European Spallation Source

Control System Study

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Scope

This document identifies the fundamental requirements of the ESS control system given the existing understanding of the ESS design. A rough conceptual design will be prepared, emphasizing the most critical issues and technologies; comparing existing solutions and discussing whether they are sufficient or whether some critical new development must be envisioned. The document addresses the issues set forth in the document memo_cosylab_091211.pdf, written by Steve Peggs and Todd Satogata on December 10, 2009.

Executive Summary

Control system development is a low risk activity in constructing the European Spallation Source (ESS). The risks can be classified as technical and organizational. The reasons for a small technical risk are: 1) major control system software platforms have matured significantly in the last decade, with focus of development shifting towards ease of adoption and usability, 2) large improvements of CPU performance have simplified software and hardware development, with increasing availability of standard commercial off the shelf (COTS) hardware components.

ESS will be constructed by a number of partner institutions in an international collaboration, thus increasing organizational risk as control system integration will be performed by a large number of independent teams. In addition, control system integration comes late in the project and integrates with all other subsystems. As a consequence, problems in this phase can soon affect the critical path of the overall project.

In order to address these risks and to facilitate control system development, several assumptions have already been made:

1) ESS will use the EPICS control system.
2) Linux will be the operating system in the ESS controls service tier.
3) ESS will use the Oracle relational database system.

Control system recommendations are grouped according to time of their applicability, as some decisions have to be made immediately and some should be deferred to later stages in the project. In this document, the recommendations are classified as: 1) immediate recommendations (April 2010), 2) recommendations for the end of the design update phase (end of 2012), 3) recommendations for construction phase (end of 2016).

The most important immediate recommendations are:

1) Initiate collaborations on control system development with similar projects, in particular SNS, ITER, FRIB, XFEL and JLab 12 GeV Upgrade.
2) Join the XAL application development framework collaboration.
3) Introduce a naming convention early in the project. Decide if the same naming convention names equipment as well as control signals.
4) Provide a standardized "Control Box" platform to ESS partner institutions, with first prototype delivery in late 2010.
5) Release Control Box software and hardware in (approximately) yearly cycles.
6) Integrate the control system of the linac and the target.

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1. Introduction

1.1. Working Assumptions and Recommendations

The ESS project will have the following major milestones:

- **The three year milestone**: end of year 2012, end of the Design Update Phase.
- **The seven year milestone**: end of year 2016, just before installation gets into full swing.

Some decisions should be made well before the first milestone and others should be deferred until the seven year milestone. Therefore, the recommendations in this document are classified according to the relevant milestones:

- **Assumptions**: decisions that were already taken and are treated as input parameters in this document. Marked as Assumption.
- **Immediate recommendations for the project** (April 2010) and best practices that should be taken into account early on: marked as Recommendation (I).
- **Three year milestone recommendations**: marked as Recommendation (III).
- **Seven year milestone recommendations**: marked as Recommendation (VII).

Assumptions and recommendations from the whole document are gathered below, as a conclusion and quick reference for technical audience.

1.1.1. Assumptions

1.1.1.1. Organizational Assumptions

Assumption #23: The personnel protection system (PPS) and machine protection systems (MPS) will not be direct parts of the single controls network.

Assumption #24: All subsystems that need to take into account nuclear engineering safety regulations are not part of the control system (e.g. target protection system).

Assumption #49: Fast LLRF control loops are not in the scope of the control system but interfaces to control them are.

Assumption #47: Master clock generation is in the domain of the control group.

1.1.1.2. Implementation Assumptions

Assumption #1: The Control Box metaphor will be used: develop a standardized platform (hardware, software, and development and test procedures) that will be distributed to partners in the ESS collaboration.

Assumption #21: Linux will be the operating system in the service tier.

Assumption #22: ESS will use the EPICS control system.

Assumption #31: ESS will use the Oracle relational database system.

Assumption #42: ESS will use EDMS [13].

1.1.2. Immediate Recommendations and Best Practices

1.1.2.1. Organizational Recommendations

Recommendation (I) #2: Initiate collaborations on control system development with similar projects such as SNS, ITER, FRIB at MSU, XFEL, and JLab 12 GeV Upgrade. In particular, ESS should sign a collaboration agreement with ITER on sharing information with respect to Control Box development.

Recommendation (I) #3: Integrate ESS controls across all beam systems, including the injector, linac, and target.

Recommendation (I) #37: Join the XAL collaboration.

Recommendation (I) #43: Introduce a naming convention early in the project. There should be a process in place that checks naming convention compliance. A person (the naming tzar) should be assigned to address naming at the project level, and to assist control system developers when they are in doubts on how to handle naming.

Recommendation (I) #44: Decide whether to use the same naming convention to name control signals as well as equipment.

Recommendation (I) #45: Define the scope of EDMS usage at ESS.

1.1.2.2. Best Practices

Recommendation (I) #26: Develop Control Box software and hardware in (e.g., yearly) cycles. The main strategy is to start with software-only aspects (which are easiest to develop, test and distribute), and as soon as possible deliver a Control Box with a simple standardized hardware interface, such as infrastructure PLC control.

Recommendation (I) #27: Propagate real-time information between subsystems only by means of the timing system, i.e. no other real-time communication should propagate between different subsystems.

Recommendation (I) #53: Avoid all analogue signals in control room.

1.1.2.3. Implementation Recommendations

Recommendation (I) #25: Follow the ITER design approach for Control Box internal structure [24].

Recommendation (I) #39: Evaluate CSS for its applicability at ESS.

Recommendation (I) #46: Use a naming convention that is consistent with EDMS.

1.1.3. Three Year Milestone Recommendations

1.1.3.1. Organizational Recommendations

Recommendation (III) #4: Define target control interfaces (e.g., for neutron choppers).

Recommendation (III) #6: Prepare a Work Breakdown Structure and task schedule for control system development.

Recommendation (III) #7: Check and regularly iterate the bottom-up plans with the initial task plan.

Recommendation (III) #8: Define and track all control system development and maintenance activities as tasks.

Recommendation (III) #19: Invite operators from other facilities (e.g., SNS) to participate in design activities of the ESS controls.

Recommendation (III) #34: Assign a role of GUI tzar: a person within the control group responsible for enforcement of user interface design guidelines for all control room applications.

Recommendation (III) #40: Assign a full-time tool developer position for the construction phase.

1.1.3.2. Best Practices

Recommendation (III) #9: Use a dedicated project management system to track all the developments of control system group from the start of control system development.

Recommendation (III) #10: Provide automated and convenient interface tools connecting RDBs to EPICS configuration files. The tool should be able to generate bottom-up artifacts from the model.

Recommendation (III) #11: Distinguish between 1) development and early testing and 2) factory acceptance at the partner institutions. The process [54] for the first option should be straightforward (make life of developers easy, everything for development and initial testing should be installed and be run on a single developer machine), while the second is more stringent and acts as a local integration test by the partner institution.

Recommendation (III) #12: Launch a pilot project in ESS Control group, introducing a prototype development process and development tools.

Recommendation (III) #13: Enforce development standards defined in a short *development guidelines* document.

Recommendation (III) #14: Perform regular internal code reviews.

Recommendation (III) #15: Set up a continuous integration build server.

Recommendation (III) #16: Use a version control system (e.g. Subversion).

Recommendation (III) #17: Provide FAT checklists and guidelines to add additional tests and distribute them together with Control Boxes.

Recommendation (III) #18: Set up an ESS development process that is iterative and agile, with a waterfall style of development for each iteration.

Recommendation (III) #20: Provide a simulation framework for the ESS, along with a few simulated operation scenarios.

Recommendation (III) #41: Gather detailed requirements for the equipment database and investigate existing solutions. Decide what solution(s) to use, and in case of using several solutions, design a mechanism for keeping them in sync.

1.1.3.3. Implementation Recommendations

Recommendation (III) #30: Evaluate the needs for real-time operating system. The key decision criterion is how timely the application must respond: if fast reaction times are required (less than a few milliseconds), a real-time operating system should be used.

Recommendation (III) #32: Define a set of procedures when introducing alarm states from the very beginning. SNS has based its recommendation on an industry standard book: Alarm Management: Seven Effective Methods for Optimum Performance, by Bill R. Hollifield and Eddie Habibi [27].

Recommendation (III) #33: Select a single software platform (operating system and version) for operator consoles.

Recommendation (III) #35: Use a single subnet and a centralized naming server instead of UDP broadcasts for discovery of EPICS process variables.

Recommendation (III) #36: Use software frameworks as a basis to develop high-level control room applications.

Recommendation (III) #38: Use XAL for ESS physics application development environment and participate in XAL development efforts from the beginning of ESS project.

Recommendation (III) #51: Prepare a list of operator stations in the ESS control room. Provide the number of stations, and their assignments. Recommended assignments for stations are: chief operator station, accelerator operator station, physics / diagnostic station, conventional facilities station, test station, target station, alarm station.

Recommendation (III) #52: Provide a list of detailed operations use cases (e.g. machine tuning, normal machine operation, accelerator physics run, commissioning of a new device). Provide a list of control system tools and applications that are required by each use case. Base the list on experience from SNS.

1.1.4. Seven Year Milestone Recommendations

1.1.4.1. Organizational Recommendations

Recommendation (VII) #5: Involve the Operations and Accelerator Physics groups in controls application and service development.

1.1.4.2. Best Practices

Recommendation (VII) #29: Select the hardware platform after the three year milestone. When making the decision, base it on **usability** (i.e. what you can do with the platform and how well the relevant tools are debugged) and **longevity** (i.e. how long will it take before the platform becomes obsolete/outdated).

Recommendation (VII) #50: Ensure the control room consoles enforce accountability and a reasonable level of security without hindering operations.

Recommendation (VII) #54: Gather requirements for an electronic log book at ESS

1.1.4.3. Implementation Recommendations

Recommendation (VII) #28: Select one standard bus architecture with standardized I/O modules.

Recommendation (VII) #48: Develop a custom timing master generator, based on FPGA. Use a commercial off-the-shelf solution for the transport layer and timing receivers.

1.2. Glossary of Terms

AFS	*Andrew File System.*
API	*Application Programming Interface.*
ATCA	*Advanced Telecommunications Computing Architecture.*
BEAST	*Best Ever Alarm System (SNS)*
CMM	*Capability Maturity Model.*
COTS	*Commercial* off-*the-shelf.*
CS	*Control System.*
EDMS	*Engineering and Equipment Data Management Service*
EPICS	*Experimental Physics and Industrial Control System.*
ESS	*European Spallation Source*
FAT	*Factory Acceptance Test.*
FPGA	*Field Programmable Gate Array.*
FTE	*Full-Time Equivalent.*
GUI	*Graphical user interface.*
HMI	*Human Machine Interface.*
I/O	*Input/Output.*
IOC	*Input/Output Controller.*
JMS	*Java Message Service.*
LLRF	*Low Level Radio Frequency.*
MPS	*Machine Protection System*
NFS	*Network File System.*
Operator interface	User interface (frequently, but not always, a GUI) through which the operator interacts with the system for monitoring and controlling processes or individual *process variables.*
OPI	See *Operator interface.*
PPS	*Personnel Protection System*
Process variable	Current status of a process under control. Process variables can be simple (e.g., temperature inside the cryostat) or more complex (e.g., voltage-versus-time during the last second sampled at

	100Hz). In a wider sense, the term *process variable* also refers to *setpoints*.
PCI	*Peripherial Component Interconnect.*
PCIe	*PCI Express.*
PV	See *Process Variable.*
RDBMS	*Relational Database Management System.*
SAT	*Site Acceptance Test.*
Setpoint	The requested value for a process variable.
SMB	*Server Message Block.*
WBS	*Work Breakdown Structure.*

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2. Organizational Issues

The project will accept in-kind contributions from ESS project partners. An in-kind contribution is the supply of a technical component or group of components or work package(s) for the ESS. In-kind contributions can be delivered by partners instead of, or in addition to, a cash contribution to the ESS Company. They are therefore accounted as partners' contributions to the ESS. This is similar to the approach taken by the FAIR project in Darmstadt, Germany and ITER project in Cadarache, France.

