Accelerator Controls

Stephane Deghaye (BE-CSS-FST)

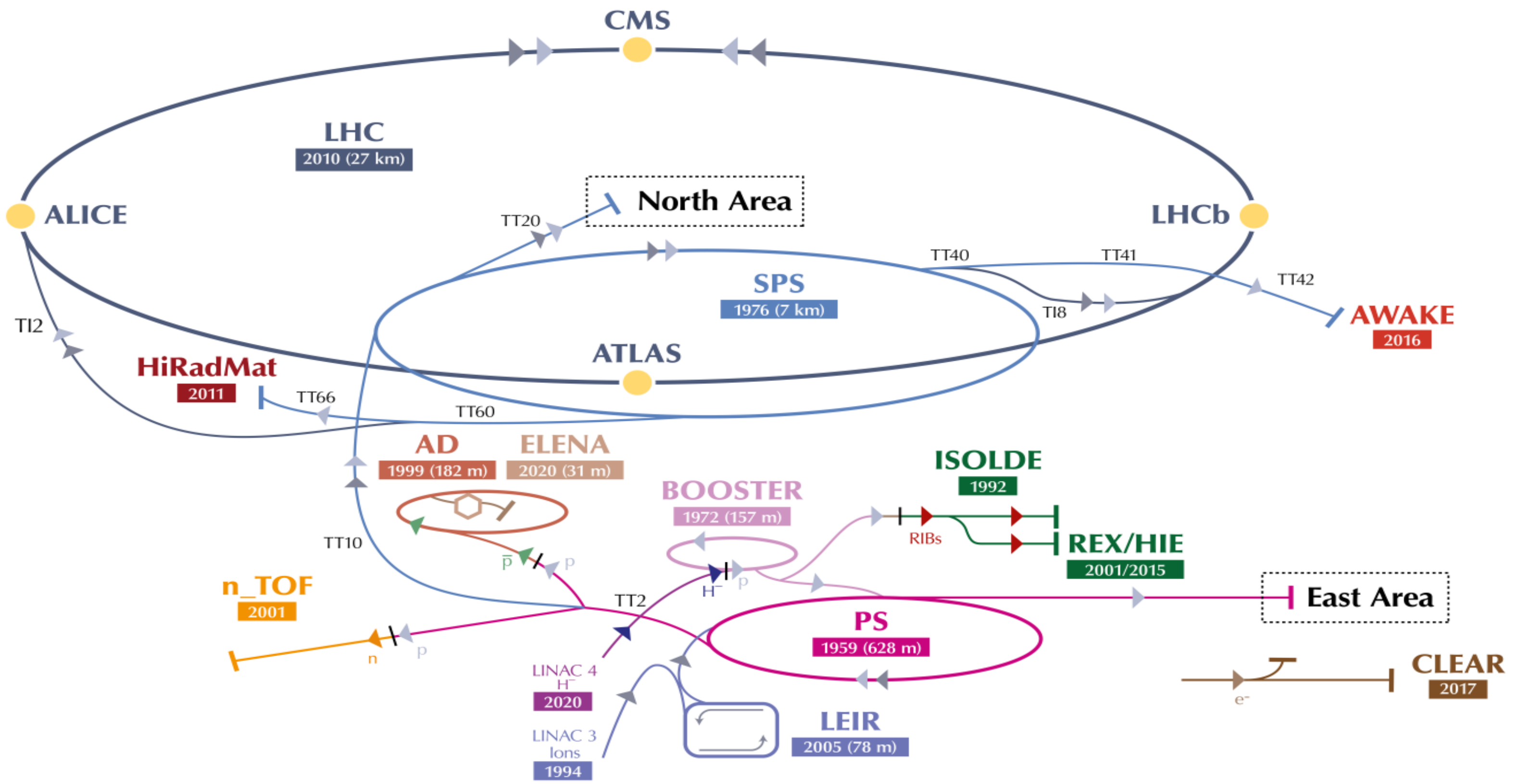
29th & 30th of November 2021

Agenda

1. What is an accelerator made of?
2. Control System Requirements
3. Implementation Philosophy
4. A bit of History
5. Hardware & Software Architecture
6. CERN examples & Key Components
7. Detailed implementations and concepts

CERN Accelerator Complex

CERN Accelerator Complex



H⁻ (hydrogen anions) · p (protons) · ions · RIBs (Radioactive Ion Beams) · n (neutrons) · p̄ (antiprotons) · e⁻ (electrons)

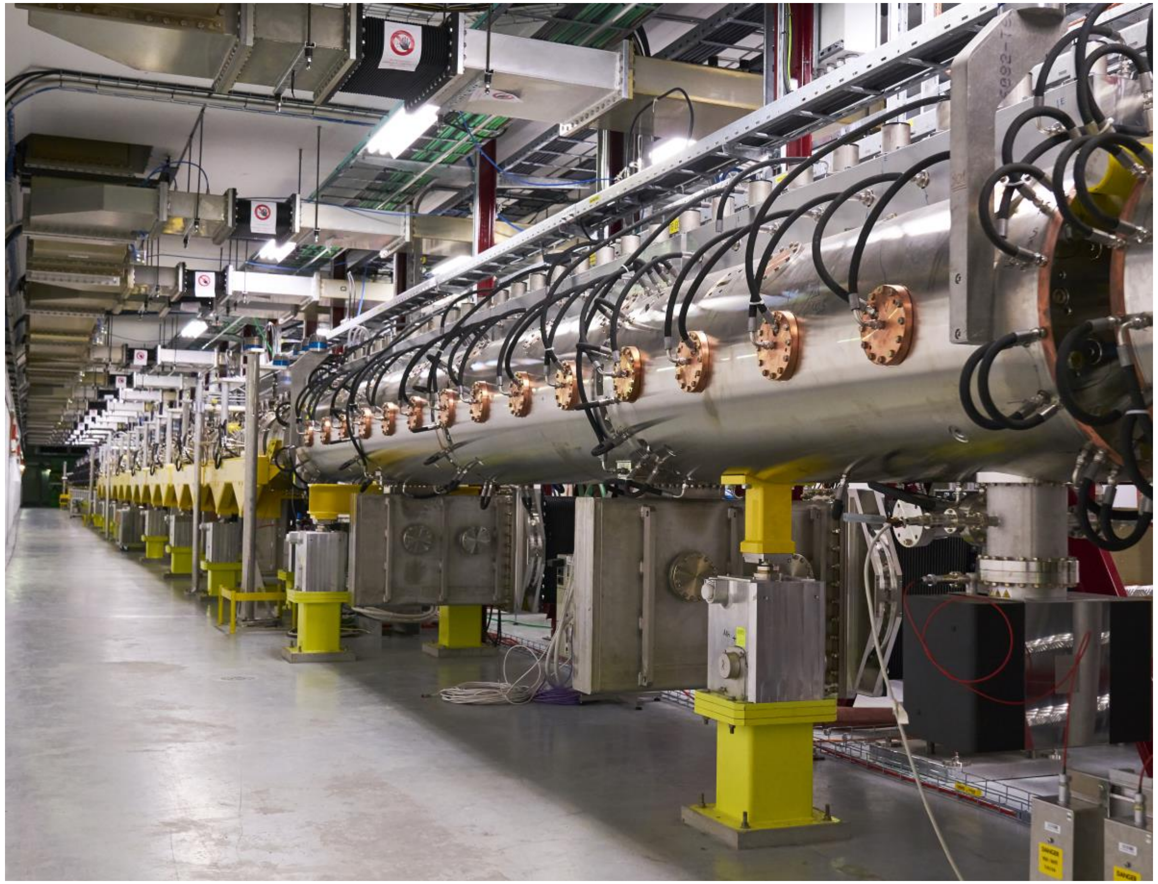
LHC - Large Hadron Collider // SPS - Super Proton Synchrotron // PS - Proton Synchrotron // AD - Antiproton Decelerator // CLEAR - CERN Linear Electron Accelerator for Research // AWAKE - Advanced WAKefield Experiment // ISOLDE - Isotope Separator OnLine // REX/HIE - Radioactive EXperiment/High Intensity and Energy ISOLDE // LEIR - Low Energy Ion Ring // LINAC - LINear ACcelerator // n_TOF - Neutrons Time Of Flight // HiRadMat - High-Radiation to Materials

What is an accelerator made of?

