Consoles

The ESS systems are operated in parallel from various workplaces on the site. Most prominent is the main control room, which centralises the human operation of the proton accelerator and the target station and provides a place for supervision for the facility as a whole.

Figure 7: ESS Main Control Room in a virtual reality model

The main control room is planned to be manned with an accelerator, target and ICS specialist as permanent operators and to provide workspaces for up to approximately 25 persons. The main control room layout includes 13 permanent workspaces with partially fixed-function desks, such as for the operation of the Personnel Safety Systems. Additional workspaces and a meeting room are available, as shown in the back of Figure 7. Neutron experiments are not operated from the main control room, but from ICS-provided consoles in the experimental areas, which are customised to the particular experiment needs.

5.5. Personnel Safety Systems

Providing and ensuring safe conditions for ESS personnel is essential. The Safety and Protection Group in ICS division is responsible for functional safety realised by electrical, electronic and programmable electronic safety related systems, which at ESS are called Personnel Safety Systems (PSS).

The Safety and Protection Group is responsible for developing and operating all of the Personnel Safety Systems, including design, manufacturing, commissioning and maintenance. The Personnel Safety Systems protects personnel from the facility's prompt ionising radiation hazards generated by particle acceleration or radiofrequency systems. Furthermore, the Personnel Safety Systems identify and mitigate other hazards such as cryogenic hazards (burns, oxygen deficiency), oxygen depletion hazards, high voltage hazards, magnetic field hazards, laser hazards and motion control hazards.

"PSS controlled areas" are identified as hazardous areas where personnel might be affected, such as the accelerator tunnel, target utility rooms, the target bunker and areas at the neutron instruments.

The following types of personnel safety systems are realised:

- Safety interlock system: This personnel safety system ensures that access to controlled areas is prohibited if the beam production is permitted. Conversely, if access to controlled areas is allowed, beam production is not permitted. In the case of an emergency, all hazardous equipment under control is switched off. Emergencies are triggered by events such as elevated dose measurements and intrusions to PSS controlled areas.

- Access control systems monitor the conditions for enabling the entry stations to "PSS controlled areas" and control door subsystems for openings and access.

- Oxygen deficiency hazard monitoring systems alarm personnel by activating signalling lights and sounders.

The Personnel Safety Systems are developed in compliance with the international functional safety standard IEC 61508 [23], a widely adopted practice within the accelerator based research domain.

6. ICS PRINCIPLES

The ICS division uses technologies and engineering methods from different control system domains in order to achieve the overall best results for ESS.

To exploit the strengths of different technologies and engineering domains to the best benefit, the ICS division applies the systematic approaches to *system life cycle management*. Each approach is tailored to utilise the domain-specific best practices, which are often described in standards or engineering literature. The ICS approaches are continuously harmonised with the overall ESS engineering management, particularly as described in the ESS Handbook for Engineering Management [19].

Most ESS control systems enable conventional functions, including control for beam production and related enabling systems such as cooling, studies of machinery behaviour, neutron experiment execution, experimental data acquisition, processing, storage and analysis. The *integration* of ESS systems realised by such conventional control systems requires well-organised development, installation and transition to operation. This is executed according to the system life cycle model described ICS Integration Strategy [17]. This approach is based on the systems and software engineering standard ISO 15288 and the closely related INCOSE Systems Engineering Handbook, thus implementing best practices in Systems Engineering for complex systems.

Machine Protection is a major factor for reaching the ESS neutron production availability goals. To address this *mission-critical* relevance appropriately, a special approach to life cycle management has been developed and is applied to the Machine Protection Systems-of-Systems [25]. It combines concepts and principles from the functional safety domain based on the IEC 61508 [23] and IEC 61511 standards with Systems-of-Systems Engineering. The approach is explained in detail in the "Machine Protection – Systems Engineering Management Plan" [16], which also clarifies the relation to local protection systems and constituent systems such as the ion source, proton beam choppers, various sensor systems etc. which participate in realising Machine Protection at ESS.