The ESS control group will provide the organization and infrastructure to make this kind of collaboration efficient for components that will be controlled by the ESS control system. The control group will provide a well defined set of procedures, interfaces and hardware that will standardize and integrate the deliveries of different collaborating partners. This will be achieved by applying the Control Box metaphor on both technical (architecture) and organizational aspects of the control system.

> **Assumption #1:** The Control Box metaphor will be used: develop a standardized platform (hardware, software, and development and test procedures) that will be distributed to partners in the ESS collaboration. The Control Box is central to the Controls portion of the three-year Design Update Phase.

> **Recommendation (I) #2:** Initiate collaborations on control system development with similar projects such as SNS, ITER, FRIB at MSU, XFEL, and JLab 12 GeV Upgrade. In particular, ESS should sign a collaboration agreement with ITER on sharing information with respect to Control Box development.

ITER is a machine with a similar time plan of controls and integration development and has a similarly complex organization of partner institutions to ESS.

> **Recommendation (I) #3:** Integrate ESS controls across all beam systems, including the injector, linac, and target.

SNS has a very positive experience with integration of linac and target controls. There should be no artificial distinction between linac and target, although the experimental (a.k.a. Science) stations can be separate, with some exceptions. Most notably, the timing system must be shared.

> **Recommendation (III) #4:** Define target control interfaces (e.g., for neutron choppers).

> **Recommendation (VII) #5:** Involve the Operations and Accelerator Physics groups in controls application and service development.

Some examples where Operations and Accelerator Physics group can be involved are high level applications, user interface/architecture, physics modeling and support.

2.1. Project Planning

ESS controls project planning should be conducted in phases. First, a requirements study and conceptual design should be written, after which it will be possible to prepare the work break down structure and project plan.

Requirements study. The goal is to identify **critical** requirements for the accelerator project with respect to the control system, in terms of complexity, performance, political issues (e.g. large collaborations), schedule, etc. In this phase, ESS controls should also conduct interviews with all the relevant stakeholders of the control system.

Conceptual design. Based on the input from the requirements study, provide the outline of the control system design. Review the most critical requirements with stakeholders and discuss their impact on design. Make a list of all "known unknowns" at this stage and their potential impact on the overall design and on designs of subsystems. Enumerate and categorize all the risks and write possible mitigations to reduce them.

We recommend planning the development of the control system both top down and bottom up.

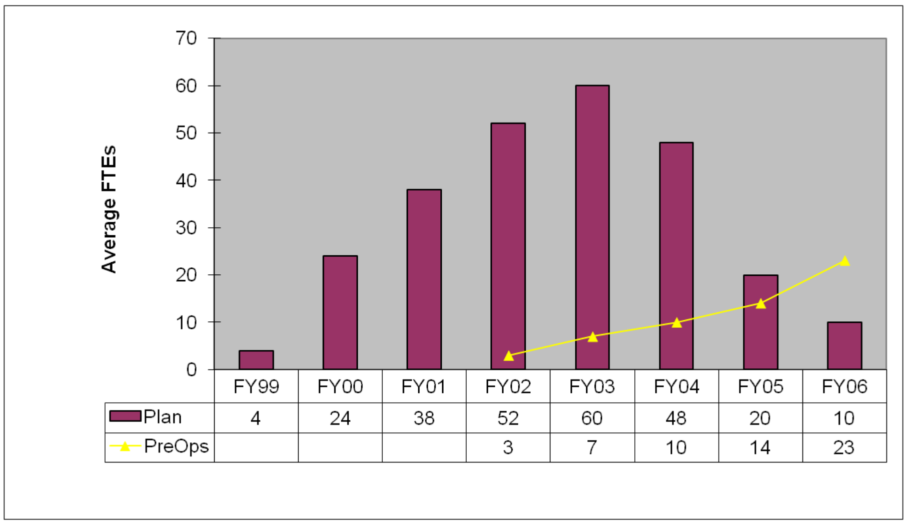
2.1.1. Top Down Planning

Provide a breakdown of costs (time and material) to develop, test and commission the components of the control system. The time unit of planning should be a man-month. The plan should include design and development (timing, MPS, control system services, control room applications,...). Two documents should be prepared:

1. ***Work Breakdown Structure (WBS)*** [3], a spreadsheet focusing on what work should be completed. Define a comprehensive classification of project scope - prepare a hierarchical list of all subprojects/tasks of the project, with time estimates: design(s), development hardware and software that will be used in the entire facility, development of subsystems, commissioning, documentation and ongoing tasks (project management and interaction with stakeholders, training, etc). Try to compile the first signal list (list of devices) for the whole project.
2. Then, prepare ***a detailed project schedule (Gantt chart)***. First, prepare a draft resource list with availability of each resource for the duration of the whole project. Make some decisions on how to combine the following: existing control group members (taking into account their competencies and ongoing work on other projects), new hires, collaboration efforts and outsourcing. Then, on the basis of WBS and resource availability, prepare a project schedule, considering dependencies, critical paths and risks. Define internal milestones and conform to externally defined milestones. Also include the effect of issues that arise as a consequence of risks to overall project schedule. Clearly enumerate all contingencies.

2.1.1.1. Control Group Personnel and Hiring Profile

Use the WBS and Gantt charts as inputs to provide a personnel hiring plan. As a guideline and first approximation, we present the SNS staffing plan [19].



	FY99	FY00	FY01	FY02	FY03	FY04	FY05	FY06
Plan	4	24	38	52	60	48	20	10
PreOps				3	7	10	14	23

Figure 1: planned staffing level for the Integrated Control System (ICS) throughout the construction part of the SNS project.

The planned staffing levels for the SNS are displayed in Figure 1. Each project allocates their groups in different ways, in this case ICS includes in addition to traditional "controls": machine protection, personnel protection, timing, and conventional facility controls.

The yellow line shows staff starting to come on line under the Operations part of the SNS project. The plan called for a total of 33 FTEs as SNS moved into the transition from construction to operations, and this was meant to be the steady-state operation number. In reality, there are 38 people in the SNS control group in 2010: 1 group leader, 25 engineers, 2 post docs and 10 technicians. Five of the engineers spend approximately half their effort as team leaders. For the technicians, 2 are on-site contractors with contracts renewed annually. As necessary, staff is supplemented with off-site contract work to handle additional load. The difference between the early plan and the current situation at SNS can be attributed to many accelerator upgrade and improvement projects that followed initial SNS design, installation, and commissioning.

2.1.2. Bottom Up Planning

Once the WBS and project schedule are prepared, define and track all activities as tasks, each with a well defined scope, time plan, team (task manager and developers) and justification as to how this task fits into the big picture. For each task, write a document that should be a maximum of two A4 pages long, using a consistent template and providing a short task description, task goals, dependencies, assumptions and next steps, architecture, a descriptive picture, and task outline.

Recommendation (III) #6: Prepare a Work Breakdown Structure and task schedule for control system development.

Recommendation (III) #7: Check and regularly iterate the bottom-up plans with the initial task plan.

These tasks fall into one of the following types: design tasks, studies and prototypes, and implementation tasks.

This formalization helps define the scope and deliverables before the actual work is started, which is not always the case in control system groups. This increases the focus and efficiency of the developers, usually members of the control group. As an additional benefit, defining short task summaries enables these documents to be used as a basis to request quotes from an external supplier who is familiar with ESS control system development and requirements.

> **Recommendation (III) #8:** Define and track all control system development and maintenance activities as tasks.

2.2. Project Management System

The SNS control group has a very positive experience of introducing a dedicated project management system (called Controls Request Tracker at SNS) into their control group [4]. At SNS, the system not only provides standard request tracking features, but is interfaced to the SNS Logbook and will be interfaced to work control system, used throughout ORNL.

SNS has introduced the system after commissioning. However, since the SNS experience was very positive, we suggest that a project management system is used from the start of project controls development.

Some examples of project management and issue tracking systems are:

- Bugzilla [5] is a "Defect Tracking System" or "Bug-Tracking System". Defect Tracking Systems allow individual or groups of developers to keep track of outstanding bugs in their product effectively. Pros: Bugzilla is free and has a very wide user support. Cons: it is not a full project management system, as it focuses primarily on software bug tracking.
- JIRA [6] combines issue tracking, agile project management, customizable workflow, and a pluggable integration framework. Pros: a commercial application with good support. Cons: it is a payable service with a licensing model that depends on a number of users. There are discount for research institutions.
- Cosy Project Manager (CPM) [7] is a scientific project management and control tool which focuses on research institutes. Pros: tailored for control groups, used at SNS, very customizable with full access to all the code. Cons: Installation is not free (work for installation is charged), the tool is not widely adopted, and there is limited support.

ESS should also consider possible integration of several of these systems (e.g., CPM project reports with Bugzilla interface for entering bug reports).

> **Recommendation (III) #9:** Use a dedicated project management system to track all the developments of control system group from the start of control system development.

2.3. Development Procedures

ESS plans to adopt a top-down approach (everything flows from the database) for controls and physics development. This approach was attempted before, but was not carried out in full (e.g. in SNS). At this stage, several projects (ITER, NSLS-II) are also planning to use this approach. We propose collaboration with both projects on how to make the top down approach a success.

The factors determining success of a top-down approach are more organizational than technical. Nonetheless, some technical processes must achieve a suitable level of maturity to make the top-down approach feasible – in particular, the model must be stored in a database in such a way that it can be then be used to generate artifacts normally obtained with manual bottom-up activities (e.g., generation of EPICS database from the signal list). Further discussion of this topic is in Section 4.

The top-down approach introduces two significant risks to the project.

The first is frequently termed "**analysis paralysis**": a lot of time and effort spent on planning, analyzing and modeling, without actual prototype artifacts (executable code, configured IOCs, etc.) being produced. With a long enough delay, management can decide to abort the top-down approach as unproductive and just "start coding", proceeding with only a full-blown bottom-up approach.

The second is the risk of having an **unrealistic development process** and **limited development tool support** in place that is difficult or even impossible to follow in practice, which would then be frequently bypassed, preventing the measures necessary for the success of a top-down approach (e.g., naming conventions and user interface guidelines) from being properly enforced.

To mitigate the two risks, we propose the following:

> **Recommendation (III) #10:** Provide automated and convenient interface tools connecting RDBs to EPICS configuration files. The tool should be able to generate bottom-up artifacts from the model.

This issue is very important, so we recommend having a person (utility programmer) assigned to develop these tools as a priority. One example is a tool for generating EPICS configuration database files from signal list stored in the model.

> **Recommendation (III) #11:** Distinguish between 1) development and early testing and 2) factory acceptance at the partner institutions. The process [54] for the first option should be straightforward (make life of developers easy, everything for development and initial testing should be installed and be run on a single developer machine), while the second is more stringent and acts as a local integration test by the partner institution.

2.3.1. Development Guidelines

Where possible, tools should be developed and used that automate conformance to the standard. For example, instead of specifying a code formatting convention in a particular programming language, a code formatting tool should be chosen and configured to fully automate this task.

> **Recommendation (III) #12:** Launch a pilot project in ESS Control group, introducing a prototype development process and development tools.

> **Recommendation (III) #13:** Enforce development standards defined in a short *development guidelines* document.

> **Recommendation (III) #14:** Perform regular internal code reviews.

2.3.2. Signal List

For every subsystem, a signal list should be established in a pre-defined format. It should be a part of every subsystem's design reviews and acceptance tests.

The signal list shall feature all the hardware I/O signals as well as any required software signals generated by IOCs that are of interest to other subsystems or to the general ESS control system. In principle all these signals should be logged by the central ESS control system.

The signal list should be entered into the model early in the process. In an ideal case, the signal list document (input for design reviews) would be generated from the model, avoiding a duplicate and error-prone work of first composing the document and then entering signals into the model.

2.3.3. Self-description

Subsystem configuration data is stored in different file formats, sometimes even in different places (e.g. EPICS database files and PLC configuration files). We recommended that all configuration data is stored in one place that easy to display and edit, and is under version control.