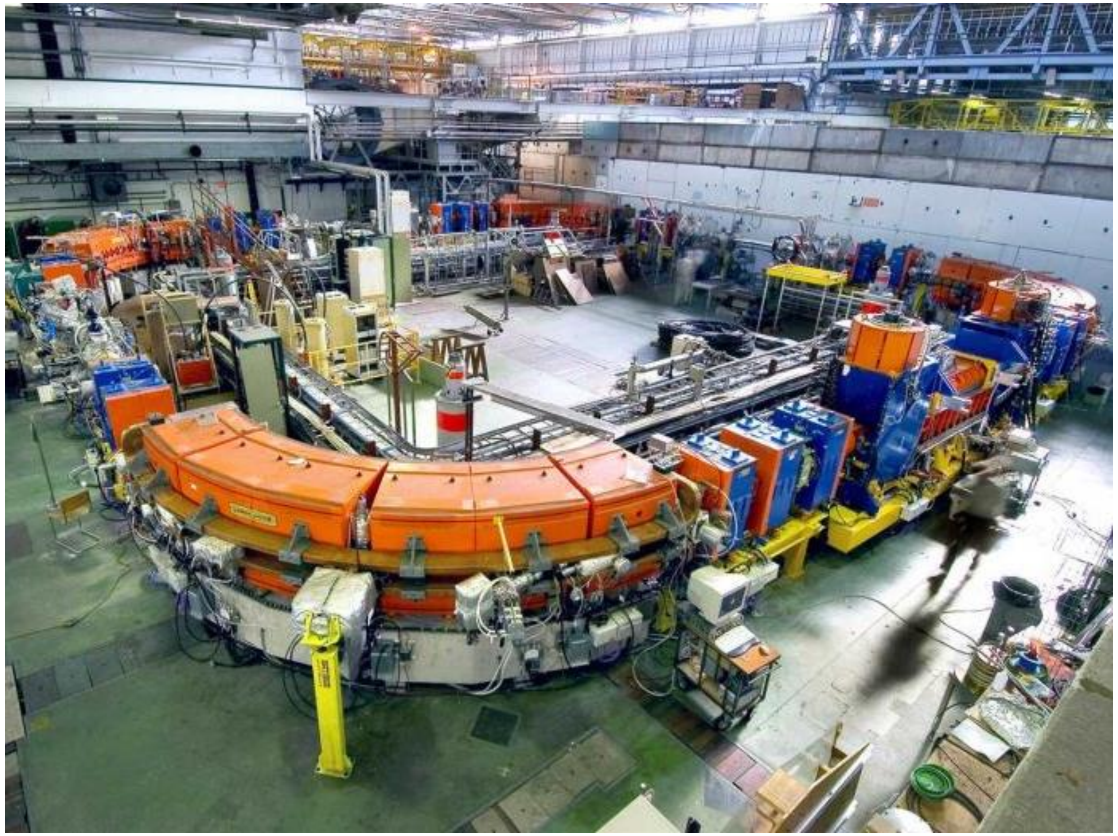
Particle accelerators are either linear or circular

What is an accelerator made of?

Linac4



LEIR



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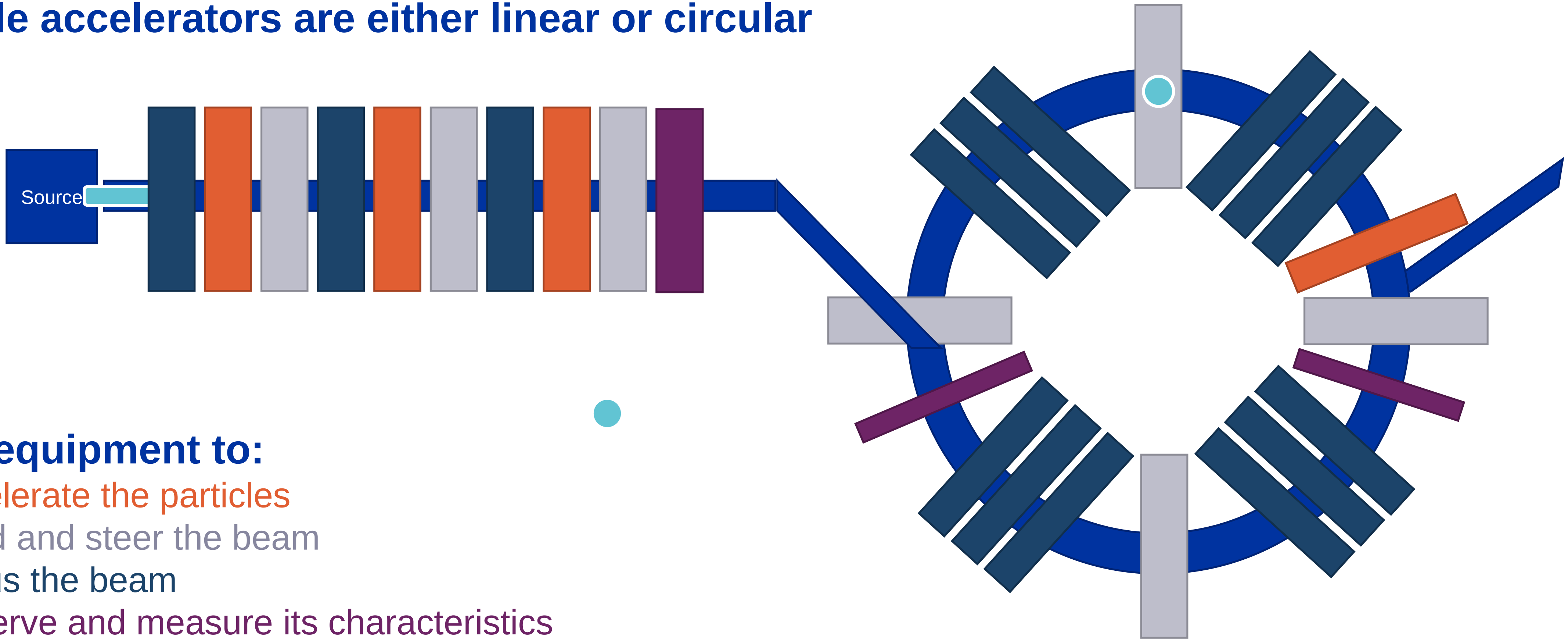


Need equipment to:

- Accelerate the particles
- Bend and steer the beam
- Focus the beam
- Observe and measure its characteristics
- Inject in and extract from the accelerator

What is an accelerator made of?

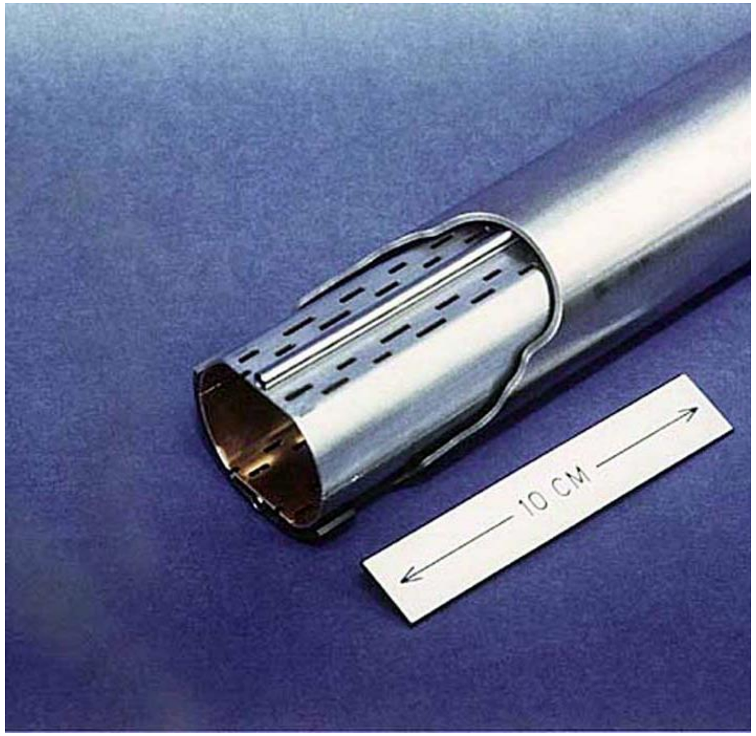
A beam pipe in which the beam circulates

+

Elements in and around the pipe to:

- Steer and focus the beam
- Accelerate the beam and give it structure
- Measure the beam
- Inject and extract the beam
- …

Oversimplified view !!



