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CONTROL SYSTEM DEVELOPMENT AND INTEGRATION AT ELI-ALPS*

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Abstract

ELI-ALPS will be the first large-scale attosecond facility accessible to the international scientific community and its user groups. Control system development has three major directions: vacuum control systems, optical control systems, as well as the integrated control, monitoring and data acquisition systems. The development of the systems has asked for different levels of integration. In certain cases low-level devices are integrated (e.g. vacuum valves), while in other cases complete systems are integrated (e.g. the Tango interface of a laser system). This heterogeneous environment is managed through the elaboration of a common and general architecture. Most of the hardware elements are connected to PLCs (direct control level), which are responsible for the low-level operation of devices, including machine protection functions, and data transfer to the supervisory control level (CLIs, GUIs). Certain hardware elements are connected to the supervisory layer (cameras), as well as the Tango interface of the laser systems. This layer handles also data acquisition with a special focus on the metadata catalogue.

INTRODUCTION

Extreme Light Infrastructure (ELI) is the first civilian large-scale high-power laser research facility to be realized with trans-European cooperation in three sites. ELI's long-term objective is to become the world's leading user facility utilizing the power of state of the art lasers for the advancement of science and applications in many areas of societal relevance [1]. The main objective of the ELI Attosecond Light Pulse Source (ELI-ALPS) pillar is the establishment of a unique attosecond facility that provides ultra-short light pulses with high repetition rates.

The typical layout of *beamline systems* at the ELI-ALPS is as follows (see Fig. 1): the laser source produces pulses in the femtosecond duration range, which is connected via a beam transport system to one or more secondary source(s). Secondary sources are designed to produce attosecond pulses from the femtosecond laser pulses by utilizing various technologies based on Gas High-Harmonic Generation (GHHG) and Solid High-Harmonic Generation (SHHG). Beamline systems may have end stations as their closing system.

Beamline systems contain a high number of controlled devices, most importantly optomechanics (translation stages, motorized mirrors, irises, etc.), cameras and detectors, and in certain sections vacuum devices (vacuum pumps, valves, gauges, etc.)

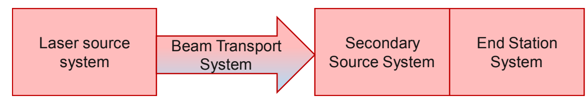

Figure 1: Research technology overview.

METHODOLOGY

Motivation

ELI-ALPS research technology in its current state of development already contains numerous devices to be controlled by the control system. This number is currently around 100, but in the final state of the facility with all the beamlines implemented, we expect more than 2000 devices total. Regarding the number of device types, the current figure is around 40, which is expected to be approximately double by the end of installation. Since the devices form a highly heterogeneous environment, their integration into one system poses challenges that can be overcome only by a unified strategy. The control system design and development has been carried out by considering similar projects [2-9] as well as industrial standards and recommendations.

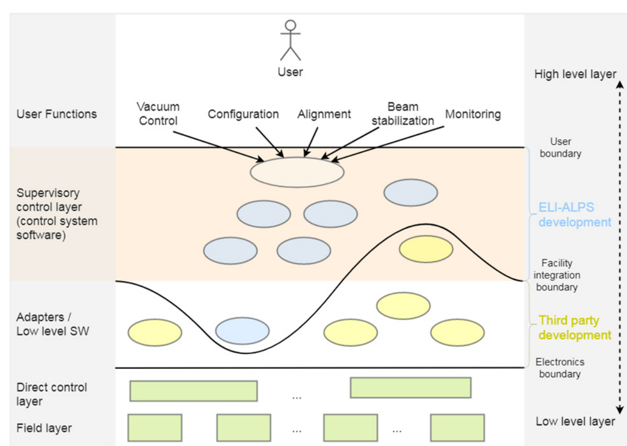

Figure 2: Control system scheme.

Control System Functions

While keeping standard control system design considerations in mind, control system development at ELI-ALPS follows a demand driven approach where focus is always given to areas where the research infrastructure reaches a certain implementation phase.