The boot-time configuration files should be generated (as much as possible) from these single-source files.

2.3.4. Development Infrastructure

To aid development according to modern software and hardware engineering practices, the following infrastructural services will likely be required:

- At least one file server (e.g., NFS, AFS or Windows shares – SMB) to facilitate efficient file sharing between developers, and consistent development system environment.
- **Recommendation (III) #15:** Set up a continuous integration build server.

  A continuous integration (build) server can build the full ESS controls code base, then execute automated test suites whenever source code or a model under version control change. Nightly builds should be executed to catch problems early in the code integration process.
- Central EPICS services, such as archiving. Several instances of the archiving server might be required (e.g., one per subsystem).
- **Recommendation (III) #16:** Use a version control system (e.g. Subversion).
- Issue tracking tool (e.g. Bugzilla). Consider integrating this system with general project management system or use one system for both activities. (See Section 2.2)
- A database (e.g., Oracle or MySQL) for storing the model. Several replicas of the database should be available, including:
  - The central (production) database.
  - A subsystem database, shared by subsystem developers.
  - A developer's database, local to the developer's computer (e.g., to facilitate offline development and to decouple the developer from the rest of the team when required).

2.3.5. Quality Management

The development process should have the following key activities (Figure 2):

- **Analyze requirements**. Define what is required of a (sub)system both in terms of functionality (e.g., what parameters need to be controlled), as well as in terms of non-functional requirements (e.g., performance – number of operations per unit time, scalability – the amount of data involved, security – access rights for various types of users, etc.).
- **Define architecture.** How the (sub)system is structured in further subsystems, and identification of components (subsystem that are not further subdivided). Assignment of responsibilities to the subsystems, and identifications of interfaces, data flows and dependencies between subsystems and external systems.
- **Define external interfaces**. Definition of interfaces – either user interfaces (e.g., mock-up screens) or application programming interfaces/APIs – with other subsystems.
- **Prepare test plan**. In this activity, the tests are defined against which the subsystem will be verified once the implementation is complete. The tests are either automated or manual.
- **Prepare environment**. In this activity, the development environment is set up. However, the bulk of this effort can be performed once for the entire project by setting up the Control Box metaphor (Section 3.2). As a result, each subsystem development team would get a Control Box, along with instructions and examples on how to develop and test the developed functionality.
- **Verify**. Verification activities to ensure that the subsystem is built according to specifications. Any issues should be tracked with the issue tracking tool. The verification is done in according to the test plan, and is performed twice:
  - By the partner institution development team / subsystem development team (the **Factory Acceptance Test – FAT**). In this execution of the test plan, external subsystems may need to be simulated, and only a subset of the full model is used.
  - By the Lund integration team (the **Site Acceptance Test – SAT**).

  The vast majority of functionality can be tested in an internal acceptance test – FAT – by the subsystem development team, which will greatly reduce the load on ESS controls and systems integration staff when accepting deliverables from the ESS partners.

  Recommendation (III) #17: Provide FAT checklists and guidelines to add additional tests and distribute them together with Control Boxes.

(In the figure, other activities are shown, but for brevity we stress only the most important ones in the above description.)

Each of the activities should be described in more detail, giving step-by-step instructions to the developers on how to follow them. Also, a check-list should be provided for each of the activities to avoid problems early in the development process, preventing costly rework. The check-lists should be based on industry practices, but they will evolve throughout the project.

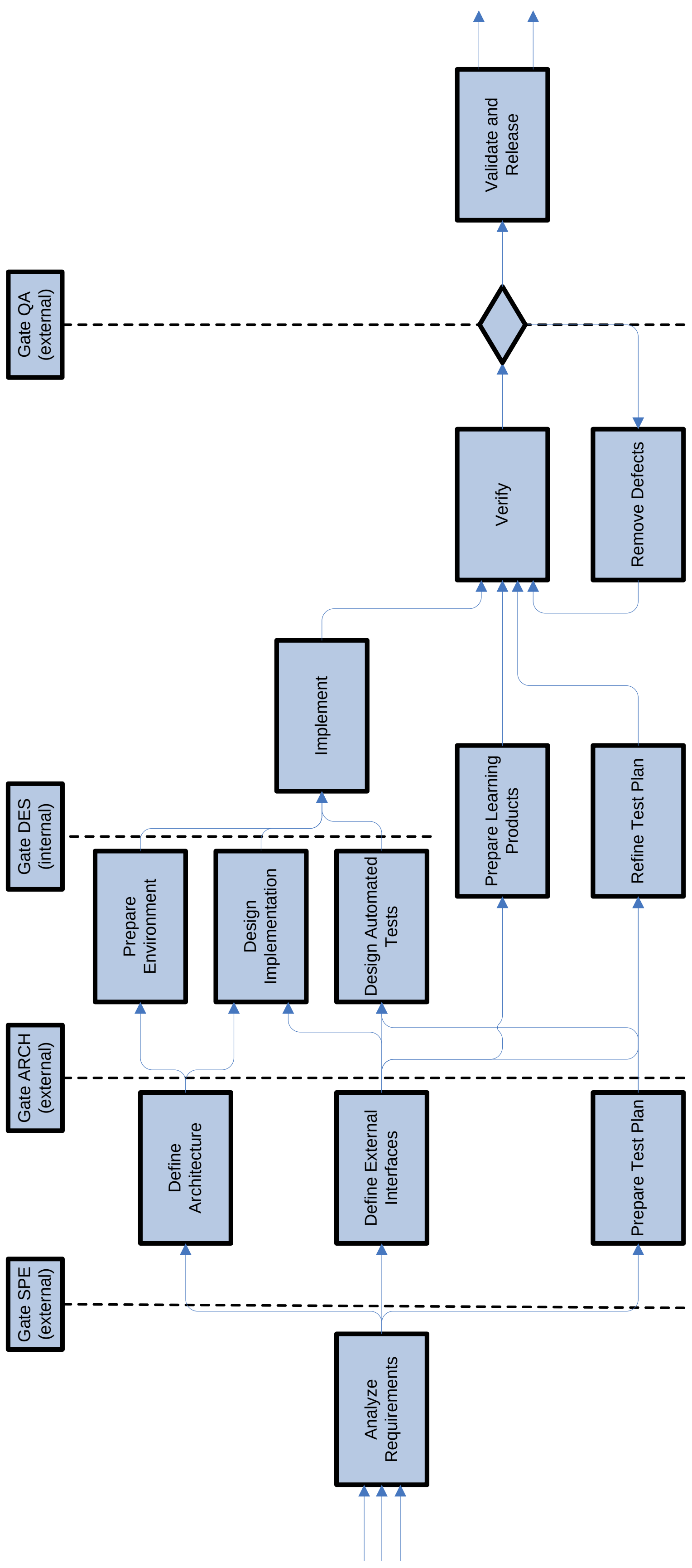


Figure 2: a possible development process workflow.

Wherever possible, automate verification of the check-lists, or the tool support should be such that check-lists would be impossible to violate. For example, when defining a new signal, the naming convention rules would be used by the signal entry tool to prevent violation of the naming convention.

Though the depicted development process implies a waterfall-style of development, we note that the process should be iterative and agile as well.

> **Recommendation (III) #18:** Set up an ESS development process that is iterative and agile, with a waterfall style of development for each iteration.

To achieve this, each subsystem would be built not in a single repetition of the depicted process, but in several repetitions. Each repetition would address some of the functionality, in such a way that the process can be carried out in a rather short amount of time (at most a few months).

Also, during actual construction (*design* and *implementation* activities shown in the workflow) several intermediate releases – iterations – should be planned, so that stakeholders (e.g., the operators) can experience the behavior early, and steer further development if needed. This way, requirements specification phase can be less exhaustive. Also, requirements analysis is usually fairly abstract, and attempting to be too detailed in that phase can lead to the analysis *paralysis syndrome* discussed above.

> **Recommendation (III) #19:** Invite operators from other facilities (e.g., SNS) to participate in design activities of the ESS controls.

> **Recommendation (III) #20:** Provide a simulation framework for the ESS, along with a few simulated operation scenarios.

During the development process, controls should strive to simulate the machine at all appropriate levels: e.g., within the EPICS database and in XAL.

Quality management standards should be adopted to enable the iterative continuous improvement process described above. For example, the ISO 9001 standard [50] and CMM level 5 [51] require that the development process is continuously improved. In the proposed approach, the reported issues would be analyzed to determine what the cause of an issue was, and based on this analysis; check-lists would be refined.

3. ARCHITECTURE

Assumption #21: Linux will be the operating system in the service tier.

Assumption #22: ESS will use the EPICS control system.

For the ESS control system, a slightly modified three-tier architecture is suitable [12]. The three tiers, depicted in Figure 3, are:

1. **User interface** (upper right in the figure). These are graphical and non-graphical user interfaces. Most of them will be in the control room, but some will be elsewhere, e.g., for site-wide monitoring of the ESS status, and for remote access.
2. **Central services** (upper left in the figure). Computer services that need to run continuously irrespective of user's activities, e.g., for archiving of process variables' values, monitoring of alarm states, slow feedback loops, model of the machine as a whole, and management of activities that require coordination of several subsystems.
3. **Equipment interfaces** (bottom in the figure). This tier is responsible for interaction with equipment and devices. It serves two purposes: to provide an abstract representation of equipment to higher layers through which the equipment can be monitored and controlled, and to implement real-time control loops.

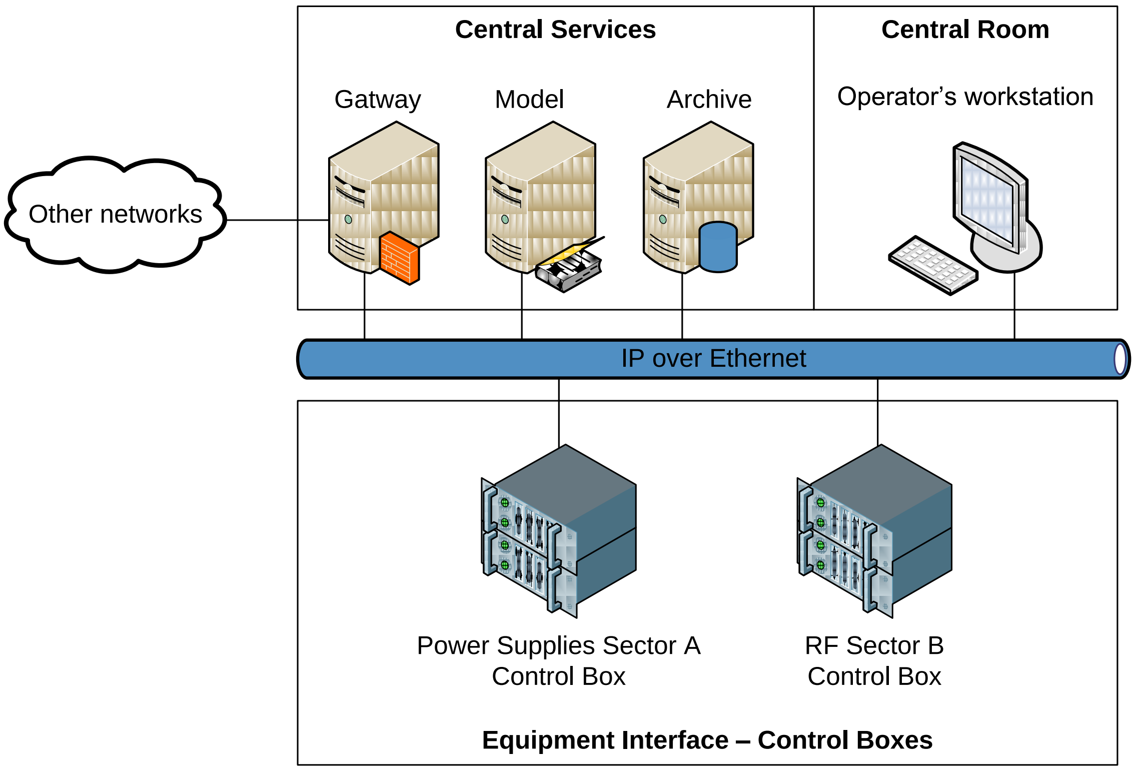


Figure 3: a three-tier architecture of the ESS control system.