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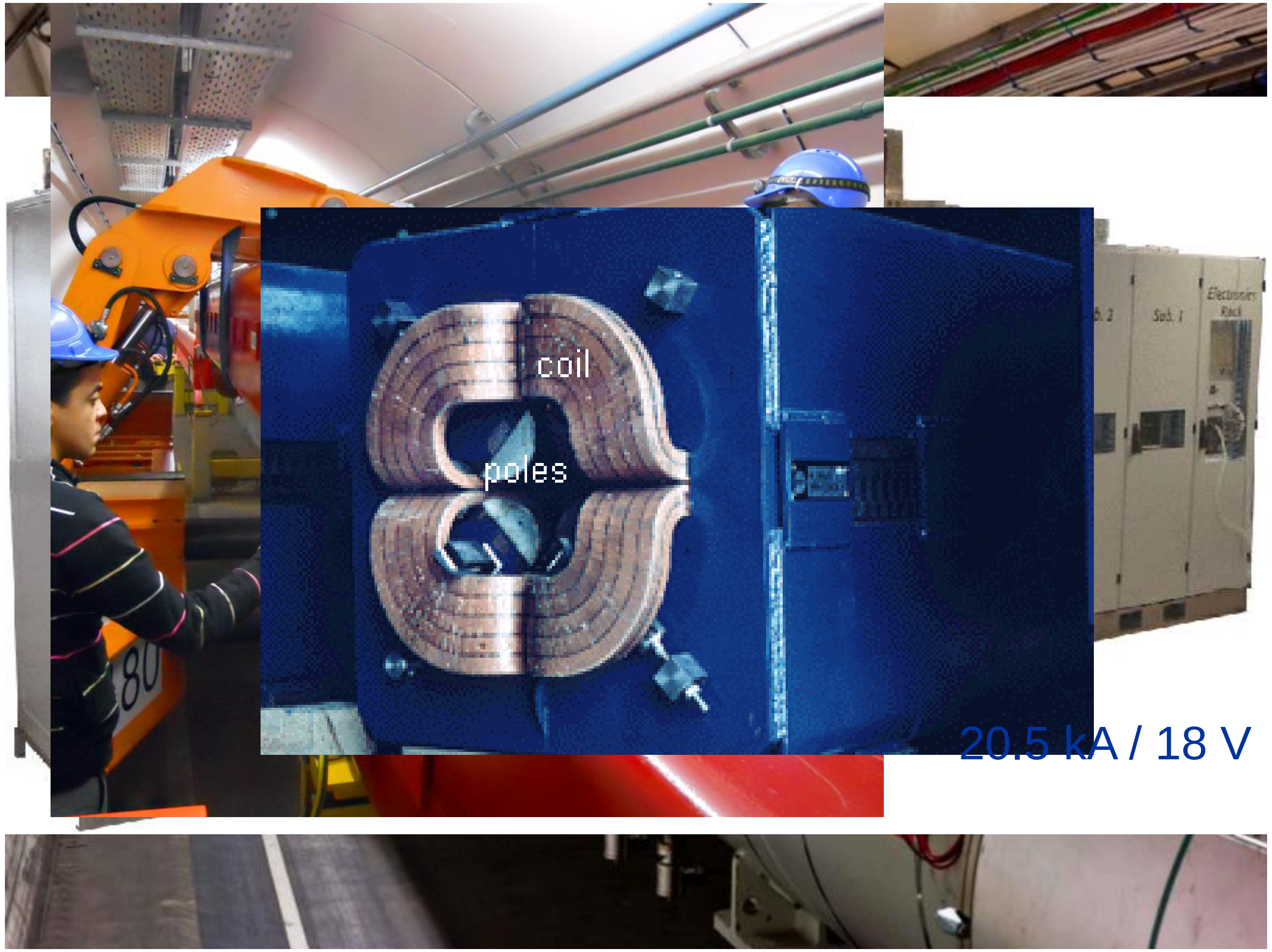

Oversimplified view !!

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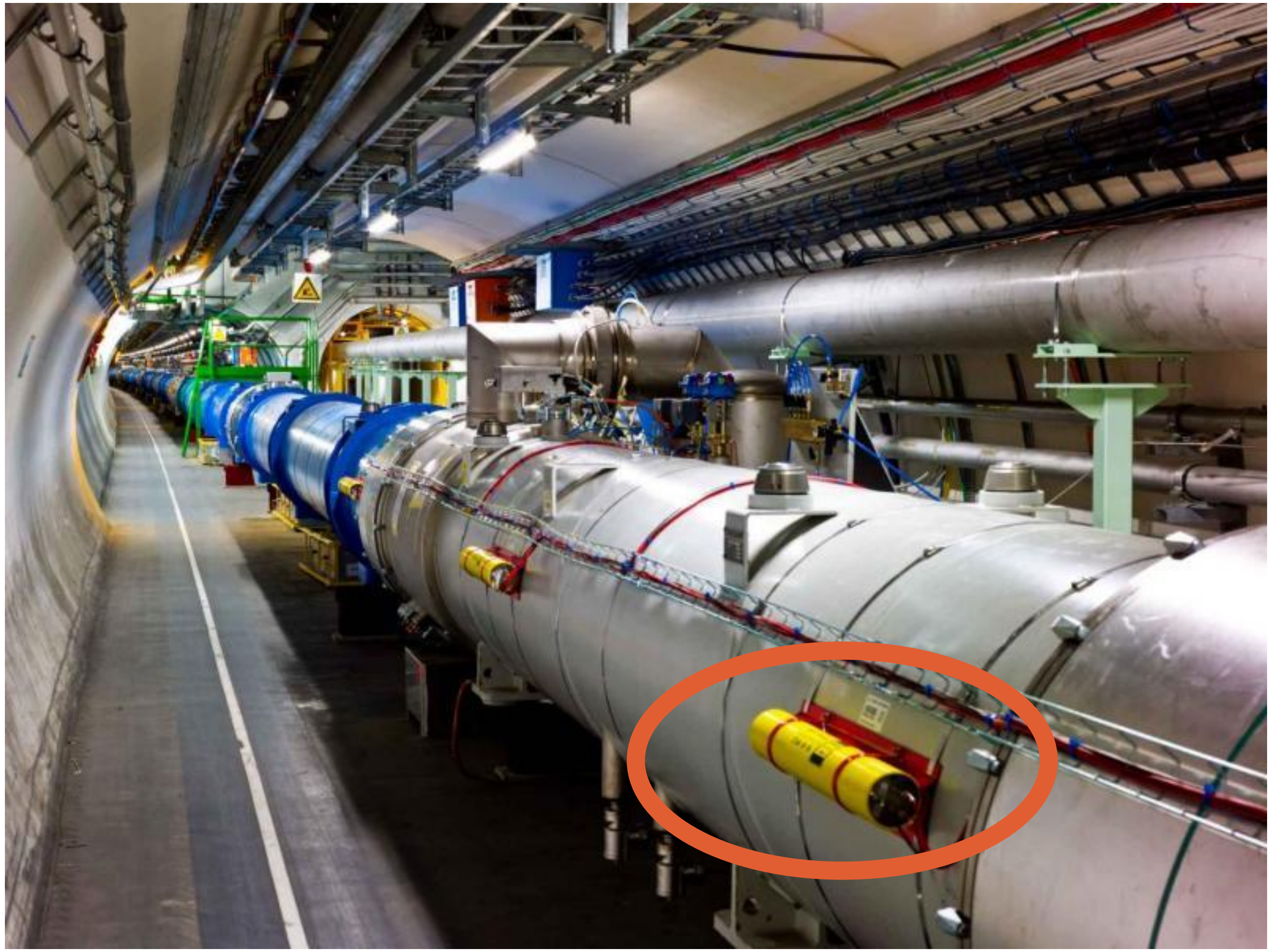
Oversimplified view !!

What is an accelerator made of?

Beam Position Monitor
Beam Position Monitor



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Oversimplified view !!

Transfer line

Septum

Why a Control System?

- Particle accelerators are made of many components to control and monitor the beams produced.

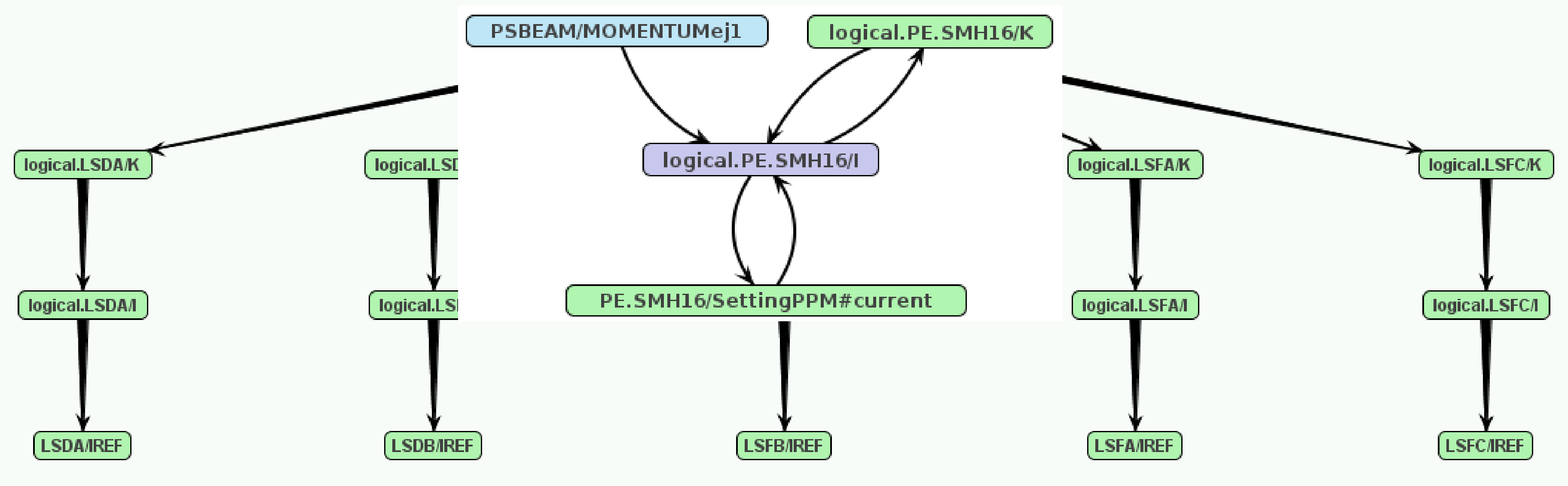
- The physicists and operators need to be able to remotely control and monitor these elements ➔ this is the role of the **Control System**.