A general scheme to visually represent the major goals of control system developments are shown in Fig 2. In this scheme the low level layer consists of all controllable devices that together comprise our research infrastructure.

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This layer can have multiple sublayers, of which the topmost is the Direct control layer, and anything below that is the Field layer. It is not always the case that we need to deal with hardware devices, however. In certain scenarios, some devices or small groups of devices already have associated software control components with various interfaces which the control system can connect to. At the other end of this spectrum there are complete subsystems, themselves consisting of possibly hundreds of devices, that are delivered with their own control system. For example, the primary laser sources (cf. Fig. 1) are all delivered with their own control system that is responsible for providing the required functionality of that complex subsystem, and also providing an interface to ELI-ALPS control systems. All these device and subsystem interfaces together form the landscape that has to be considered as the base on which all control system development is built (Fig. 2 "Facility integration boundary").

The high level layer below the "User boundary" contains components that are directly provided for use to our internal and external users. Their requirements drive what functionality is to be provided by the control system.

To summarize, the goal of control system development is to

- provide a user interface (or interface components) ensuring that requirements coming from the side of the users are fulfilled. In some cases, this is ensured by a HMI panel located inside the laboratory, in other cases a GUI is made available for remote access. Users with programming skills can use a CLI to write scripts, or directly access functionality through an API.
- communicate with devices and subsystems below the facility integration boundary such that the required functionality is achieved. This is where the heterogeneity of the environment manifests itself, and depending on the circumstances, we need to deal with individual devices, groups of devices through a common controller, all the way up to complex subsystems such as primary laser sources. Independently of their internal structure and level of complexity, each of these units appear as one unit to the control system that can be accessed through a well-defined interface.

Based on the above, we can talk about the environment of the control system, which is the area below the facility integration boundary. These are the components and subsystems that the control system connects to or communicates with, but which themselves are not part of the control system. These are:

- Personnel Safety System (PSS)
- Infrastructure services (e.g. cooling water, technological gases, electricity, pre-vacuum)
- Building information system (temperature, humidity, vibration data)
- Data storage services
- Primary laser source control systems
- End-station control systems

The control system of ELI-ALPS ensures the safe and reliable operation of research equipment of the facility. In particular, the control system

- monitors, logs, archives, operates and controls the vacuum, optomechanical, diagnostic and data acquisition devices, and the related processes.
- its Machine Protection Subsystem (MPS) prevents damage of the equipment that may be the result of hardware failures or user actions.
- cooperates with the laser sources over the provided interfaces supplied by the laser manufacturer.
- provides electrical and software interfaces to the safety system.

Control system development has three major directions: vacuum and gas control system (VGCS), optical control system (OCS), and the central integrated control, monitoring and data acquisition systems (ICS). The VGCS and OCS have to be built mainly from individual hardware devices procured by ELI-ALPS, while the ICS has to deal with every subsystem in its environment (see Fig. 3). In this paper, we concentrate on the above and describe them in their own sections.

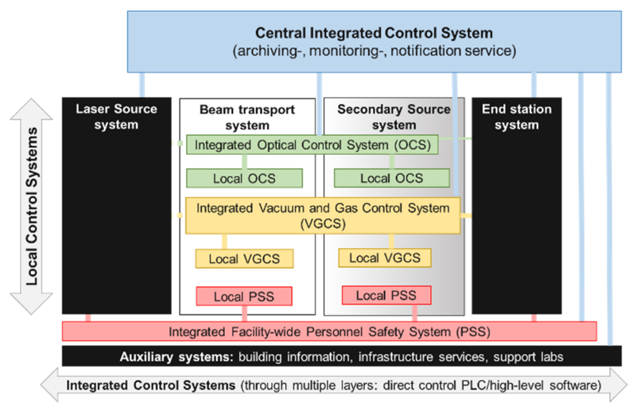

Figure 3: Targets of main development directions.