The three tiers are physically on separate computers. The characteristics of these computers on each tier are as follows:

- The computers of the user interface tier focus on ergonomics and usability. Examples: *Apple iMac*, *Microsoft Windows* or a *Linux* distribution optimized for desktop use (e.g., *Gnome* or *KDE* user interface).
- The computers of the service tier offer high CPU performance, reliability and – depending on purpose – have access to substantial storage capacities. Examples: *HP ProLiant*, *Dell PowerEdge*, etc. *Linux* will be used as operating system of this tier.
- The computers of the equipment interface tier have a wide assortment of different input/output capabilities. The platform would likely be modular to allow various types of input/output through field buses and custom-developed hardware. Examples: *National Instruments PXI*, *ATCA*, *VME*, etc.

3.1. Scope of Control System

The scope of the ESS control system is control of all equipment that is responsible for producing and steering the beam from source to target, including all the support subsystems (vacuum, HVAC, etc), and all the relevant control system services (archiving, alarms, compare/restore, etc).

Assumption #23: The personnel protection system (PPS) and machine protection systems (MPS) will not be direct parts of the single controls network.

Assumption #24: All subsystems that need to take into account nuclear engineering safety regulations are not part of the control system (e.g. target protection system).

The PPS, MPS, and other systems should be monitored through network gateways and/or dedicated control system hardware, but this hardware should only provide read-only readbacks of those systems' states for archiving and correlation to other machine activity.

3.2. The "Control Box" Metaphor

The Control Box metaphor is based on the philosophy adopter by ITER [23]. In ITER terminology, the Control Box philosophy is realized with the concepts Plant System Host, mini-CODAC and plant system I&C.

The main purposes of the Control Box are to:

- allow independent and yet standardized subsystem controls development,
- encourage and enforce consistency between sub-systems (including target and experimental stations),
- facilitate testing of new components (e.g. EPICS drivers),
- allow factory acceptance testing of subsystems through the control system,
- validate technology decisions,
- reduce the risks early to prevent unexpected surprises at project integration time,

- force the controls group of ESS to make and document early decisions and prevent chaotic behavior of all parties involved,
- minimize throw-away hardware and software development

The Control Box hardware and software are composed of two main logical parts:

- services and operator interfaces,
- device control with an EPICS IOC.

An example structure of a control box is shown in Figure 4.

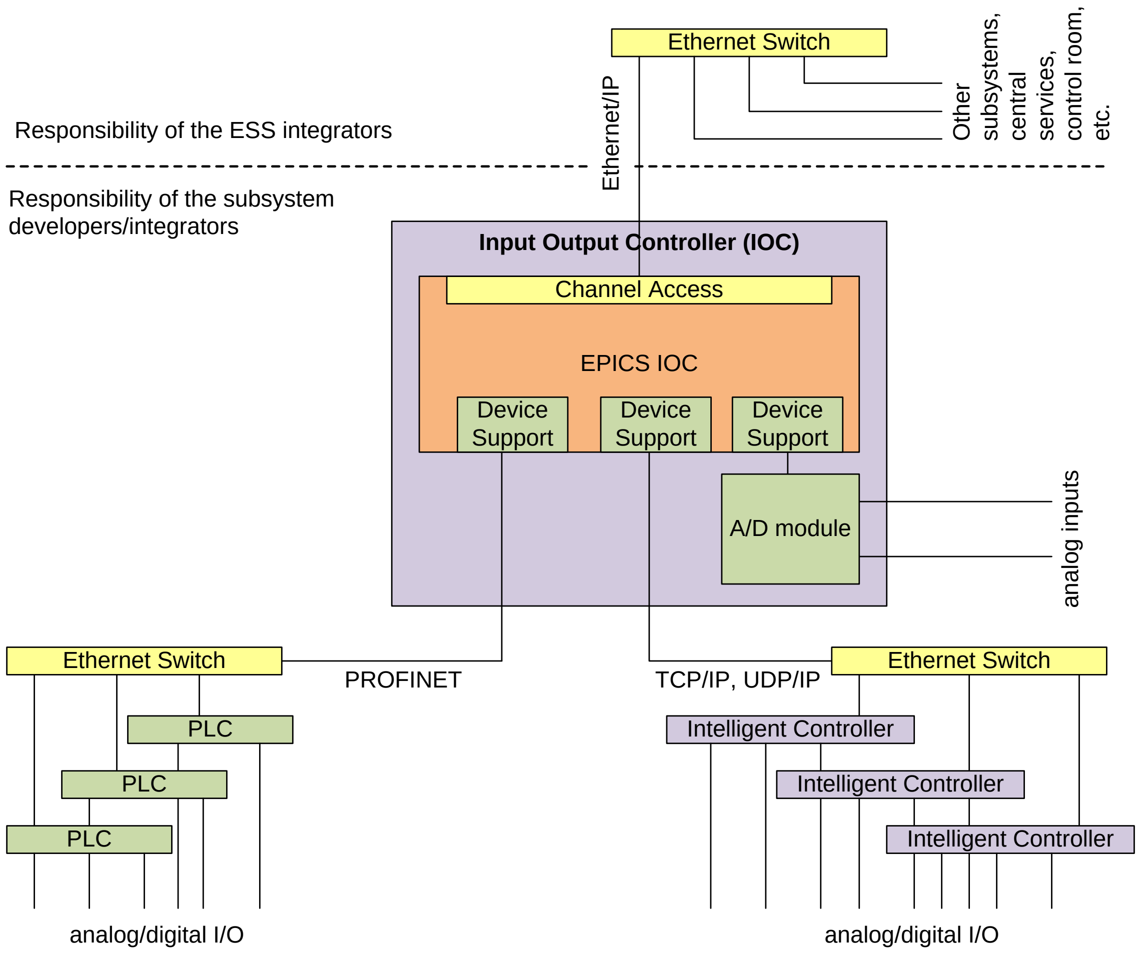


Figure 4: a schematic of example Control Box components for a representative Control Box example.

Possible layouts and structures of Control Boxes should be specified.

<u>Recommendation (I) #25:</u> Follow the ITER design approach for Control Box internal structure [24].

See the documentation by ITER [24] on different possible structures of a Control Box. The equivalent for Control Box internal structure in ITER terminology in this document is "plant system I&C".

A generic Control Box consists of:

- One or more input/output controller (IOC) computers.
- Zero or more I/O modules (analog-digital converters and digitizers, digital-analog converters, serial interfaces, etc.) attached to the IOC computer's hardware bus.
- Software:
  - A real-time or non-real-time operating system, depending on requirements on IOC processing. For example, IOC real-time control loops require an IOC real-time operating system.
  - The EPICS real-time database which maintains the values of all process variables under responsibility of the IOC.
  - EPICS device support, which implements drivers for communication with equipment.
  - EPICS Channel Access, which allows the process variables on the Control Box to be accessed from other computers in the network, and can retrieve values of process variables from other IOCs.
- PLC subsystems for slow industrial controls (e.g., water cooling; HVAC, etc) are connected to the IOC with one of several standard communication mechanisms, such as PROFINET or Modbus TCP/IP.
  - We recommend use of an Ethernet-based bus. This way, the same kind of cabling and switching equipment that is used for other networks is also used for PLCs. Furthermore, the PLC network is easier to connect to the IOC, as a regular network interface card and associated drivers are used instead of a special-purpose PLC bus adapter.
  - Control of a large number of PLC devices may require an Ethernet switch.
  - We recommend use of a separate network for PLCs, so the PLC network traffic is predictable. Otherwise, network traffic could interfere with operation of the PLCs, which are in some cases safety-critical.
- Intelligent special-purpose controllers (e.g., possibly LLRF controllers).

3.2.1. Control Box of Complex Subsystems

In the simplest case, all controlled equipment of a subsystem is located close to the control box, so that the control box's instrumentation can be directly connected to the equipment with signal cables. Such an example might be the ion source and the chopper line, both located at the linac's front end.

In a more complex case, the equipment covers a wider geographical area. For example, the numerous SC cavities, with their associated klystrons and cryo-modules, will be spread along almost the entire linac. In this case, it would be impractical to control them with a single control box.

Thus for each section of length along the linac, we propose to have one control box for each type of equipment. This control box distribution should be optimized between performance, complexity, and cost.

For one-of-a-kind subsystems (e.g., the beam injector), there should be a single control box.

3.2.2. Control Box Development

The Control Box should not be completely defined and developed too early in the project, as the technology landscape to support it is rapidly evolving. We therefore recommend iterative Control Box development.

> **Recommendation (I) #26:** Develop Control Box software and hardware in (e.g., yearly) cycles. The main strategy is to start with software-only aspects (which are easiest to develop, test and distribute), and as soon as possible deliver a Control Box with a simple standardized hardware interface, such as infrastructure PLC control.

In the future versions, functionality will be added (e.g. hardware support, including timing and feed-forward), and tools and support will evolve with available technology.

3.3. Equipment Interface

This section represents the main concepts involved in interfacing hardware equipment to the ESS control system.

Partitioning of the system into subsystems is very important. It is best to separate the control system in subsystems that are closed entities and can be assigned to one vendor, either to an internal team, collaborating institute or to a commercial company (e.g., for the vacuum subsystem).

The Control Box metaphor assures that these systems are treated separately (e.g. not sharing hardware interface units). This implies that strict guidelines for their development must be provided. This will enable clear division of responsibilities and makes integration much easier, particularly for a project with distributed subsystem development such as ESS.

There are two types of an equipment interface, hard real-time equipment interfaces and non real-time equipment interfaces.

A **hard real-time equipment interface** is needed whenever the Control Box must to respond in hard real-time to external events. Recent experience at other facilities indicates that a hard real-time equipment interface is needed only in the minority of cases, because specialized hard real-time subsystems and intelligent special-purpose controllers already address the real-time aspects of control. For example, LLRF hardware will already close real-time control loops. However, when hard real-time is needed, a real-time operating system must be used on the IOC, or the functionality must be implemented in hardware (e.g., FPGA).

Most of the equipment will not require a real-time interface to the control system, as it will not be involved in distributed real-time feedback loops.

> **Recommendation (I) #27:** Propagate real-time information between subsystems only by means of the timing system, i.e. no other real-time communication should propagate between different subsystems.

Following this recommendation isolates all aspects of subsystem real-time behavior to those subsystems. They can then be developed and fully tested earlier in the process, during factory testing and acceptance (Section 2.3.5), rather than later site testing, acceptance, and integration.

A **non real-time equipment interface** has limited responsibility for making process variables and parameters of hard real-time control loops available to other subsystems and user interfaces.

Some equipment has its own real-time control (e.g., PLC systems, temperature regulation, motion controllers, LLRF fast control feedback loops, etc.). Here the control system only needs to slowly control the parameters of these low-level control loops and monitor their diagnostics (e.g., monitoring of PLC registers, setting reference temperature, manipulation of PID control loop parameters, etc.).

Some equipment needs to exhibit real-time behavior, but can be controlled in a feed-forward manner (e.g., high-level control of the superconducting RF). In this case, the control system distributes the information on what actions to take (e.g., waveforms defining value of setpoints as a function of time), and the timing system (see section 5.1) distributes the time and event triggers.

3.3.1. I/O Interfaces

We recommend reducing the number of different I/O types to minimize the required driver development and maintenance.

> **Recommendation (VII) #28:** Select one standard bus architecture with standardized I/O modules.

Examples of I/O modules:

- Time receiver module for providing synchronized time across the entire facility for time-stamping of acquired values and synchronizing time-critical activities. (See Section 5.)
- Ethernet for main control system integration and interfacing of network attached devices (interfacing also serial or GPIB devices and instruments via RS-232 or GPIB to Ethernet converters); this also includes read-only interface to safety and equipment protection systems
- Analog and digital I/O, e.g. for power supply readback.
- Digitizers of various sample rates and precision, e.g. digital oscilloscopes, spectrum analyzers, and other high-bandwidth devices.