Control System Requirements

Control System Key Requirements

Act on accelerator elements (settings & states)

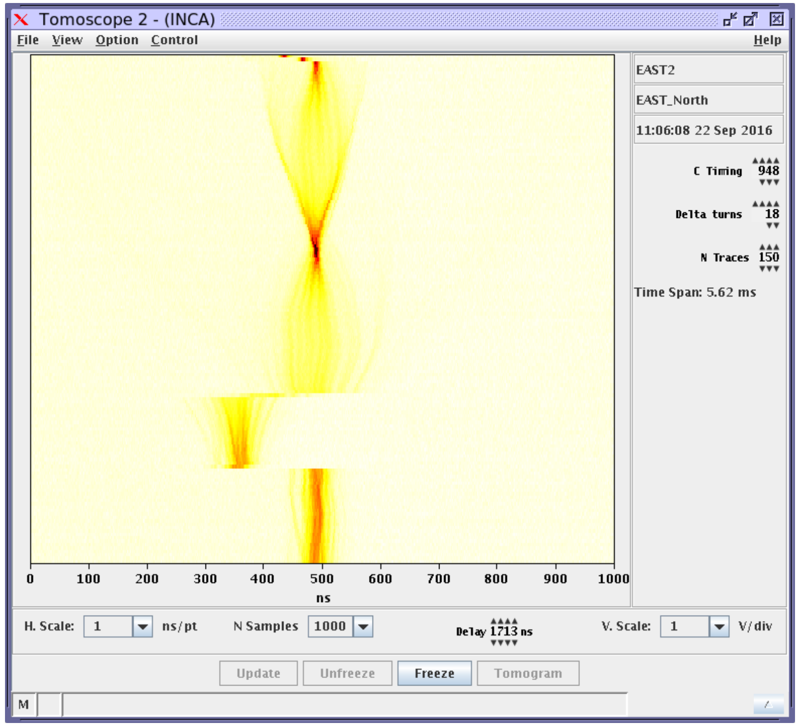
- Minimum: direct access to the hardware values
- Ideal:
  - Model-driven control to work at a higher level
  - Global transactional synchronisation



Control System Key Requirements

Monitor the elements (instruments & actuators)

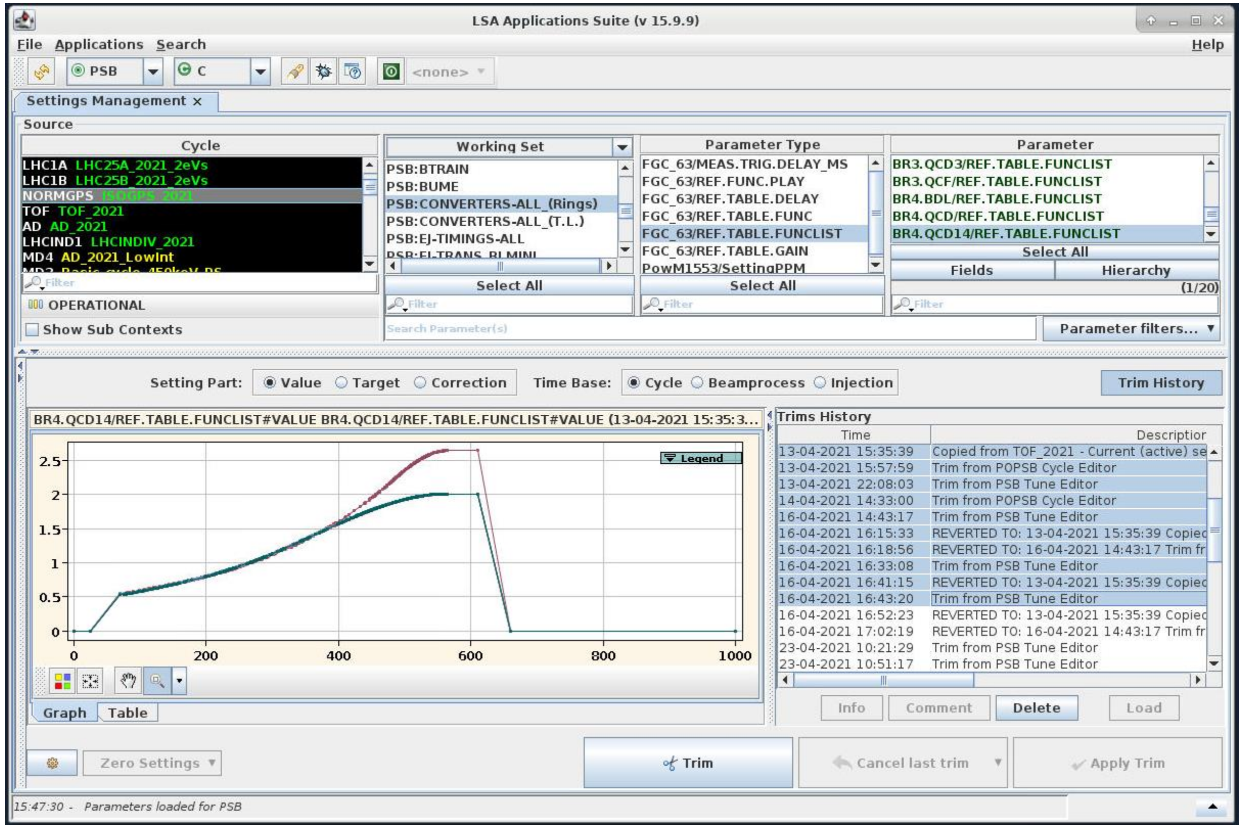
- Minimum: Display raw acquisitions
- Ideal: Time-tagged, coherent acquisitions, post-processing for quick detection of abnormal situations



Control System Key Requirements

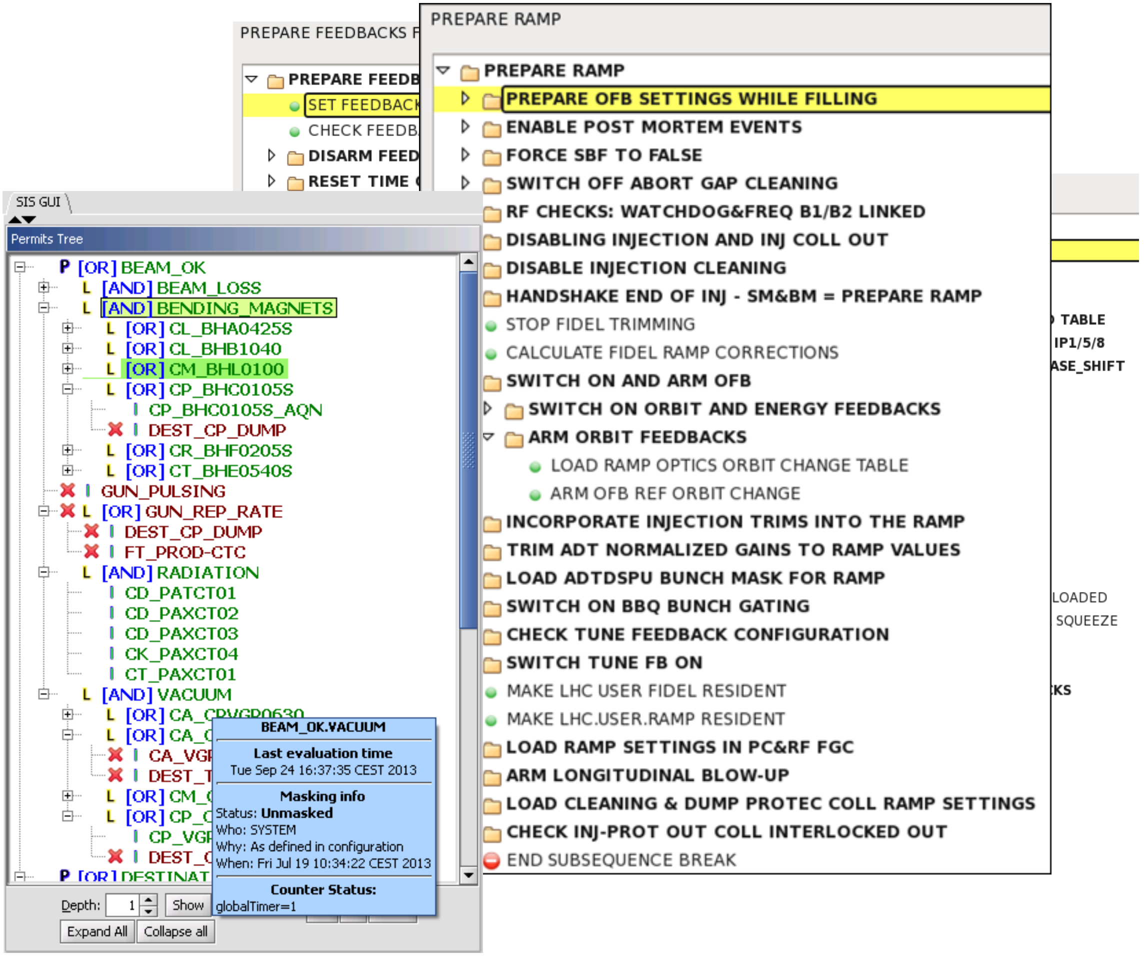
Long-Term Memory of Settings & Acquisitions

- AKA Logging
- Accelerator performance & post-mortem analysis, fine tuning of the machines
- Minimum: structured time-series in a simple format (CSV, SDDS, etc.)
- Ideal: Years of data (settings & acquisitions) with performant data extraction & analysis tools



More Control System Requirements

- **Automation**
  - **Generate initial values, play sequences, feedback loops, etc.**
  - **Minimum: Non-interactive scripts**
  - **Ideal: Model-driven generation, flexible sequencer (almost like a debugger), automated actions (decision tree, machine learning)**