ARCHITECTURE

Control System Layers

During the control system development at ELI-ALPS the general scheme of control systems has been followed [2]: consisting of a field layer, a direct control layer and a supervisory control layer (also referred to as control system software in this paper). The majority of the devices controlled by the VGCS and the OCS have been procured by ELI-ALPS, so integration had to start on the lowest level. To illustrate the approach, Fig. 4 shows a more detailed layered architecture.

The field layer contains either controllable devices or controllers to which the devices are themselves connected.

The direct control layer consists of PLCs, which are connected to controllers and devices in the field layer. PLCs serve as a central information gathering and execution unit, which is necessary to implement functionality related to Machine Protection System (MPS) and Personnel Safety System (PSS). This applies to all vacuum devices

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and to most of the optomechanical components. Devices and controllers that are not involved in any PSS/MPS related functionality do not need to be connected to a PLC, for example, cameras whose only purpose is to gather diagnostics data fall into this latter category.

The adapter layer contains software components, which communicate with the field layer or the direct control layer, as necessary. In case of the PLCs the used communication protocol is based on OPC-UA publish subscribe model: the software components subscribe to the data change events of the corresponding data nodes in the direct control layer, and get informed when the data changes. This way the PLC hides the manufacturer specific communication details from the layers above and provides a clean, unified interface. In other cases, when the adapter is communicating with the controllers or the devices directly, the adapter must contain the device specific communication protocol.

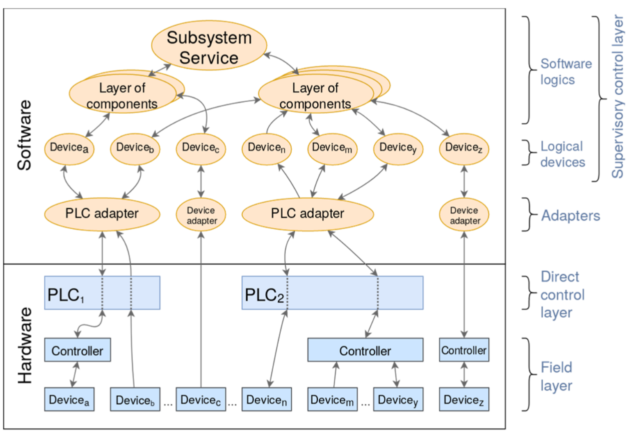

Figure 4: Layers of the Control system – low level device integration.

One level up, there is **the logical device layer** whose purpose is to contain components that represent the individually controllable hardware devices on the software side. As such, there will be a one-to-one correspondence between logical devices and the hardware devices which they control. The responsibility of logical devices is to reflect the states, attributes and commands of the devices. Above the logical device level there can be several more layers of components that implement successively more complex functions by having more and more devices under their control. This layering continues as necessary until we arrive at a single component (subsystem service) that implements all the functions that are required for the given subsystem.

Many logical devices have been developed by using the Tango controls framework [9].

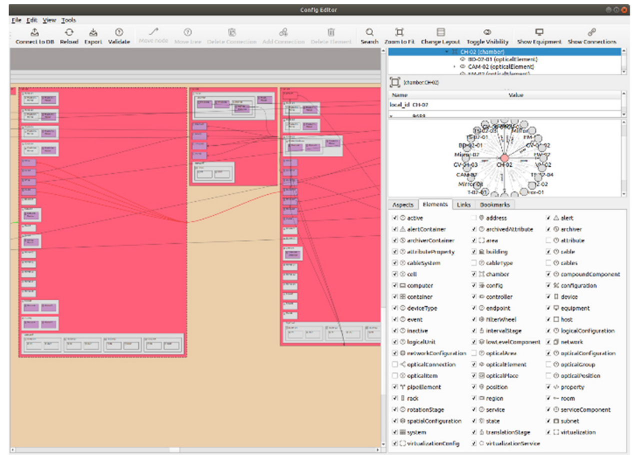
Figure 5: Configuration editor.