3.3.2. Hardware Platforms

There are three main candidates for a general control system IOC platform: VME, ATCA, PCI, and their derivatives. In the table below we qualitatively summarize their principal characteristics according to the following, and rank them relative to each other:

- **Vendor support**: how many commercial vendors of crates and modules exist? A large number implies that the probability of finding an off-the-shelf module for a particular task is larger. Also, a notion on the trend of vendor support is given.

- **Maturity**: how long has the platform has been available and how frequently it is used? Greater maturity implies lower risk and lower probability of backward-incompatible changes in the future.
- **Longevity**: how long is the platform expected to be available? Assessment is given with the ESS's lifetime (several decades) in mind.
- **Maximum transfer rate:** how much data can the platform transport between the modules in a given time? This is a measure of performance, implying both throughput as well as latency.
- **Topology:** how can the modules interact with each other? Master-slaves means one master module orchestrates communication with other modules (slaves), and slaves do not directly interacting with each other. In case of ATCA, the topologies are:
  - Star: each module is connected to a central hub. Modules can interact directly with one another via this central hub. In case of Gigabit Ethernet backplane, the central hub is very similar in function to an Ethernet switch.
  - Dual star: the central hub is duplicated, and each module is connected to both hubs. This provides redundancy in case of hub or link failure.
  - Full mesh: each module is directly connected (point-to-point) to every other module.
- **Form factor**: how large is the physical size of a module, in terms of the module's height in a rack? Larger form factor allows more I/O points on the module, but also increases the amount of rack space that is unused for non-I/O modules.
- **High availability**: how suitable is the platform for high-availability applications? (e.g., support for redundancy).
- **Software support**: how likely will software support (Linux driver, EPICS device support) will be available for a module.
- **Cost**: ranking relative to the cost of the crate and modules.
- **Users**: number of accelerator controls users that have adopted the platform.

	VME	ATCA	PCI[1]
Vendor support	High/Declining	Low/Growing	Medium/Stable
	3	2	**1**
Maturity	High	Medium	High
	1	2	**1**
Longevity	Medium	High	High
	2	**1**	**1**
Max. transfer rate	VME: 40MB/s VME64: 80MB/s VME64x: 160MB/s VME320: 320MB/s	1Gbps, 10Gbps (Gigabit Ethernet); 250MB/s/lane (PCIe)	PCI: 133MB/s PCIe: 250MB/s/lane (up to 16 lanes)
	2	**1**	**1**
Topology	Master-slaves	Star Dual star Full mesh	Master-slaves
Form factor	6U (64 bit) 3U (32 bit)	12U (ATCA) 2U (µTCA)	3U
High availability	Medium	High	Medium
	2	**1**	2
Software support	High	Medium	Medium

[1] PXI, a PCI extension for instrumentation, is being used at CERN, LANL, ORNL and many other accelerators, such as for instrumentation, test and measurements among the selected platforms at ITER). PXI is an open industry standard, modular and rugged, and leverages COTS with built-in timing and synchronization.

(Linux, EPICS)	**1**	2	2
Cost	High	High	Medium
	3	2	**1**
Users	SNS, SLS, Diamond Light Source, …	ITER (considering)	CERN (LHC collimation), LANL, ORNL, ITER (planned)
	1	3	2

Table 1: comparison of VME, ATCA and PCI hardware platforms.

If the decision on the hardware platform needed to be made today, one could consider these pros and cons:

- VME: the conservative approach
  - Pro: significant software support, extensive know-how in accelerator controls community.
  - Con: performance not very high (but likely sufficient), uncertain vendor support in a decade or two.
- ATCA: the cutting edge
  - Pro: high performance, flexibility, endorsed by vendors and the telecommunications industry.
  - Con: instrumentation still evolving, few users in accelerator controls community.
- PCI: the middle ground
  - Pro: high performance, widely endorsed by vendors.
  - Con: few users in accelerator controls community.

The hardware platform requires a clear decision, for which an agreed set of requirements must be produced. We believe that the best way is to go for lowest total cost of ownership and lowest risk by making similar decisions as were made in other contemporary projects. One should not look for the best platform in terms of performance, although top performance means that it will be still adequate in a few years time. But this is not enough. Instead, one should look for a platform that will be most likely accepted by the majority **in the industry**. That means that one shouldn't look just at other labs. The reason is that a well accepted technology determines a complete and broad market that not only provides many manufacturers (and thus lowest prices) but also a vast number of users that will be using and developing the same technology, leading to more available COTS solutions and more developers who are familiar with the selected hardware platform.

<u>**Recommendation (VII) #29:**</u> Select the hardware platform after the three year milestone. When making the decision, base it on **usability** (i.e. what you can do with the platform and how well the relevant tools are debugged) and **longevity** (i.e. how long will it take before the platform becomes obsolete/outdated).

3.3.3. Software Platforms

The IOC operating system might need to provide real-time performance, but this is only required for feedback loops that span several IOCs, and these are expected to be rare: most of the fast real time feedback loops will be developed below the level of the IOC.

<u>**Recommendation (III) #30:**</u> Evaluate the needs for real-time operating system. The key decision criterion is how timely the application must respond: if fast reaction times are required (less than a few milliseconds), a real-time operating system should be used.

The choice of the operating system should consider several factors. Of course, the latencies must be sufficiently low to meet the requirements. Apart from this, the operating system should allow management of deployed software (e.g., via a package management system), so that configuration management of deployments is simplified. A crucial aspect of the operating system selection is manageability of installed application software (e.g., IOCs and control system infrastructure, such as EPICS). In particular, the operating system should have configuration management mechanisms that support software installation, upgrades, and maintenance from a centralized location. This is an important aspect for production where software releases need to be tightly controlled. This is also an important aspect for development and testing, where development against an unexpected version of software can result in unnecessary confusion and debugging efforts.

For some operating systems, EPICS is already available in form of installable packages:

- For the NSLS-II project, BNL has packaged EPICS in Debian-compatible packages (DEB) [52], primarily meant to be compatible with Debian stable distribution, but in principle also useful for other DEB-based Linux distributions such as Ubuntu.
- The ITER project has packaged EPICS in Red Hat Enterprise Linux compatible packages (RPM). Apart from EPICS RPMs, ITER has also developed tools that allow developers to conveniently package their applications (IOCs and operator interface screens) in installable RPMs.

We note that packaging EPICS – and ensuring that the packaging remains in sync with the evolving underlying operating system – requires significant effort, on the order of one person-year for initial packaging, and 10% FTE for maintenance. Though this effort is still less than the overheads and productivity loss when packaging is not used, we recommend leveraging of one of the above packaging approaches for EPICS.

For production environments, an approach where the IOCs boot from a network file system is common (e.g., SNS uses it to boot VxWorks-based IOCs). This way, central administration of all IOCs is manageable.

However, configuration of the development environment, servers and control room workstations must be under full centralized control, as otherwise uncontrolled changes to the environment are easy to perform and difficult to detect.

For ESS, Mac OS is under consideration as the operating system for operators and developers, since ESS employees have the most experience with it. However, we note that Mac OS in not widely used as a software platform in other accelerator sites that use EPICS, which means that ESS would need to rely mostly on its own resources if this operating system choice is extended to main control room controls. Alternatively, ESS can use Mac hardware and use Linux distributions mentioned above, e.g. with BootCamp, VMWare, or Parallels.

3.4. Service Tier

Various software and hardware services reside in the service tier. These include both standard internet services, such as DNS for IP lookup and NTP for computer clock synchronization, and services specific to the control system such as web services, archiving, alarm monitoring, and online modeling. Services are expected to be available at all times while the facility is operational, and some should have high availability during maintenance and shutdown. Some services may require significant processing resources or disk storage. Services should therefore reside on powerful computing equipment, such as data center-grade servers.

We describe some of the most important services of the service tier in the following subsections.

3.4.1. Database

It is likely that a relational database management system (RDBMS)[2] will be used for storing at least some of the ESS data. Data that is suitable for storage in RDBMS includes:

- Model of the facility.
- Information about equipment, cabling, and other inventory.
- High level machine configuration parameters. An application to review this data should be written.
- Configuration of IOCs.
- Beam configurations.
- Archived values of process variables[3].
- Operator’s log book.
- Data to assist development and maintenance (project plans, issue tracking, etc.)
- Documents (e.g., designs, procurement documentation, etc.)

Several RDBMS implementations exist. We recommend, however, that ESS limits the number of different RDBMS implementations in use, to reduce the IT effort and skills required to maintain them.

[2] Even though other database technologies exist (e.g., object databases), RDBMS systems are still mainstream. We therefore suggest that ESS also uses a RDBMS, but uses object-relational mapping techniques to store object-oriented data.

[3] EPICS already has an archiving service (*EPICS Channel Archiver*), which stores process variable data in binary files, optimized for storing EPICS PVs. Therefore, an RDBMS probably won’t be used for this purpose.

Assumption #31: ESS will use the Oracle relational database system.

3.4.2. Alarm System

Each PV can have associated alarms in EPICS. The alarm concept is simple: when a value of a PV is outside certain configurable bounds, EPICS raises an alarm flag associated with the PV. All clients connected to the PV are then notified of the alarm state change.

Traditionally, the *EPICS Alarm Handler* OPI application is used to monitor the status of alarms. However, this approach has several drawbacks, among them:

- If the alarm handler OPI is not running, the alarms are not monitored.
- If two operators wish to see the alarms, each needs to run its instance of the alarm handler OPI, which increases the number of network connections to the IOCs.

To mitigate these drawbacks, ORNL has developed an EPICS alarm system called BEAST [53]. BEAST consists of two parts:

- The alarm server.
- The alarm client GUI (user interface).

The alarm server resides in the services tier. It requires several supporting services:

- A Java Message Service (JMS) broker (Apache ActiveMQ implementation), which provides infrastructure for asynchronously and reliably sending messages between processes.
- A Java-based Tomcat web server for providing access to statistics about alarms.
- A relational database for storing alarm transitions and acknowledgements, and for configuration of the alarm system.

BEAST uses JMS to send notifications about alarms to the GUI, and alarm confirmation/acknowledgement from GUI to the alarm server. Also, JMS is used for voice-based alarm annunciation, and for logging of alarm state changes in a relational database.

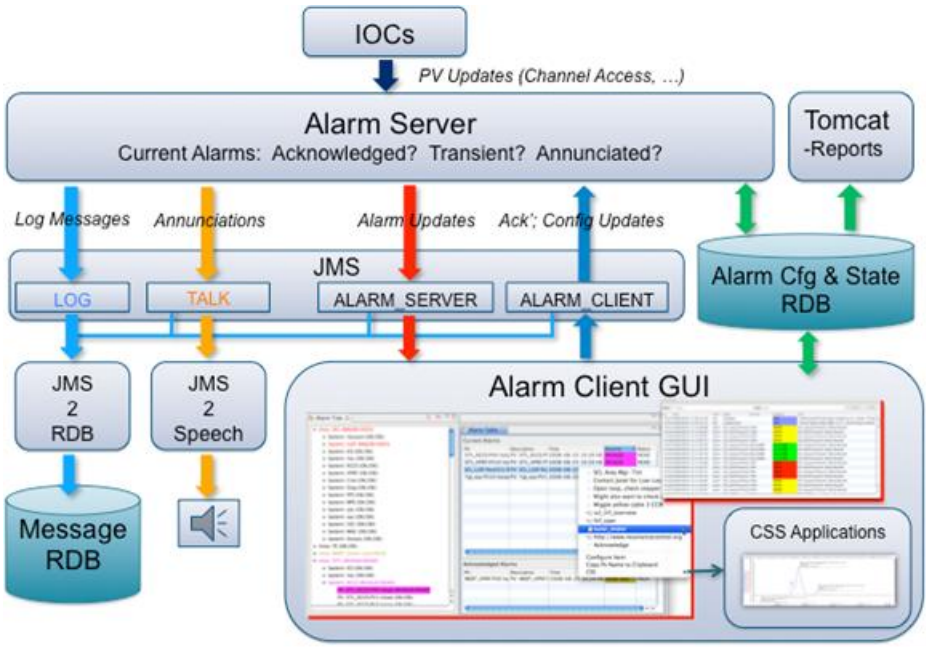


Figure 5: the EPICS BEAST alarm system architecture [37].