The Personnel Safety Systems are *safety-critical*, and thus the development, operation and maintenance are executed in compliance with suitable international standards for functional safety engineering. The Safety and Protection Group in the ICS division applies the IEC 61508 [23] and IEC 61511 [24] standards for the development of the ESS Personnel Safety Systems. Using these standards is a widely adopted approach for safety-related systems in the accelerator research facility community. The approach is described in the PSS Development and Quality Assurance Plan [20] and in the ESS Rules for Configuration Management for Personnel Safety Systems [21].

The Control Software Group organises the development of software according to the character and complexity of the developed software system. For complex software services, the development life cycle approach is following the traditional V-model, with explicit development-stage related documentation. In other cases, such as user application development or feature additions, an agile approach is applied. This differentiation allows the Control Software Group to adapt towards expectations on response time to feature requests, stakeholder inclusion in the development process, documentation and architecture quality and efficiency in resource usage.

In Agile developments, the Control Software Group creates a first working software version with limited functionality as early as possible. This prototype is then continuously evaluated with the stakeholders, for example by ESS physics and engineering groups. Based on this feedback, incremental improvements are implemented in the software. The Agile loop is repeated until the software realises the desired functionality. These iterations are managed in daily to bi-weekly stakeholder meetings. Software changes during operation due to new feature needs, technical adaptations or bug fixes are realised by further Agile loop iterations.

7. ICS ORGANISATION

The matrix organisation applied in ICS division relates the ICS line management to the ICS project management.

At the heart of any efficient organisation is the *Line management function* that builds permanent groups and temporary teams, secures commitment and motivation in those teams to provide the necessary competence and capacity needed for the organisation to deliver. To execute activities in the organisation in a structured and systematic way, line management creates a *Project management function* and hands the executive mandate to the project managers.

Line = Who and How
Project = What and When

7.1. Line organisation

The ICS division is organised hierarchically in a group structure. Four domain competence groups exist:

The Hardware and Integration Group

The Hardware and Integration Group develops, implements, operates and maintains the non-safety-critical control systems of the ESS, including the EPICS integration and timing system. The HWI teams also engages in customising base technologies, such as industrial automation and MicroTCA based systems, for its application by stakeholders.

The Safety and Protection Group

The Safety and Protection Group coordinates and executes the development of highly dependable systems. For enabling a high neutron beam availability, the group coordinates the realisation of machine protection functions at ESS and executes the development, operation and maintenance of dedicated machine protection systems. For worker safety, the group develops, operates and maintains the ESS Personnel Safety Systems.

The Control System Software Group

The Control System Software Group provides software toolsets needed for the management and operation of technical ESS systems. The group's scope is software such as controls configuration management tools, alarm handling tools, systems for troubleshooting and documentation of the machine history and physics-related applications.

The Control System Infrastructure Group

The Control System Infrastructure Group designs, implements and maintains the backbone data and communication networks for the control and timing systems, the ESS control rooms, data centres and other equipment required for the reliable operation of the control systems. The group provides operations workstations, servers and file storage required for operation of the facility. This group is responsible for implementing the ESS main control room, which allows the facility to be controlled from a central location.

The ICS Management Team

The ICS Management Team executes and supports line and project management functions, and establishes consistent architectures, technology standards and systems engineering for the ICS division.

Each group is viewed as a separate organisational unit with its own line manager and organisation context description. ICS line managers are responsible for developing and maintaining the strategy for keeping the ICS division organisation concurrent with ESS needs. This strategy is formulated in the ICS organisation context description[1]. Figure 8 shows the organisational chart of the ICS division.