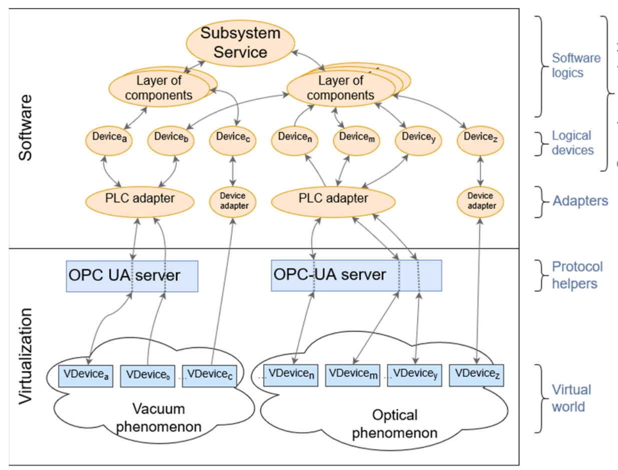

Figure 6: Layers of the Control system – virtualized devices.

The configuration of the control system plays an important role in the command and control ecosystem. The aim of the configuration is to give a static description of the properties and relationships of the relevant components. The configuration management for the integrated control system software of ELI-ALPS is described in detail in [10]. A custom build editor is created to visualize and edit the configuration database (see Fig. 5). Among others, each controllable device is present in the configuration. This serves two purposes. First, it enables the control system to check in runtime whether connected devices are the ones described in the configuration, this way enhancing security and stability of operation. Second, for development and testing purposes the virtualization of the hardware devices is reasonable based on configuration data, so a local control system can be partially functional without using real hardware in the low level layers. Virtual devices are created in a virtual world, where vacuum or optical phenomenon is simulated to the degree that testing of the control system becomes possible (see Fig. 6).

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Control Modes

Any local control system can either be in expert or in service mode depending on the level of control allowed for the user.

The expert mode user has full control over each individual device of the (sub)system, without any automatic features, except the MPS interlocks ensured by the direct control layer (PLCs). Expert mode will provide the possibility of batch execution of commands too.

Service mode is intended for non-experts and provides a subset of the expert mode functionality in a user friendly manner on one hand, as well as integrated and automated functions on the other hand. Automation will build on expert mode functionality without exposing unnecessary details of that functionality to the non-expert user. Examples of such functions are: optical path configuration selection, pumping down a vacuum section, or measurements involving the coordinated control of translation stages and detectors. The latter is widely known as a scan, and frequently forms the basis of experimental data collection.

The support for different modes above necessitates some kind of authentication and access control to be built into the control system. We plan to build on the standard LDAP directory service already in use for office purposes, so internal and external users benefit from a simple and coherent mechanism while working at the facility.

VACUUM AND GAS CONTROL SYSTEM

The Vacuum and Gas Control System (abbreviated as VGCS) of the ELI-ALPS is responsible for the safe and reliable operation of the facility's vacuum system. Its main functions are

- to monitor, operate and control the high vacuum processes, high vacuum process values of research technology systems;
- to prevent vacuum equipment damage caused by prevacuum or other supply systems related failures
- to prevent research technology system damage caused by vacuum components and/or vacuum equipment failure;
- to cooperate with the standalone and autonomous vacuum subsystem of the laser sources and the facility wide pre-vacuum system over the provided interfaces;
- to provide electrical and software interfaces to the different control and safety systems, such as the Personnel Safety System or to the local control system of the respective beamlines.

Mechanical layer: Consists of all the vacuum and gas related mechanical components such as chambers, vacuum pipes, etc.

Vacuum field layer: Consists of all the vacuum and gas related controllable and monitorable electrical components.

Direct control layer: Consists of the hard wired electrical connections to the vacuum field and supervisory control levels and also the logic solver, which executes the low level logic of the VGCS.

Local control system layer: consists of software components which communicates with the underlying direct control level via a well-defined programming interface and communication protocol, and executes the high level logic of the VGCS. The software components are structured in layers as well, containing successively more complex functions. Graphical User Interfaces (Fig. 7) and connections to the Central Control System are also part of the local control system layer.