Recommendation (III) #32: Define a set of procedures when introducing alarm states from the very beginning. SNS has based its recommendation on an industry standard book: Alarm Management: Seven Effective Methods for Optimum Performance, by Bill R. Hollifield and Eddie Habibi [27].

3.5. Control Room Software

Control room software is all the software that is used directly by the operators in the control room. Since control room software is so exposed to the final users of the control system, its perceived usability has a very large effect on the overall satisfaction of the users with the control system.

SNS has prepared a document on HMI [21]. However, the SNS document focuses heavily on HMI design with a generic EPICS tool called EDM. The ESS document should provide more general guidelines that are less dependent on the specific tools used.

Recommendation (III) #33: Select a single software platform (operating system and version) for operator consoles.

Recommendation (III) #34: Assign a role of GUI tzar: a person within the control group responsible for enforcement of user interface design guidelines for all control room applications.

3.6. Computer Networks

For the ESS control system, a single computer network will be sufficient. The network will likely be based on the Ethernet physical level, and will leverage IP, TCP and UDP protocols via EPICS.

The network interfaces of most computers would be 1Gbps, however some computers with large I/O or data processing requirements may need a 10Gbps interface.

Commercial off-the-shelf switching equipment (e.g., HP's *ProCurve* and *Cisco's* switches) should be sufficient to accommodate the network traffic of the ESS control system.

Topology of the controls network will probably be a star, with several levels of switches:

- Edge switches for interconnecting of control boxes/equipment interfaces.
- Edge switches for connecting user interface consoles in the control room.
- A system of backbone switches.

Our preliminary estimate is that edge switches should have ports with at least 1Gbps capacity, and the backbone should be implemented with 10Gbps switches. Uplinks from edge switches to the backbone should also be over 10Gbps links.

In some cases when control boxes will be connected with sophisticated instrumentation equipment via Ethernet, a switch will be needed between the equipment and the control box.

Physical topology should take into account two things:

1. Traffic patterns. For example, if there is intense traffic between nodes A and B, the number of hops (switches) on the path from A to B should be minimal, and all links should be of sufficient capacity.
2. Physical location of nodes. Switches should interconnect to nodes that are nearby. For example, each section of the linac could have a switch.

In principle, all controls equipment could be on the same subnet. For example, if the 10.x.0.0/16 subnet is chosen, about 60.000 IPv4 addresses would be available, which should be sufficient for ESS control needs. This would introduce fewer issues with network administration, but UDP broadcasts would be received by all nodes on the subnet. UDP broadcasts can be minimized or eliminated in EPICS by using a centralized naming service to locate process variables.

If several subnets are chosen, network administration issues would need to be addressed. In particular, routing on the gateway routers would need to be properly configured, and in case physical boundaries between subnets don't match logical divisions, virtual local area networks (VLANs) would need to be introduced and properly configured. Also, at least one EPICS Channel Access Gateway [17] would then be used to allow access of process variables across subnet boundaries. Use of the Channel Access Gateway introduces two drawbacks:

- Configuration is nontrivial for cases when data communication between subnets is needed.
- Additional latency occurs during data transfer, because it intermediates in the relay of all PV data, not just during name resolution

We note that even though centralized naming server implementations exist (e.g., [14]), they should be thoroughly tested. Additional features, such as access control, might need to be implemented; Channel Access Gateway already provides access control.

Recommendation (III) #35: Use a single subnet and a centralized naming server instead of UDP broadcasts for discovery of EPICS process variables.

3.7. Software Frameworks

In this section we survey the recommended frameworks for developing control system applications. A software framework, in computer programming, is an abstraction in which common code providing generic functionality can be selectively overridden or specialized by user code providing specific functionality. Frameworks are a special case of software libraries in that they are reusable abstractions of code wrapped in a well-defined API, yet they contain some key distinguishing features that separate them from normal libraries [32].

For each of the frameworks, we provide the scope of the framework's applicability and emphasize its strengths. Then we list the risks and drawbacks of the framework that are either inherent in the framework's architecture, or are specific to the framework's application to ESS. Finally, we propose what steps to take to address or mitigate these risks.

Firstly, we note that software frameworks are important and should be used, as they address non-functional requirements, such as scalability, look & feel of the graphical user interface, communication among distributed processes, etc. By leveraging a framework, the developers of control system applications can focus their efforts on the functional requirements of the application(s) they are developing, significantly improving their efficiency.

> **Recommendation (III) #36:** Use software frameworks as a basis to develop high-level control room applications.

3.7.1. XAL

A Java programming infrastructure for high level applications has been developed and is being used for the Spallation Neutron Source (SNS). The framework provides a hierarchal view of the accelerator and hides most of the underlying control system details. The hierarchy is database configured, facilitating application sharing across different beamlines, shielding the programmer from detailed knowledge of signal names, and allowing wholesale updating of applications. An important part of the framework is an online model, which can be consulted for design values, live machine values or user selected tuning values [47].

Since it is impossible to provide everything early on, flexibility is required from application developers. This was the reason that XAL was developed: it has enabled rapid application development of physics applications at SNS.

At its core, XAL supplies the model of the accelerator, making adaptation of the top-down model-based approach of ESS more straightforward. Other frameworks, in particular CSS, do not (yet) provide an accelerator physics model.

Apart from the model, XAL also provides a general-purpose application development framework, and a suite of user interface widgets (e.g., for charting).

If possible, a single application development framework should be used. This will improve interoperability between applications, ensure common look-and-feel across all applications, and make development easier, as there would be no need to decide on which framework to take for a particular application (there being only one), and developers would be able to focus on a single application framework, improving the quality of their skill-set.

The widgets provided by XAL are very likely generally useful. E.g., if the application framework is based on Eclipse Rich Client Platform of CSS (see section 3.7.2), the widgets of XAL could still be used, even though even the graphics toolkit is different [35].

Recommendation (I) #37: Join the XAL collaboration.

Recommendation (III) #38: Use XAL for ESS physics application development environment and participate in XAL development efforts from the beginning of ESS project.

3.7.2. Control System Studio

Control System Studio (CSS) is based on the Eclipse Rich Client Platform and is the result of a continuing collaborative effort between DESY [33] and SNS. CSS is an environment that allows the implementation of applications for use with control systems. Because these applications are implemented in one environment, they present a common look and feel to the user. CSS is designed to give facilities the ability to customize the functionality contained within the environment by choosing the various applications or plug-ins that are included. CSS is developed using the Eclipse development environment and is written in Java [49].

Recommendation (I) #39: Evaluate CSS for its applicability at ESS.

CSS already provides several plug-ins that provide the following user interfaces:

- User interface for alarms (viewing, acknowledgement, guidance for resolving alarm conditions).
- Engineering, SCADA-style screens for subsystems (BOY and SDS plug-ins).
- Viewing and editing of EPICS databases (DCT).
- Monitoring of EPICS Channel Access traffic on the network.

3.7.3. Other Frameworks

The frameworks mentioned above are the most comprehensive toolkits that are presently available for developing applications integrated with EPICS. However, there exist toolkits that cover some of the application development needs, for example:

- Qt framework [36] facilitates development of highly responsive cross-platform GUI applications in C++. Qt is already integrated with EPICS [37].
- EDM is an editor and run-time engine for engineering screens. It allows widgets to be bound to EPICS PVs (either for monitoring values which then update the widgets dynamically, or by setting values to the PVs). It is very responsive and allows development of screens in a short time; however it is difficult to make good-looking and flexible screens.

3.7.4. Comparison of Software Frameworks

For each of the frameworks, we provide the scope of the framework's applicability and emphasize its strengths. Then we list the risks and drawbacks of the framework that are either inherent in the framework's architecture, or are specific to the framework's application to ESS. Finally, we propose what steps to take to address or mitigate these risks.

XAL:

Strengths: physics modeling, high performance GUI widgets, EPICS integration

Drawbacks: off-the-shelf application framework not leveraged, not very wide-spread

Preliminary advice: decouple physics modeling and GUI widgets from the rest of the framework and use in the framework chosen for ESS. Join the XAL collaboration.

CSS:

Strengths: extensible user interface, large number of applications, support for engineering screens, look&feel uniformity, EPICS integration.

Drawbacks: some plug-ins/components are duplicated (SNS and DESY version), somewhat heavyweight if all plug-ins are installed

Preliminary advice: Choose as application framework. Decide which plug-ins are useful for ESS. Adapt parts of XAL for CSS (physics model, GUI widgets).

Qt:

Strengths: very responsive applications, good looking user interface, consistent look-and-feel.

Drawbacks: limited use in EPICS community.

Preliminary advice: follow rate of adoption in the EPICS community.

EDM:

Strengths: very responsive, easy to compose engineering screens.

Drawbacks: technologically and aesthetically outdated, difficult to maintain look&feel.

Preliminary advice: use CSS instead.

	XAL	CSS	EDM	Qt
Complexity (high: steep learning curve)	Medium	Low	Low	Medium
	3	**1**	2	4
Strength of collaboration	ORNL, SLAC	DESY, SNS, possibly ITER	Not actively developed anymore	Nokia (Qt framework), NFRI (Qt+EPICS)
	2	**1**	4	3
Support for physics	High	None	None	None
	1	2	4	3
Support for large datasets	3	4	2	**1**
Flexibility/extensibility	2	**1**	4	3
Support for internationalization	3	**1**	4	2
Help system for end-users	3	**1**	4	2
Users	ORNL, SLAC	DESY, SNS, possibly ITER	All major EPICS shops	NFRI
	3	2	**1**	4

Table 2: comparison of XAL, CSS, EDM and Qt software frameworks.

3.7.5. Tools

The ESS project will benefit from a common software infrastructure that addresses non-functional aspects, such as remote/distributed communication, look and feel, security model, logging/diagnostics, ESS-specific installation configuration, etc.

Significant leverage will be obtained by choosing a common, readily available framework such as EPICS, but ESS-specific adaptations, customizations and additions will nonetheless be required -- for example, export of TraceWin and Trace3D lattice descriptions from ESS databases.

Recommendation (III) #40: Assign a full-time tool developer position for the construction phase.

4. Data Management

When the ESS control system is built and integrated, it will be distributed across several hundred control boxes, and there will be dozens of applications running in the control room and on central servers. The control boxes will be distributed around the racks in the facility, interconnected with numerous cables and to various kinds of equipment.

In such a large system, it is recommended that an inventory of all equipment and control points is maintained in a central database, so that information about location and interconnectedness is conveniently available. Such a database can be used to support the following scenarios:

1. Quickly locate a control box (e.g., because it is faulty, or it needs to be modified).
2. Determine where a certain process variable is hosted.
3. Determine where a certain process variable is used, to evaluate impacts of its change to the rest of the system.
4. Understand avalanches of alarms by tracing connections between components in fault.
5. Obtain documentation (technical documentation, purchasing documents, installation history, etc) associated with equipment.
6. Generate a signal list for automated archiving or logging, to support viewing and correlation of historical settings and/or readbacks of certain process variables.

Engineering a single database solution that would support all the uses stated above is possible, but would require significant development effort. Instead, we recommend that existing solutions are adopted and integrated, as follows:

1. For technical, purchasing, and installation documentation, a documentation and installation management tool (e.g., CERN's EDMS system).
2. For inventory information (process variables and their hosts), a tool such as IRMIS
3. For historical values of process variables, a tool such as EPICS Channel Archiver

In some cases, information between systems might overlap. In such cases, one of the systems should be designated as the owner of a particular piece of information, and processes should be developed to reliably copy this information to other systems.

4.1. Bottom Up vs. Top Down Approach

In many existing controls projects, the central database/inventory was introduced late in the project, usually to support installation or maintenance activities. Thus construction of this database was done in a bottom-up fashion: EPICS IOCs were configured and brought together, and then the database was populated by »reverse engineering« the installation.