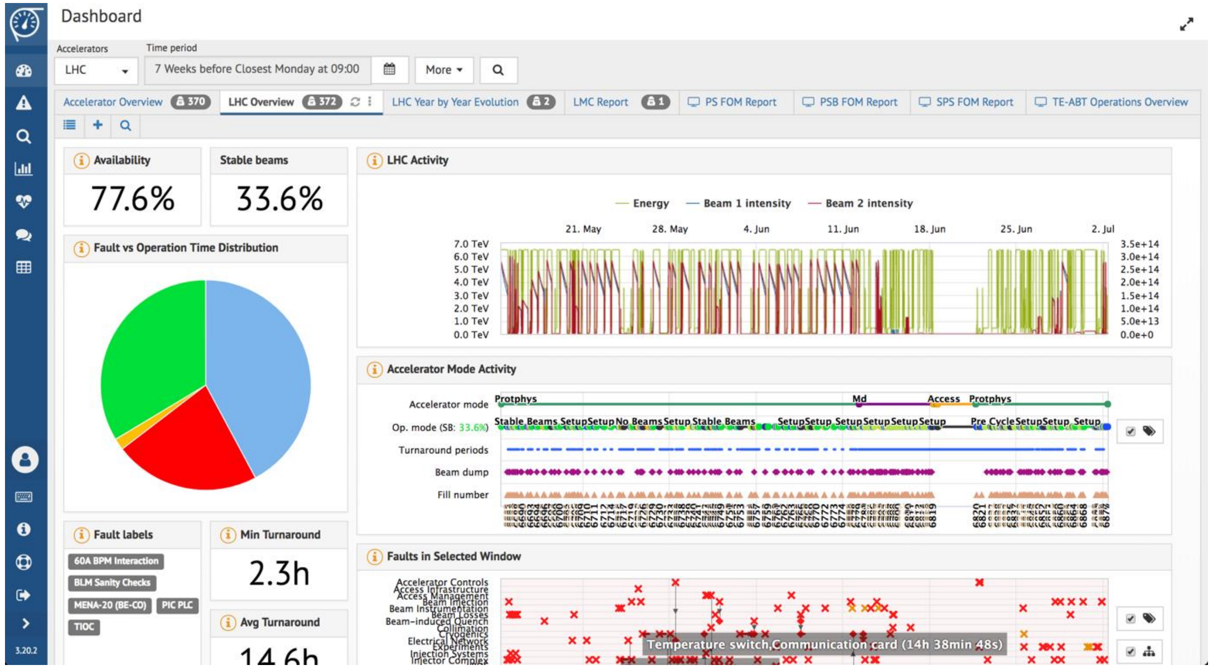


More Control System Requirements

- **Safety for machine protection & operational availability**
  - **Minimum: Machine interlock to protect the hardware**
  - **Ideal: High-level fast-reaction interlocks and role-based access to prevent the wrong action at the wrong time**

More Control System Requirements

- **Diagnostics**
  - **Detection, identification, and follow-up of problems in the controls infrastructure**
  - **Minimum: Non-interactive status screens**
  - **Ideal: Online monitoring, remote interventions (e.g. power cycle), failure prediction (Machine Learning), analysis tools**



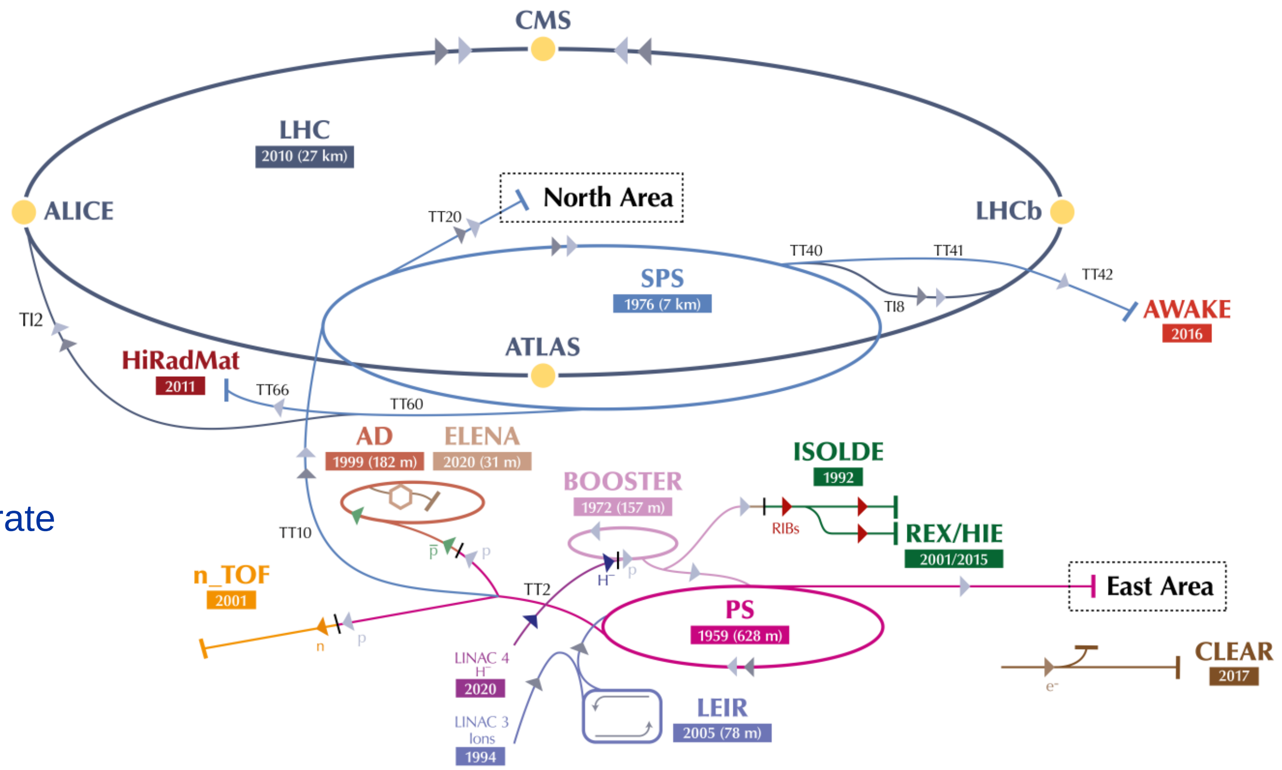
And many more…

Controls Complexity

- **Many requirements from physicists and operators**
- **Accelerators made of many elements**
  - Early accelerators, e.g. Proton Synchrotron (PS), were small

    < 5’000 devices
  - Latest accelerators, e.g. LHC, are much more complex to operate

    30’000+ elements



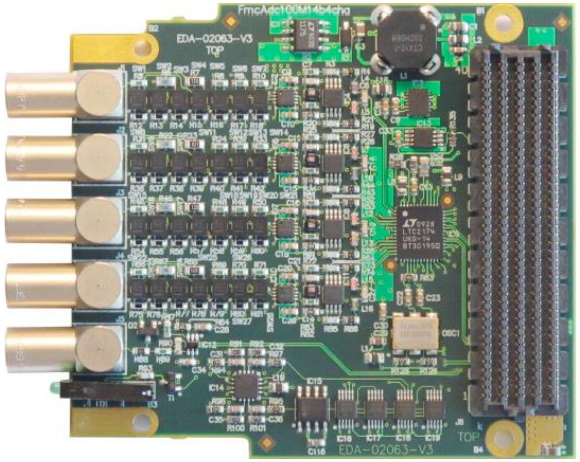
- **The Control System’s job is to hide the complexity and help you to do your job as efficiently as possible.**

Implementation Philosophy

Implementation Philosophy - Hardware

As much as possible:

- **Apply vertical industrial control system solutions**
  - PLCs for industry-like process control (electricity, cooling & ventilation, vacuum, cryo)
- **Restrict home-made HW development to specific applications**
  - Beam optics controls (i.e. all power converters),
  - Injection and Extraction systems,
  - Beam instrumentation,
  - RF,
  - Collimation,
  - Timing Systems,
  - Etc.



Don't Reinvent The Wheel !!