Devices of the VGCS are valves, gauges, and (turbomolecular) pumps. Valves are read and controlled by direct digital signals from the PLC. In case of gauges and pumps device attributes are read via the serial interface. For speed and safety reasons pumps are controlled by direct digital signals. See Table 1.

Table 1: Vacuum Devices of LTA4 Laboratory

Device role	Type	Amount
Gauge	Pfeiffer HPT 200 PB	10
Valve	VAT Series 264	16
Gate Valve	VAT Series 121	10
Turbo pump	Edwards STP-iXR2206	9

The PLC provides the following interface towards the software layer:

- Valves: reading of open or closed state, commands for opening and closing
- Gauges: reading the pressure
- Pumps: reading device attributes (temperatures, speed, set point, etc.) and commands for starting and stopping the pump or setting the set point value.

All functionality described above are reachable in expert mode, provided the safety checks programmed in the PLC permit the operation.

High-level functions are located in the software logics layer and they provide user friendly functionality on vacuum sections: reach pre-vacuum or high vacuum in a section or vent a section.

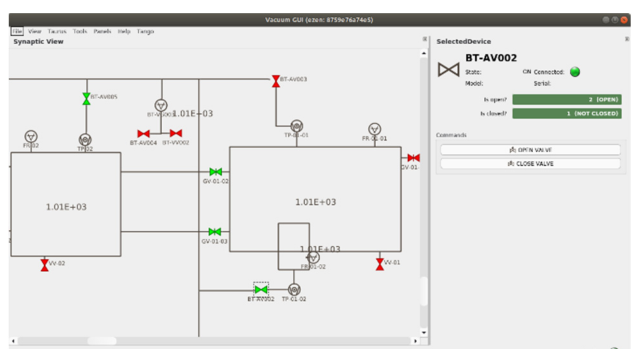

Figure 7: VGCS GUI.

There are three most typical types of vacuum sections (see Fig. 8), however, small changes according to the actual requirement of the vacuum subsystem may be possible:

- Section A: is the simplest solution. Evacuation to prevacuum happens through the TMP by opening the prevacuum valve. The TMP will evacuate the chamber to high vacuum level, while venting of the chambers

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can be done with nitrogen through venting lines opening a venting valve. The chambers are equipped with "chamber gauges", and optionally with a gas dosing valve. The aim of the latter valve is to dosing special gases into the chamber for experiment purposes.

- Section B: Same as section A, except that the evacuation to prevacuum level happens through a dedicated roughing valve, bypassing the TMP, making the process much faster.
- Section C: Same as section B, except that there is additional separation valve between the outlet of the TMP and the chamber. In that case, by closing the separation valve, the chamber can be vented without stopping the TMP. This solution is ideal for chambers opened frequently.