However, there are several benefits if the central inventory database is introduced early in machine design:

1. It is possible to simulate the system as a whole early, without having all the IOCs in place.

2. The central database can serve as an input to the installation and/or commissioning plan.
3. It is easier to enforce naming conventions (Section 4.2).
4. A name server can be easily configured from the database.

We propose that an inventory and control point database is established as soon as possible. CERN EDMS has already been adopted by ESS as the inventory database; IRMIS can be used as an EPICS-supported control point database. The linac lattice design database is a good starting point for their contents.

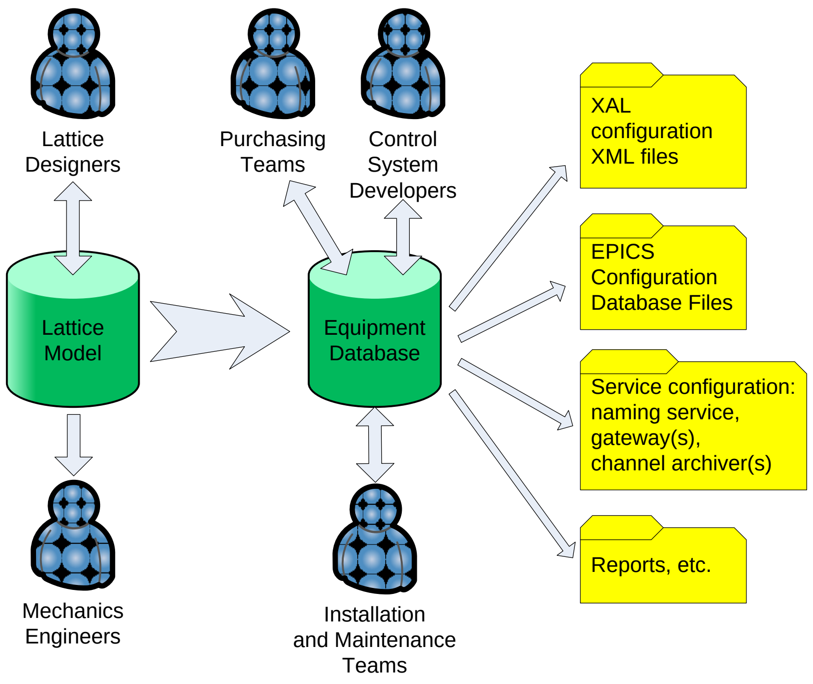

Lattice Designers
Purchasing Teams
Control System Developers
XAL configuration XML files
Lattice Model
Equipment Database
EPICS Configuration Database Files
Service configuration: naming service, gateway(s), channel archiver(s)
Mechanics Engineers
Installation and Maintenance Teams
Reports, etc.

Figure 6: flow of model data for top-down ESS control system design.

Figure 6 shows a possible application of the top-down approach. Initially, lattice designers populate a database containing the lattice model. Since this database is shared and centrally available, all lattice designers and other stakeholders are ensured that they work with the latest, consistent version of the lattice. Other benefits of the lattice model database include:

- Conversion between file formats of various lattice design tools. E.g., if a feature to upload Trace 3D and TraceWin files were provided, and downloads were available for both of these tools as well, then bi-directional format conversion would be assured.
- Physical positioning of lattice's elements – in particular, magnets and cavities – can be derived from the database, and made available to mechanical engineers for importing into CAD tools.

Once the lattice design is complete, the equipment database can be populated from the information it contains. The equipment database will need to be amended with information about additional equipment that is not modeled along with the lattice – for example, for safety, HVAC and similar. This information will thus need to be entered after the initial population process.

An equipment database can be designed to contain all relevant information about the installed system: what equipment is installed, where it is located, what PVs are associated with it, on which IOC the PVs are hosted, how equipment is interconnected with cables, etc. Such a database will be of interest to many kinds of users:

- Purchasing, which would keep a list of subsystems/components that remain to be purchased, as well as technical information (e.g., technical specification documents, test reports, etc) after the purchase is complete. Also information such as serial numbers, delivery date, warranty expiration date, etc., could be stored in the equipment database.
- Installation and maintenance teams would enter information about where a certain equipment is installed, who is responsible for it, and to be able to quickly find the equipment, e.g., in case of its malfunction.

It might be that equipment database will actually consist of several integrated databases, for example EDMS and IRMIS.

Recommendation (III) #41: Gather detailed requirements for the equipment database and investigate existing solutions. Decide what solution(s) to use, and in case of using several solutions, design a mechanism for keeping them in sync.

It is possible and feasible for the equipment database to contain all information related to equipment and its control, yielding the following benefits:

- A central database shared among various stakeholders (e.g., purchasing, installation teams, maintenance teams and control teams etc.), keeping them in sync, eliminating the need for duplicated entering of information, and reducing possibility of errors and misunderstandings.
- Ability to generate most (if not all) configuration for the control system. For example, EPICS configuration database for each IOC could be automatically generated from the equipment model, as well as XAL configuration for physics modeling in applications and configuration of central services (archiving, naming service, etc.).
- It is possible to generate a simulation configuration for the control system, testing the controls, operations and integrations aspects before the equipment is available.

A major risk that could sabotage the proposed top-down approach is not adhering to this approach during development. When trust in the central equipment database erodes, the development process naturally starts becoming bottom-up and solutions for storing partial ad-hoc information will become necessary.

4.2. Naming Convention

Assumption #42: ESS will use EDMS [13].

Specifying naming convention, i.e. consistent naming of the elements in the facility is usually spearheaded by the control group very early in the project. Selecting and enforcing consistent usage of the naming convention presents a high organizational risk, because all teams, responsible for subsystem development must conform to the convention.

In SNS, the scope of the naming convention applies to all devices (beam instrumentation, sensors, actuators, etc.), equipment (power supplies, magnets, RF cavities, targets, moderators, instruments, etc.) and signals in technical systems and conventional facilities. It does not apply to cable numbering, pipe numbering, or location designations throughout the facility [28].

At PSI, the same naming standard is applied to numbering of structural elements (magnets, etc) as well.

> **Recommendation (I) #43:** Introduce a naming convention early in the project. There should be a process in place that checks naming convention compliance. A person (the naming tzar) should be assigned to address naming at the project level, and to assist control system developers when they are in doubts on how to handle naming.
>
> **Recommendation (I) #44:** Decide whether to use the same naming convention to name control signals as well as equipment.
>
> **Recommendation (I) #45:** Define the scope of EDMS usage at ESS.
>
> **Recommendation (I) #46:** Use a naming convention that is consistent with EDMS.

4.3. Machine Model

There was no development loop between designing physics of the machine and XAL framework in the case of SNS. The steps taken at SNS were:

1. Optimize the machine
2. Finish the optimization, lock it down.
3. Put the machine parameters into some database.
4. Start building the machine, make requirements for engineers (iterative process)
5. Baseline the machine design.
6. Then put everything into the db, in a global coordinate system – location of every beam line component in the db. Add details should go into the db. Apps group defined the db structure (not the same as XAL structure). Oracle db was used.
7. Define control interfaces (list of PVs with meanings – definitions, and units).
8. Prepare input for XAL. XAL uses XML as input. So, SNS has made a tool that generates XML for XAL, from the db. Db is huge, different, changing, not accessible, slow to access, which is the reason to decouple the db and XML configuration files.

5. Hard Real-Time Subsystems

Some subsystems of the linac will need to be controlled in hard real-time. By *hard real-time* we mean a very strict deadline for the control system to respond (e.g., the end-to-end duration of a closed control loop must have an upper bound).

With present day technology, we consider the latency threshold between real-time and non-real time to be around 10ms[4]. If latencies exceed this threshold, commonly available IT equipment and protocols can be used, such as:

- Network time protocol (NTP) for time synchronization and time-stamping.
- Commodity operating systems, such as widespread Linux distributions (RedHat, Ubuntu, Fedora, Scientific Linux, …), MacOS, Windows, etc.
- Network communication libraries shipped with these operating systems.
- Standard personal and server computers.
- Commodity network switches. Nonetheless, switches should by the very least have remote management functionality, e.g., to keep track of configuration and allow for monitoring of traffic statistics in order to maintain and supervise the network infrastructure.

Equipment must be more carefully chosen if hard real-time requirements must be met. In particular, a real-time operating system, such as Linux with a real-time kernel patch, VxWorks, LynxOS, Pharlap ETS, etc. must be used. If data flows are local (i.e., they don't span several computer nodes), latencies as low as 50µs can be achieved. If data flows are distributed, latencies of 500µs are still feasible.

Where timing constraints are even stricter, dedicated solutions must be adopted. In the case of ESS, two such subsystems are:

- **Machine timing** (see section 5.1): the activities performed by equipment across the machine must be very tightly synchronized, and diagnostics data acquisition must be time-stamped with high precision and accuracy.
- **Low-level radio frequency** (LLRF, see section 5.2): Linac RF cavities will have real-time control loops to compensate for distortion of cavity response by the passing proton bunch train's wakefield.
- **ESS might also need to adj**ust the machine configuration between pulses. However, the time between two pulses – with pulse repetition rate being 20Hz and pulse duration of 1.5ms – is 48.5ms, which allows even for the use of conventional, non-hard-real time technologies in the majority of cases[5].

[4] In hard real-time, jitter and period-to-period reproducibility are actually more important criteria than the absolute latency. However, due to nature of jitter and speed of today's systems, the 10ms latency threshold is applicable for most, though not all, applications.

[5] If a large number of machine's configuration parameters needs to change between pulses, the EPICSv3 control system might have difficulties propagating the settings across the network in a timely fashion. EPICSv4, which is currently under development, will improve on this issue by allowing batched modification of a set of PVs. Pulse to

5.1. Machine Timing

5.1.1. Overview

The role of the timing system is to synchronize receiver devices—placed all around the accelerator facility—to perform device-specific actions just in time, relative to the passage of the beam. This is orchestrated by means of distributing timing-system events to all timing receivers.

Assumption #47: Master clock generation is in the domain of the control group.

Master generation clock drives the injector, all LLRF clocks, and all injector and linac instrumentation beam-synchronous triggers. This clock is by definition beam- and RF-synchronous, and will be a multiple of the design 704 MHz primary superconducting RF frequency.

The most important parameters when defining the timing system solution are:

- Number of timing receivers; this is important for estimating total cost of ownership for the timing-system solution. Additionally, the distribution infrastructure has to be taken into account when developing accuracy and jitter requirements.
- Accuracy and jitter [8]; the timing distribution layer is to a great extent defined with these parameters.
- Patterns and decision-rules complexity level for actions that must happen in real time; this will define the complexity of the timing master. The following questions have to be answered:
  - Minding power electronics requirements; how to link the operation of the accelerator with mains and possible mechanical chopper?
  - Which real-time decisions have to be made; based on the present status of the machine and all inputs? How are alternate scenarios (pre)defined?
  - On micro- and macro-level; how should the patterns of machine behavior be generated?
  - What real-time data has to be collected, processed and distributed? (GPS time, machine protection system status, etc.)…?

5.1.2. Timing System Generic Architecture

Figure 7 illustrates a modern generic timing system solution. Any crate can be used, but he one used should support a variety of processors and extension cards. Micro Research Finland (MRF) is mentioned in the text as a possible transport layer; it is available in VME and cPCI form factors. Backplane bandwidth is practically not an issue since data throughput is relatively low because the timing master FPGA handles all real-time requirements.

pulse flexibility can also be achieved by preloading multiple pulse patterns into IOCs and switching between them with timing triggers; a similar approach is taken at the BNL Booster and AGS.