- **Base the HW architecture on available standards and Commercial Off-The-Shelf (COTS)**
  - Standards for complex embedded I/O systems with high performance demands
  - COTS electronic modules for generic features (CPUs, serial controller boards, ADCs, etc.)
  - COTS desktop PCs & servers for control rooms and application servers
  - Standard fieldbuses for applications requiring real-time features and radiation hardness (e.g. WorldFIP), and less stringent applications (Profinet/Ethercat)
  - Standards for cost-effective I/O systems for networking (fieldbus controllers)
  - GPS for time stamping and overall accelerator synchronization

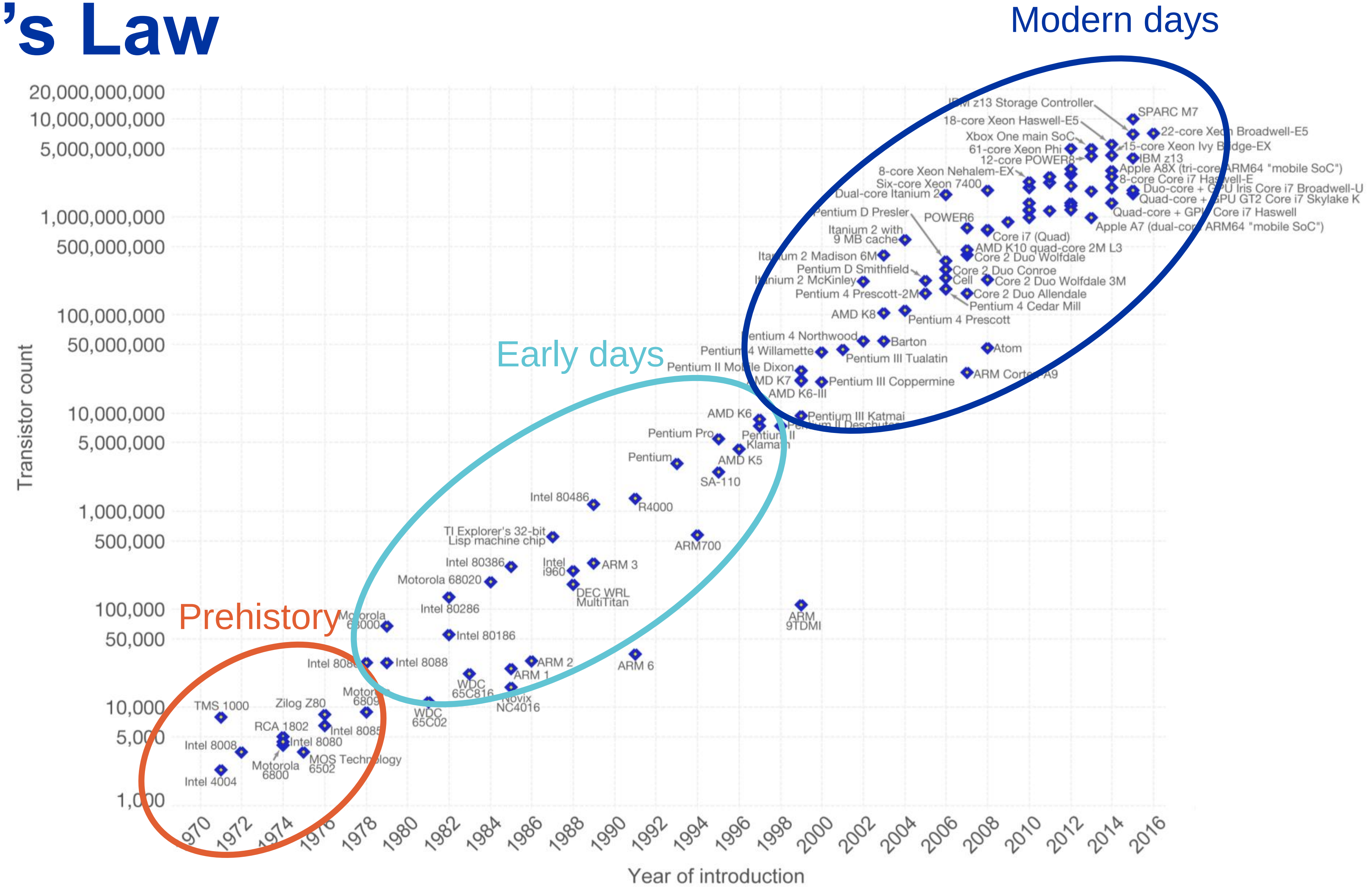
Implementation Philosophy - Software

As much as possible:

- **Apply vertical industrial control system solutions**
  - Supervisory Control and Data Acquisition Systems (SCADA) for commands, graphical user interfaces, alarms, etc. of industrial systems
- **Rely on common technologies and tools**
  - Important for aspects such as recruitment, education & training
  - DBs & Storage solutions (e.g. Hadoop)
  - Communication protocols
  - Monitoring solutions used in the industry (e.g. ICINGA)
- **Privilege Open-Source Software**
  - Avoid vendor lock-in
  - Control license cost
  - Manage the Total Cost of Ownership (TCO)

A bit of History

Moore's Law

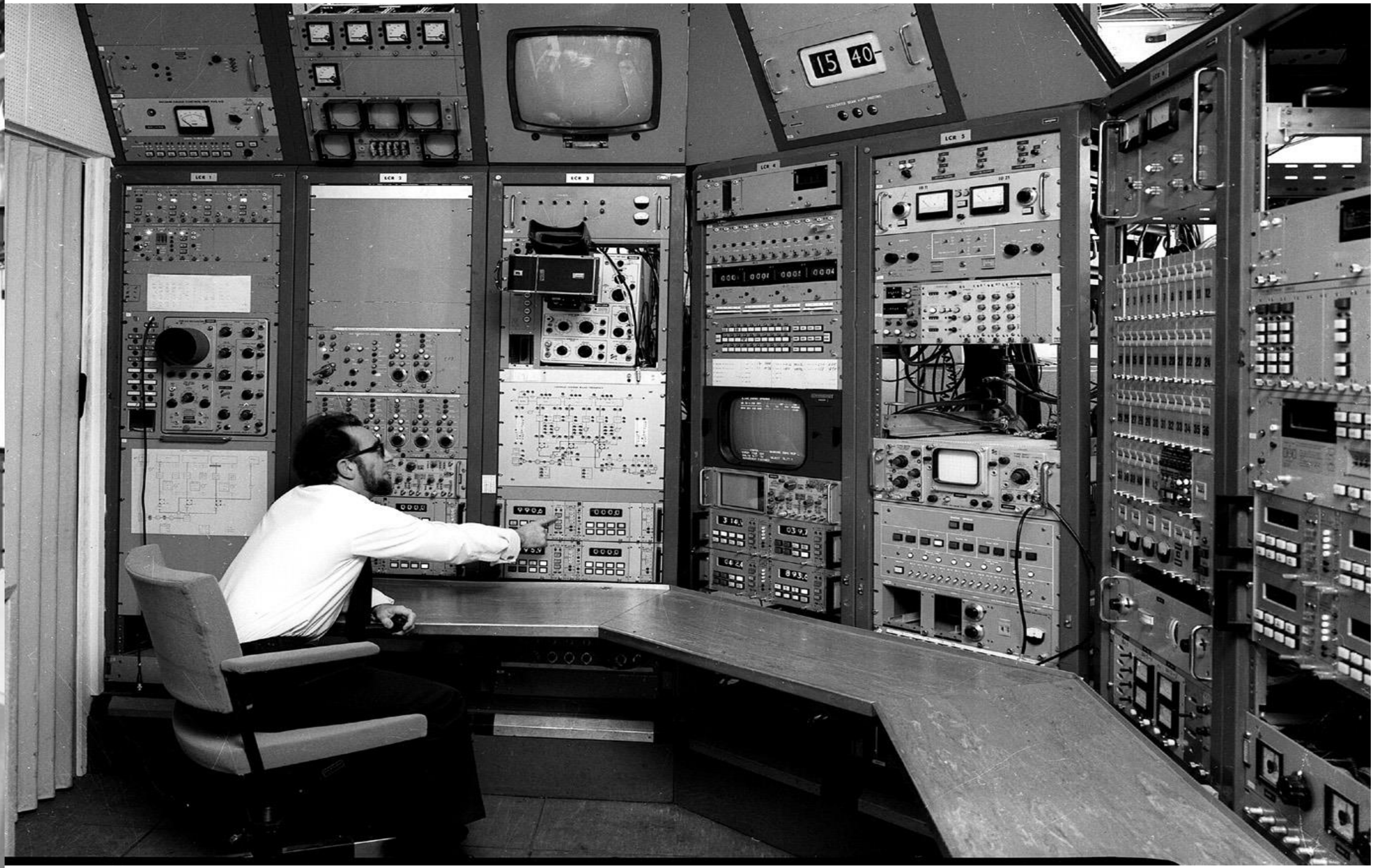


Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

Control System Prehistory

- **Accelerators are small and overall less complex (e.g. no superconducting magnets)**
  - No more than a few thousands of devices to control
- **No computing infrastructure and limited possibility to model**
- **Actuator and monitors are physically in the local control rooms (e.g. buttons, knobs, analogue oscilloscopes, etc.)**