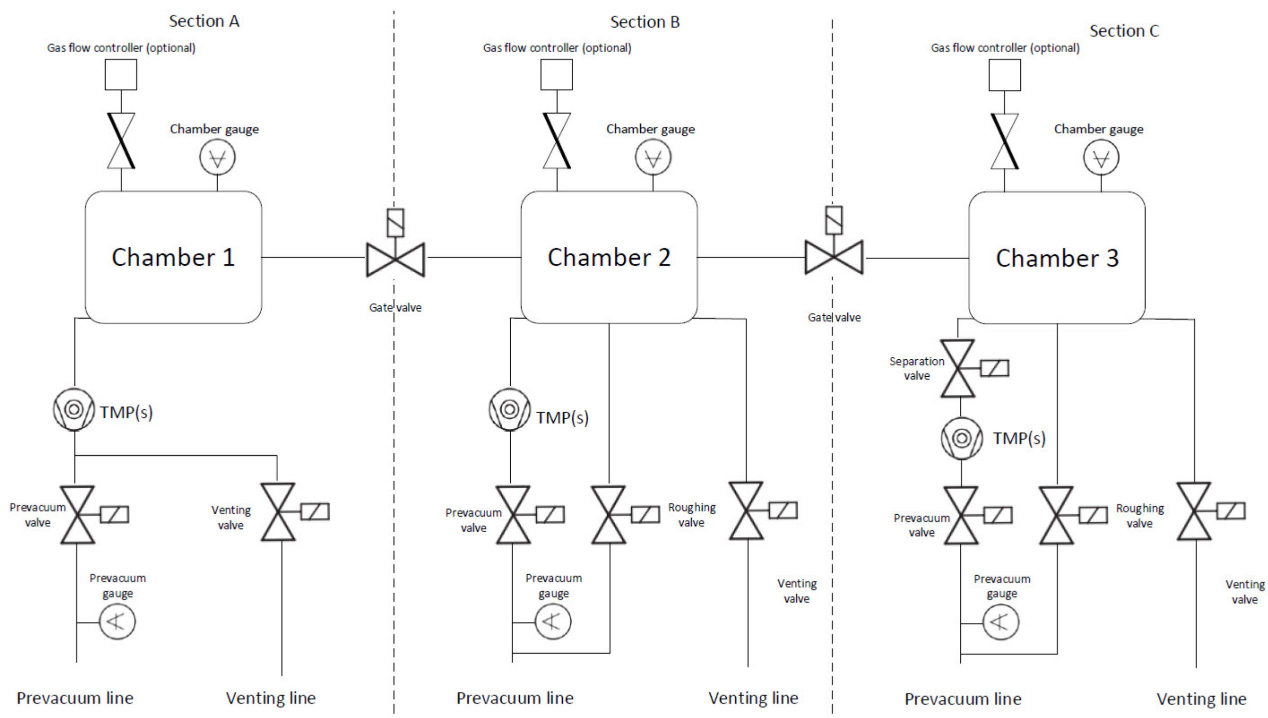

Figure 8: Most typical vacuum sections.

OPTICAL CONTROL SYSTEM

An optical control system (OCS) deals with those parts of a beamline that are directly related to laser pulse propagation. A beam in this context is a succession of laser pulses generated with some frequency, from a few Hertz to the kilohertz range.

Control functions of an OCS can be divided into the following categories:

- Beam configuration, or beam path selection
- Alignment, or beam quality tuning
- Beam stabilization
- Monitoring and diagnostics

Typical devices that belong to an OCS **field layer** are listed in Table 2 and are as follows:

- Piezo actuators are used to adjust the orientation of mirror mounts during optical alignment. Since the actuators are not aware of their actual position, their most important expert mode command is relative movement.
- Translation and rotation stages are used both in discrete and continuous mode, depending on the requirements for the associated optical element mounted on them. These stages can be moved by relative or to absolute positions or queried for their current position. Setting speed and acceleration parameters is also part of the expert mode command set.
- Cameras and other detectors provide the means to collect data about laser pulses, the effects they cause, and serve as the basis for monitoring, diagnostics and any feedback loop in the control system.

In the **direct control layer** there is a PLC with optomechanical devices connected to it. The purpose of the PLC is to implement machine protection functionality by monitoring the position of certain optical elements and prohibiting movement if necessary.

The **local control system layer** communicates with the underlying layers and provides command line and graphical user interfaces to the users. It implements expert mode commands in its present development state, service mode commands are planned when beamline implementation reaches a more mature stage and experience is gathered to specify the required functionality.

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Table 2: Controllable Optomechanical Devices of LTA4 Laboratory

Device role	Type	Amount
Translation stage	Smaract	18
Translation stage	Standa	3
Rotation stage	Standa	2
Motor controller	OWIS	3
Pico motor	NF8742	8
Camera	BlackFly PGE-1S4M-C	7

In the current state of development several friendly-user experiments were already supported. These required custom development, but the design followed the guidelines set for OCS.

In one of these experiments, an in-house custom made scanning software provided an interface to control the White Rabbit timing system with commands for setting the delayed pulse. In scanning mode, the software collected data from the oscilloscope and modified the delayed pulse repeatedly.