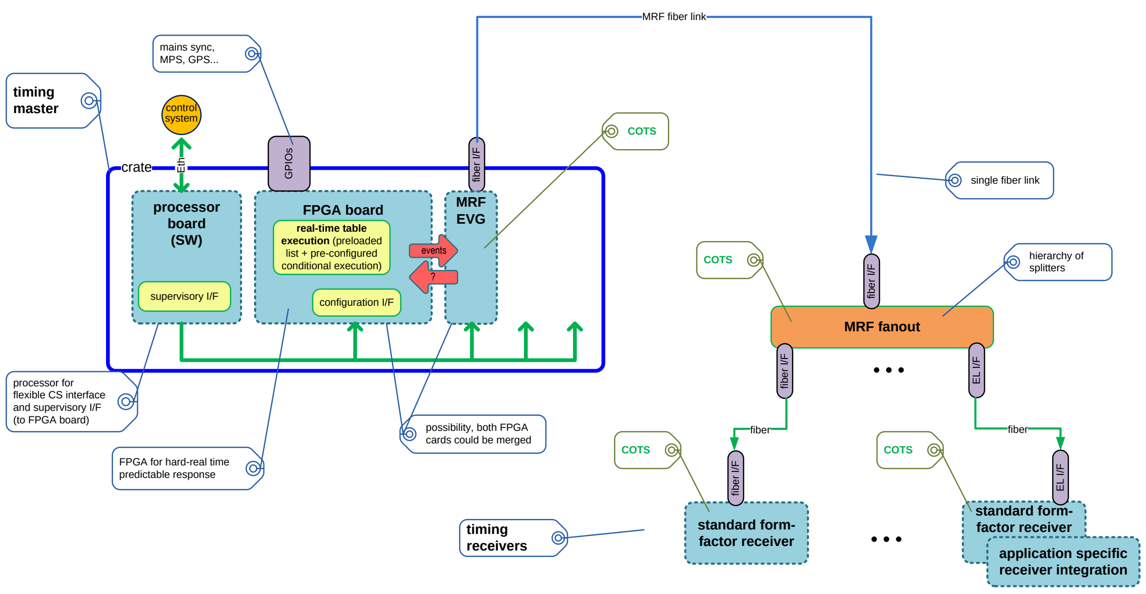

MRF fiber link
mains sync, MPS, GPS...
timing master
control system
Eth
crate
GPIOs
fiber I/F
COTS
single fiber link
processor board (SW)
supervisory I/F
FPGA board
real-time table execution (preloaded list + pre-configured conditional execution)
configuration I/F
events
?
MRF EVG
COTS
hierarchy of splitters
MRF fanout
fiber I/F
EL I/F
processor for flexible CS interface and supervisory I/F (to FPGA board)
possibility, both FPGA cards could be merged
FPGA for hard-real time predictable response
fiber
COTS
COTS
standard form-factor receivers
standard form-factor receiver
application specific receiver integration
timing receivers

Figure 7: timing-system architecture.

5.1.2.1. Processor; Control System Integration

The processor board provides the integration of the timing master into the control system. Statically prescheduled machine behavior is first loaded into processor memory. The processor then handles all required chunking and provides just in-time instructions to the FPGA for real-time execution. The processor board also provides control system readbacks to evaluate the timing system operational status.

5.1.2.2. FPGA board; Timing System Master Real-time Controller

The FPGA is required for real-time orchestration of the complete machine. For the sake of simplicity one can perceive timing master as a collection of programmable counters sending out timing events precisely correlated to each other and external conditions (also configured for hard real-time responses). This FPGA is responsible for linking the operation of the accelerator with mains (general-purpose alternating current (AC) electric power supply), for real-time decisions based on the present status of the machine and all inputs, for generating patterns, for real-time data collecting, processing and distributing…

5.1.2.3. Event Network; Real-time Distribution

After the timing system master generates events, a real-time distribution layer handles the precise delivery of timing signals. This layer handles connectivity architecture to connect many receivers to single master), encoding, and decoding. This layer must operate synchronously so all receivers respond to timing events synchronously as well.

5.1.2.4. Possible Candidate: MRF

One likely candidate for a real-time distribution layer is Micro Research Finland (MRF) [9], which provides 8 ns resolution (400 ps in advanced version) with jitter performance of 25 ps (5 ps in advanced version). A short high-level overview can be found in [10]. Regarding its suitability three scenarios exist;

1. MRF is a good match in terms of price/performance; in such a case it is highly suggested this solution is used since tremendous amount of effort was already put invested into solution; it is readily available as a commercial of the shelf product (COTS).
2. MRF performance considerably exceeds ESS timing needs, and a relatively large number of receivers are needed; in such a case one might want explore the possibility of using a custom-developed distribution layer. This would require serious amount of development effort.
3. MRF performance fails to satisfy ESS timing needs; in such a case tremendous amount of effort would be needed to develop distribution layer.

If it turns out that scheduling requirements are relatively modest then MRF could also host the real-time scheduler, replacing the need for a separate FPGA board and associated support.

For SNS, MRF would be a good match in terms of price/performance for the distribution layer (option 1). Scheduling requirements for SNS are demanding, therefore the real-time scheduler is implemented in a separate FPGA.

5.1.2.5. Prototype

If MRF is a viable solution, we propose a prototype solution based on VME; a processor board (with Linux or RTEMS and EPICS), VME-EVG-230 (VME Event Generator with the biggest FPGA) and couple of VME receivers (VME-EVR-230). In the process ESS will learn about the scheduling needs and thus the FPGA size requirements, which will guide further development.

ESS should also leverage the rich expertise and experience of the SNS timing master development.

> **Recommendation (VII) #48:** Develop a custom timing master generator, based on FPGA. Use a commercial off-the-shelf solution for the transport layer and timing receivers.

5.1.2.6. Reasons for not Directly Copying SNS Solution

There are several reasons why the SNS timing system solution should not be adopted as-is:

- SNS uses separate copper wires for event link and real-time data links (RTDL). Instead, fiber optic links should used, as they provide better reliability, jitter, bandwidth, and noise immunity.
- The SNS implementation does not address control over signal propagation delay in a systematic manner. Instead, per-device delay trimming is required, which complicates device development and commissioning, and also contributes to jitter.
- SNS requires multiple clocks for coordination of ring, linac, and target activities, leading to a solution that is tightly coupled with specifics of the machine design. Instead, a single clock would be preferred.

One might consider an “SNS event link and RTDL over-fiber upgrade” as a viable alternative to an MRF distribution layer. However this will probably lead to lower performance compared to MRF.

A technical description and further information about the SNS timing system is available [11].

5.2. Low Level Radio Frequency (LLRF)

Low-level RF (LLRF) control hardware and its embedded programming play a pivotal role in the performance of an accelerator. Modern designs implement most of the signal processing in the digital domain. This reduces the size and cost of the hardware, but places the burden of proper operation on the programming. FPGAs (field programmable gate arrays) and communications-grade ADCs and DACs enable sub-microsecond delays for LLRF controller feedback signals [45].

Some aspects of the LLRF real time control are too fast to be handled through the middle layer of the control system. A dedicated subsystem should be used for LLRF control and feedback.

> **Assumption #49:** Fast LLRF control loops are not in the scope of the control system but interfaces to control them are.

LLRF requires fast and slow feedback loops. Fast loops (faster than 1 Hz) are usually implemented in FPGA. SNS developed their own FPGA; see [18] and [46]. Slow loops (1 Hz or less) should be implemented through the control system at the field bus and EPICS level.

LLRF interfaces to other systems:

- Machine timing system,
- Provides output and input to machine protection system.

LLRF interaction with operators and accelerator control system in SNS

In the SNS control room, feedback loop parameters are changed only by LLRF experts. Operators can monitor the adjustments, but they do not modify them.

Tune up of the LLRF is rarely performed, the main cases where tune up is required are:

- Change of a beam pulse length.
- After production or accelerator physics runs. Production runs occur several times a year, after shutdowns. Accelerator physics runs are performed typically once per month.

6. Operations and Maintenance Use Cases

6.1. User Access and Security

As an example, we present the approach taken by SNS. There, three types of user access are implemented:

- Chief operator: used at only one station; has all the access rights.
- Accelerator operator: used at other accelerator operator stations; has restricted access to some common functionality.
- Target operator: has access right for target functionality only, uses dedicated target control operator consoles

Recommendation (VII) #50: Ensure the control room consoles enforce accountability and a reasonable level of security without hindering operations.

6.2. Control Room Layout

In the SNS control room, each operator station has 6 monitors and a large LCD TVs above the station. There are 11 stations in SNS the control room:

- One chief operations station
- Two accelerator operator stations
- Three physics / diagnostic stations
- One conventional facilities station. In addition, conventional facilities use their own control room.
- One test network station
- One target station
- Two alarm station, with only 3 monitors per station

Recommendation (III) #51: Prepare a list of operator stations in the ESS control room. Provide the number of stations, and their assignments. Recommended assignments for stations are: chief operator station, accelerator operator station, physics / diagnostic station, conventional facilities station, test station, target station, alarm station.

6.3. Control Room Applications

SNS has prepared a document on HMI [21]. However, the SNS document focuses heavily on HMI design with a generic EPICS tool called EDM. The ESS document should provide more general guidelines that are less dependent on the specific tools used.

Control room applications can be classified into groups as:

- Machine physics applications
- Operator screens for individual subsystems and devices
- Generic control system applications (Alarm viewer, Archive viewer, etc.)
- Workflow management applications (electronic log book, help and support pages)

For a comprehensive list of SNS applications, see [18].

Recommendation (III) #52: Provide a list of detailed operations use cases (e.g. machine tuning, normal machine operation, accelerator physics run, commissioning of a new device). Provide a list of control system tools and applications that are required by each use case. Base the list on experience from SNS.

6.4. Analogue Signals

Recommendation (I) #53: Avoid all analogue signals in control room.

All the relevant signals should be provided through the control system, preferably through appropriate analog to digital conversion so these signals may be transparently accessed and logged. In the SNS control room, there are two types of analogue signals in the control room: oscilloscope waveforms and video signals. These are both present because high refresh rates are required (~20 Hz) with large data rates.

The Australian Synchrotron Project uses a standard EPICS solution for displaying video in the control room, where 15 frames per second (fps) are routinely achieved, and the bottleneck is the IOC CPU. In the future, CPUs will be faster, thus allowing higher frame rates.

ITER has a requirement for display of video set for 30 fps. ITER is working on a dedicated system for video that will be integrated with controls. We suggest that ITER developments are closely followed as the results might be directly reusable for ESS.

6.5. Electronic Log Book

Electronic logbooks are used by operations and support shifts at all major accelerator facilities. They provide an organized, searchable interface to maintain a monologue of machine observations, analysis, results, and comments.

Recommendation (VII) #54: Gather requirements for an electronic log book at ESS.

The SNS has an electronic logbook tool called eLog [42], that is functional, stable, well-supported, and satisfies SNS electronic logbook requirements. ESS should evaluate the SNS eLog and other existing comparable solutions before ESS installation and commissioning.

Appendix A. About the Document

During the project, the following visits and discussions occurred:

- Meeting with ESS staff with a stake in control system development in Lund.
- One week visit to SNS, see meeting notes [18].
- One day visit to ITER.
- Participation on Writing Group meetings in Paris (presentation [20]) and Geneva.

Document History

Revision	Date	Changed/ reviewed	Section(s)	Modification
0.1	2010-02-10	Igor Verstovsek, Klemen Zagar, Rok Sabjan, Joze Dedic / Igor Verstovsek	All	Verstovsek: created the document, review, introduction, organizational issues Dedic: timing Sabjan: equipment access, control box Zagar: data management
0.2	2010-02-12	Igor Verstovsek	All	Sent to Todd Satogata and Steve Peggs for first review.
0.3	2010-03-21	Igor Verstovsek, Klemen Zagar	All	Incorporated comments by Todd Satogata and Steve Peggs on version 0.2, input from visit to SNS, wrote new text. Intermediate working version sent to ESS.
0.4	2010-03-26	Igor Verstovsek, Klemen Zagar / Todd Satogata, Steve Peggs	All	Updated after feedback on version 0.3 by Todd Satogata, and discussions with Steve Peggs and Todd Satogata in CERN.
1.0	2010-03-31	Igor Verstovsek, Klemen Zagar / Todd Satogata	All	**Released.**