Control System Prehistory



The Early Days

Beginning of remote controls

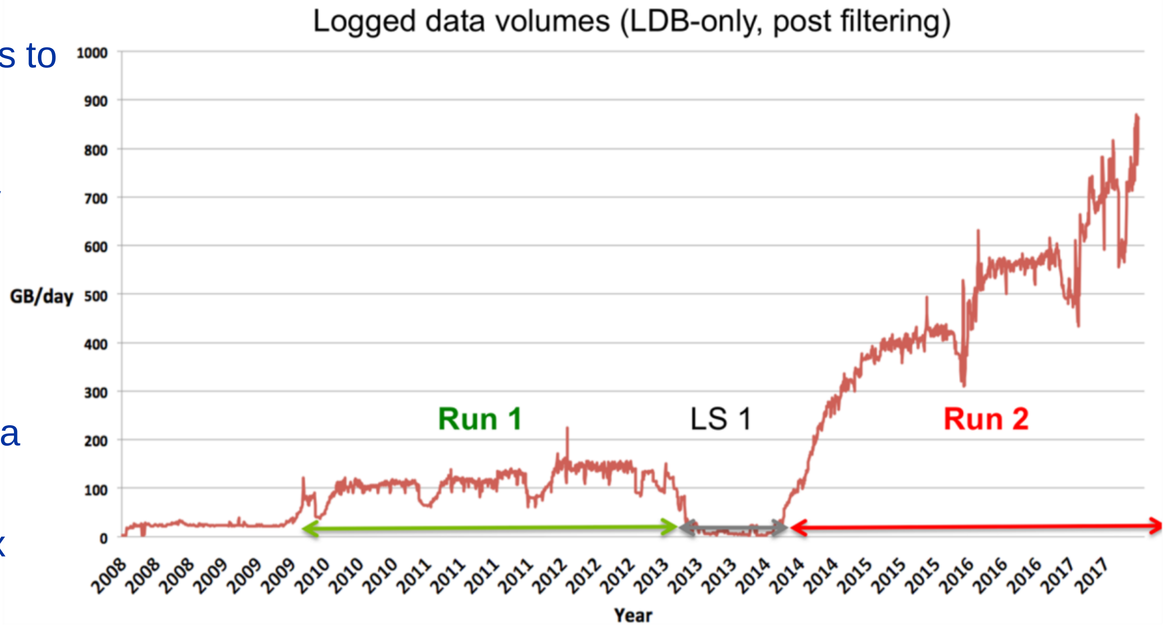
- Still limited by the available performance
- Lack of standards and common frameworks → more DIY and custom solutions
- Emergence of several controls solutions, aiming at different types of accelerators (at first)
  - EPICS (driven by US labs),
  - Tango (driven by ESRF (Fr) – synchrotron light sources)
  - CERN[1]

[1] non-exhaustive list

Modern days

- **Hardware has become powerful**
  - E.g. embedded systems at CERN in late 90s had **64 MB of RAM**; Nowadays, they have **8 GB**
  - Most of the needs are covered
  - Yet, users want more and more data (turn-by-turn acquisitions, big-data solution for the long-term storage, etc.)

- **Software industry has become a major actor worldwide.**
  - We can rely on many readily available technologies that open the doors to much more powerful systems



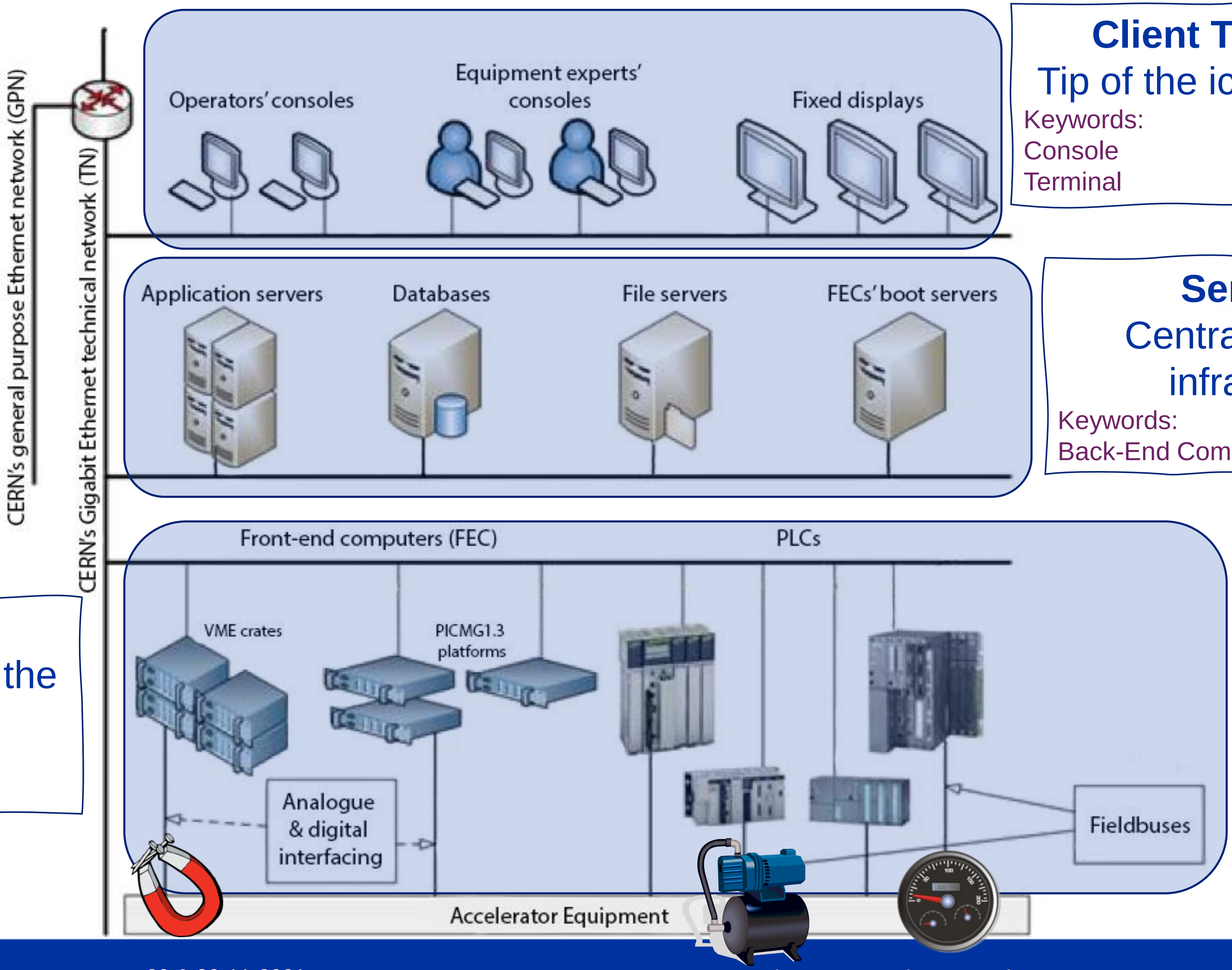
- **We still need to integrate and customise them to the very specific domain of particle accelerator controls**
  - Not all solutions are appropriate; Need to remember accelerator controls ≠ selling plane tickets
  - Mastering the different solutions with their evolution, limitations, etc. is a major challenge
  - The rhythm of updates is no longer under our control. E.g. recent Linux CentOS changes

50 years of technology evolution

High-Level Architecture

of a modern control system

High-Level Hardware Architecture



Client Tier
Tip of the iceberg
Keywords:
Console
Terminal

Server Tier
Central computing infrastructure
Keywords:
Back-End Computer (BEC)

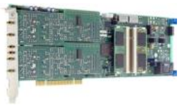
Resource Tier
Electronics close to the accelerator
Keywords:
Front-End Computer (FEC)

High-Level Hardware Architecture

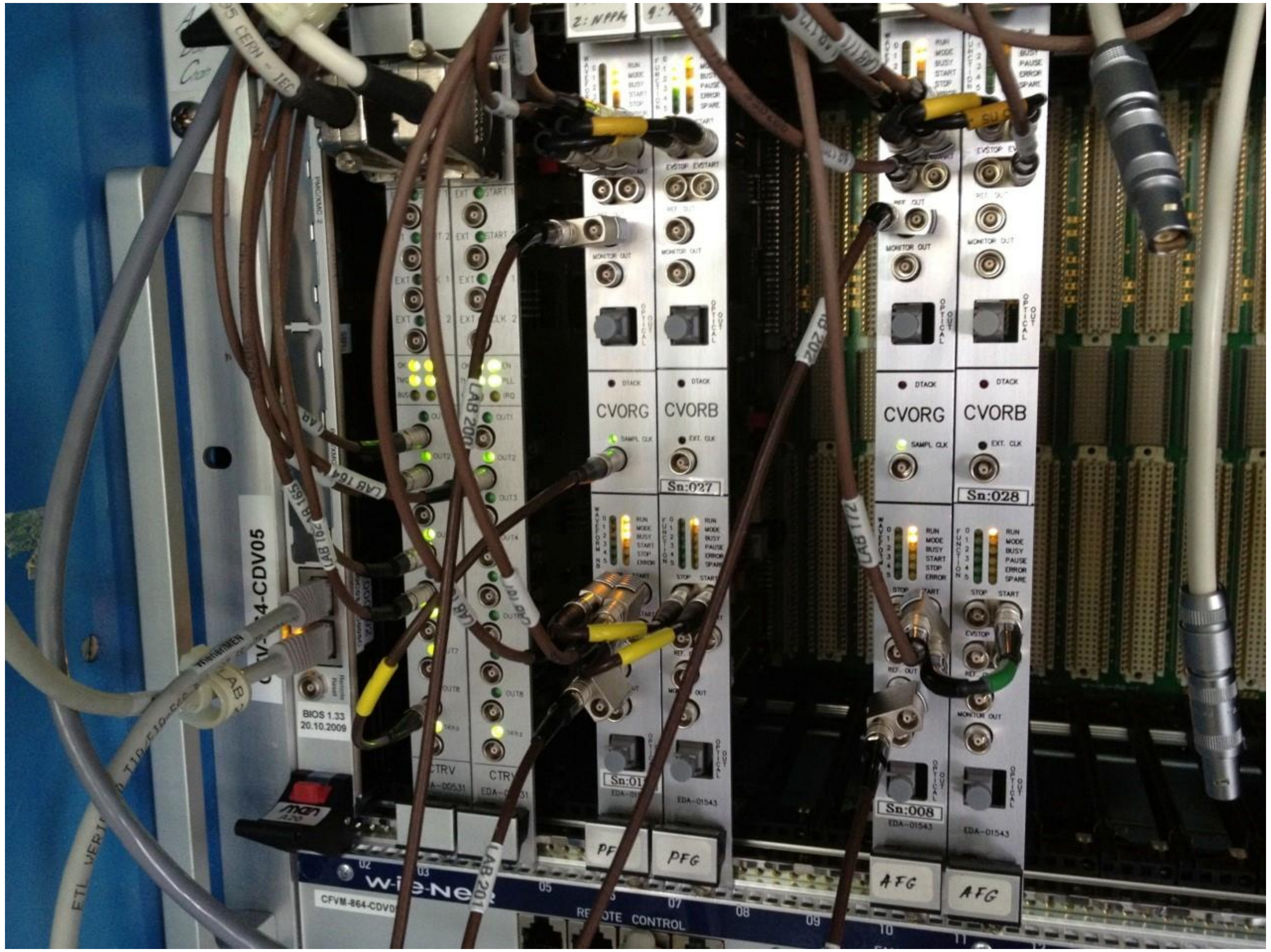
Resource Tier

- **Open enclosures**
  - Easy access
  - Better cooling and power available
  - But expensive
- **Closed enclosures**
  - Possible for simple functions (e.g. fieldbus control)
  - Cost effective; when deployed in big number, e.g. LHC power converter control gateways