CENTRAL INTEGRATED CONTROL AND DATA ACQUISITION SYSTEM

The Control System communicates with the laser sources through gateways. Some laser sources provide Tango based interfaces, others have LabVIEW or proprietary software to control the laser. Gateways are used to translate the communication protocol between the Control System and the laser source. MPS and PSS functionality is achieved by wired interlock channels connected directly to the laser source.

In most of the experiments, secondary sources and/or end station will generate the relevant and large amount of experimental data. The main functionality of the Data Acquisition System is the collection and storing of the experimental data originating from the detectors. The generated raw data is first stored locally for pre-processing and selection. The data supplemented with the corresponding metadata is moved to long term storage for post-processing by a HPC.

Archiving, Monitoring and Notification Services

The objective of the archiving function is to record the various physical parameters of devices into a database. Depending on type, devices are polled, parameters are queried and results are stored in a dedicated Archive DB as illustrated in Fig. 9.

The archiving module supports the following functions:

- Define archiving policy for device type
- Override archiving policy at device level for devices selected by the user
- Provide an automatic process running in the CS middleware to record device parameters according to the archiving policy
- Provide an interface to query archive parameters filtering by the following criteria: device type, time interval, parameter type, parameter value interval, location

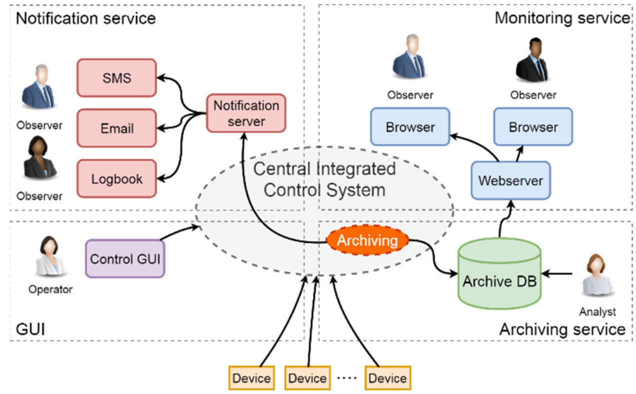

Figure 9: Archiving, monitoring and notification services.

On top of the CS there is a monitoring interface available that can display live and archived data in a browser (See Fig. 10). Attributes and states of different devices are read periodically and data is forwarded to an archive database for later analysis or presentation. Monitored devices are part of the Cooling water system, (Pre) vacuum system, Environment (BAS OPC, particle counter), chemical fridges, time lapse cameras or scientific devices. Altogether 308 devices of 26 different types are monitored. Observers use the browser to access their monitored data through a web application, which also provides access control, filtering, device and time range selection, data aggregations and dashboards.

The aim of notification service is to detect events in the collected data, and notify the event observers through the predefined channels (SMS, email, etc.)

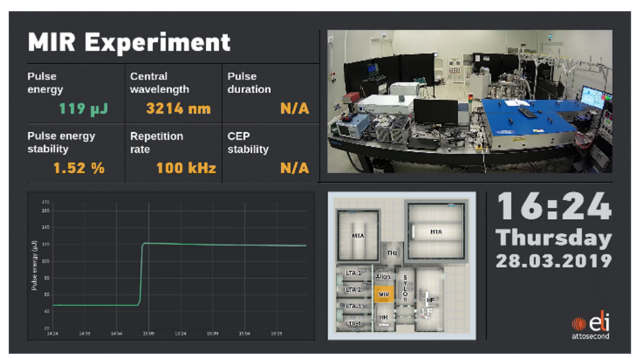

Figure 10: Monitoring the MIR primary laser.

Implementation. Data collectors of the scientific devices are developed in house while standard computer usage statistics are collected with Telegraf [11]. Mongo DB [12] is used as long term storage of the collected data. Grafana [13] web application with an Influx DB [11] as a backend is used for the monitoring service. The notification service is also an in house development with special attention to keep it as simple as possible as well as to keep the 100% test coverage due to the importance of the component.

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