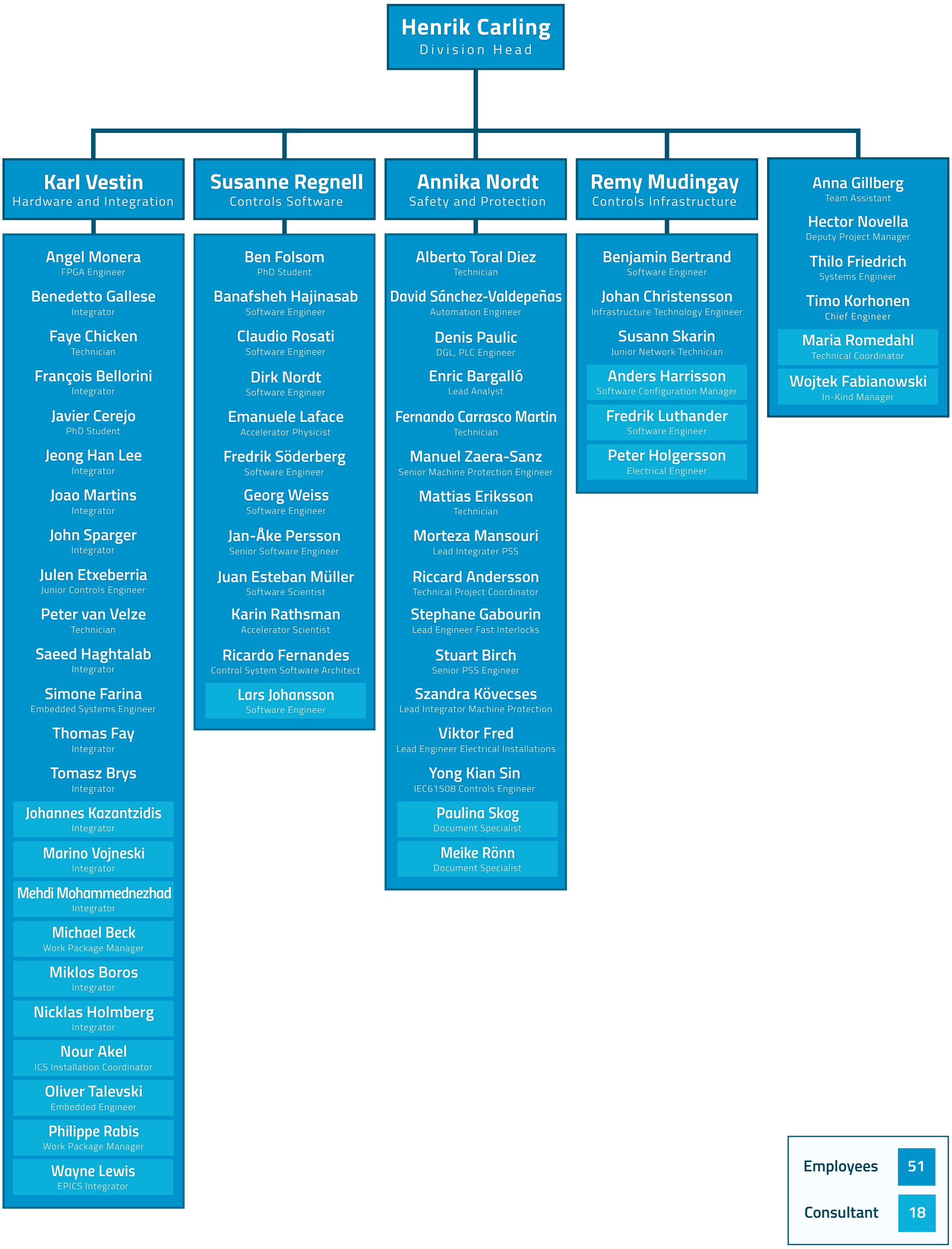

Figure 8: ICS Organisation in Q2 2018

7.2. ICS Project Management

The ICS Project managers derive executable, scheduled tasks with well-defined budgets based on stakeholder, technology and standardisation needs.

Project managers also ensure that ICS tasks are aligned and coordinated with activities of the other ESS divisions. The ICS construction project scope is organised and managed in work packages (see 7.3). These are arranged by

- the integration of ESS systems and equipment for the ESS operation and maintenance (work packages 05, 07, 09, 10, 11, 12, 13),
- the provision of software based applications for operation, maintenance and configuration management of the ESS (work packages 03, 08),
- the provision of customised technologies for the ESS (work package 04),
- general ICS management (work package 01 and 06),
- test and prototyping activities (work package 14).

The ICS long-term planning and budget allocation is managed in the central ESS planning tool Primavera P6, where the ICS plans are linked with plans of other ESS divisions. Detailed tasks and daily work is managed using the JIRA on-line collaboration tool, which supports the agile methods used in software development and also enables issue tracking, which is often used during installation and commission.

7.3. Construction Project Organisation

The tasks of ICS division for the ESS construction project, as stated in the ICS project charter [6] is organised in work packages:

Table 1: ICS Work Package Overview

01 Management
Central management services for the ICS division including in-kind management

03 Software Core
Development and integration of software core components for the integrated control system

04 Hardware Core
Selection, preparation and delivery of standardised electronics hardware equipment for control, data acquisition and timing

05 Machine Protection System
Design, install and commission the ESS machine protection systems

06 Equipment
Administrative work package to collect all equipment management in ICS. No activities

07 Control System Infrastructure
Control rooms and the control system infrastructure including data networks, computing facilities

08 Physics
Development of support tools for machine commissioning and operations based on a mathematical model

09 Personnel Safety System
Design, install and commission all personnel safety systems for accelerator, target, and neutron instruments

10 Integration - Accelerator
Accelerator controls development and integration

11 Integration - Target
Target station controls development and integration

12 Integration - Instruments
Neutron instrument controls development and integration

13 Integration - Facilities
Development and integration of controls for building management systems such as cooling water and air conditioning

14 Test Stands
Design, construction and maintenance of relevant ICS test stands and laboratory facilities

7.4. ICS Information Management

The ICS division uses ESS tools for Information Management.

The ICS Division uses the applicable ESS Information Management systems to enable access and manage human-processed engineering information in the corresponding contexts:

- ICS Project Information repository. [8]
- ICS Line Management repository. [9]
- Technical specifications of ESS/ICS systems: ESS Breakdown Structures [11]
- Asset management: Infor EAM. [12]
- Collaboration tool: Confluence and JIRA. [7]
- ESS schedule and budget planning: Primavera P6
- Engineering processes and conventions: ESS Management System. [10]

7.5. Financial key figures

Budget, in-kind contribution and risks.

The total ICS construction project budget allocated for implementing the full ICS construction scope is in the order of 80 M€. A certain proportion of this budget should be utilised as in-kind contribution from ESS member states. At the beginning of 2018, the ICS project had achieved a level of about 20% in-kind contribution. A re-baselining of the ESS construction project plans was ongoing in the first half of 2018, which may imply changes also to the ICS context.

ICS is applying proper project management practices, including risk management. The ICS risk management plan [26] is used for keeping track of a risk register and treatment actions.

8. ICS VISION, MISSION AND VALUES

ICS Vision

ESS operated efficiently, reliably and safely, with a control system that everyone loves.

Mission

To provide and maintain world-class and cost-efficient control, protection and safety systems and services for the ESS facility. To develop competence and innovative solutions that can be shared in the community through open processes.

Behaviours and Values

ICS staff and consultants follow the ESS core values [2] and the ESS code of conduct [4]. The ICS leadership and management team also implements the following behaviours as described in the ICS Organisation Context Description [1].

- Lead by example, Generate energy, Communicate
- Simplify, Push for excellence, Get results
- See the big picture, Challenge, Drive one ESS

ICS Simplified Values

The ICS division uses the following simplified values as a behaviour guide in the daily work

- Be nice!
- Use common sense!
- Have fun!

9. REFERENCES

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10. DOCUMENT REVISION HISTORY

Revision	Reason for and description of change	Author	Date
1	First issue	T. Friedrich	2018-04-27