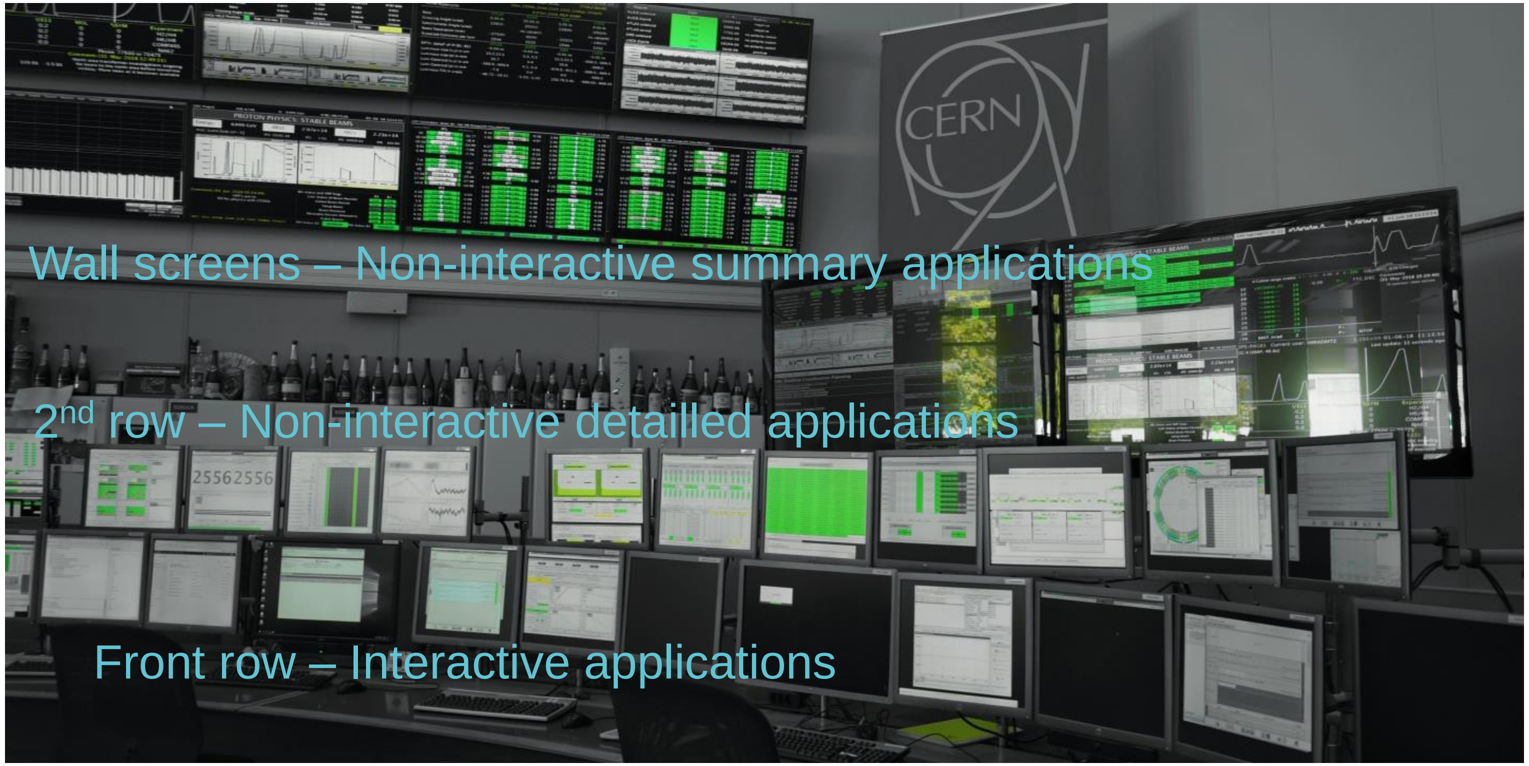


High-Level Hardware Architecture

Middle Tier

- IT-Computer-centre type of hardware
- High-density
- Highly available (redundancy and hot-swap)

High-Level Hardware Architecture



Control Room Computers

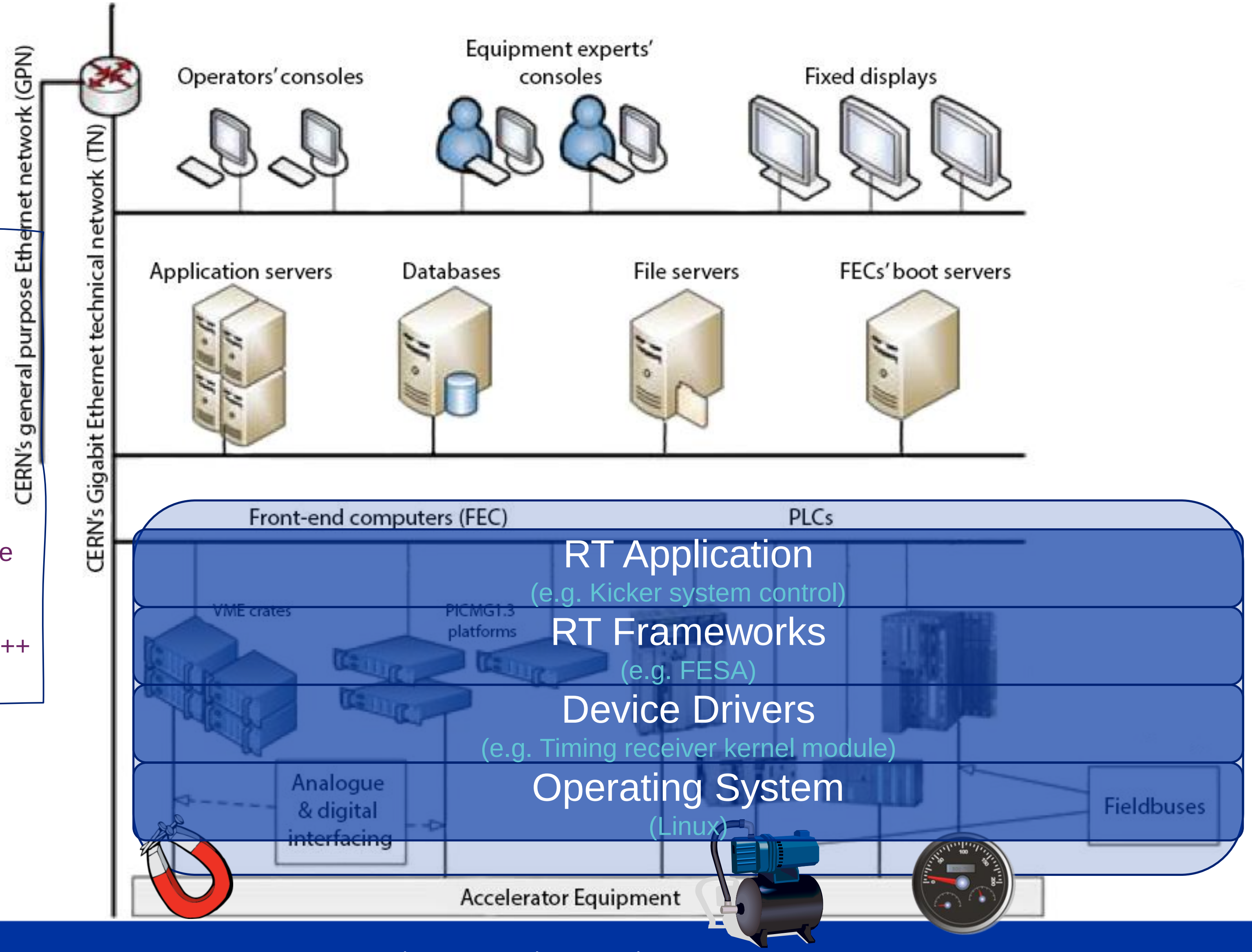
- As much as possible COTS desktop PCs but MTBF requirements might be difficult to satisfy
- Users expect modern reactive GUIs
- Several layers of screens to have as much data as possible available

High-Level Software Architecture

Front-end Tier

Real-time control and acquisition

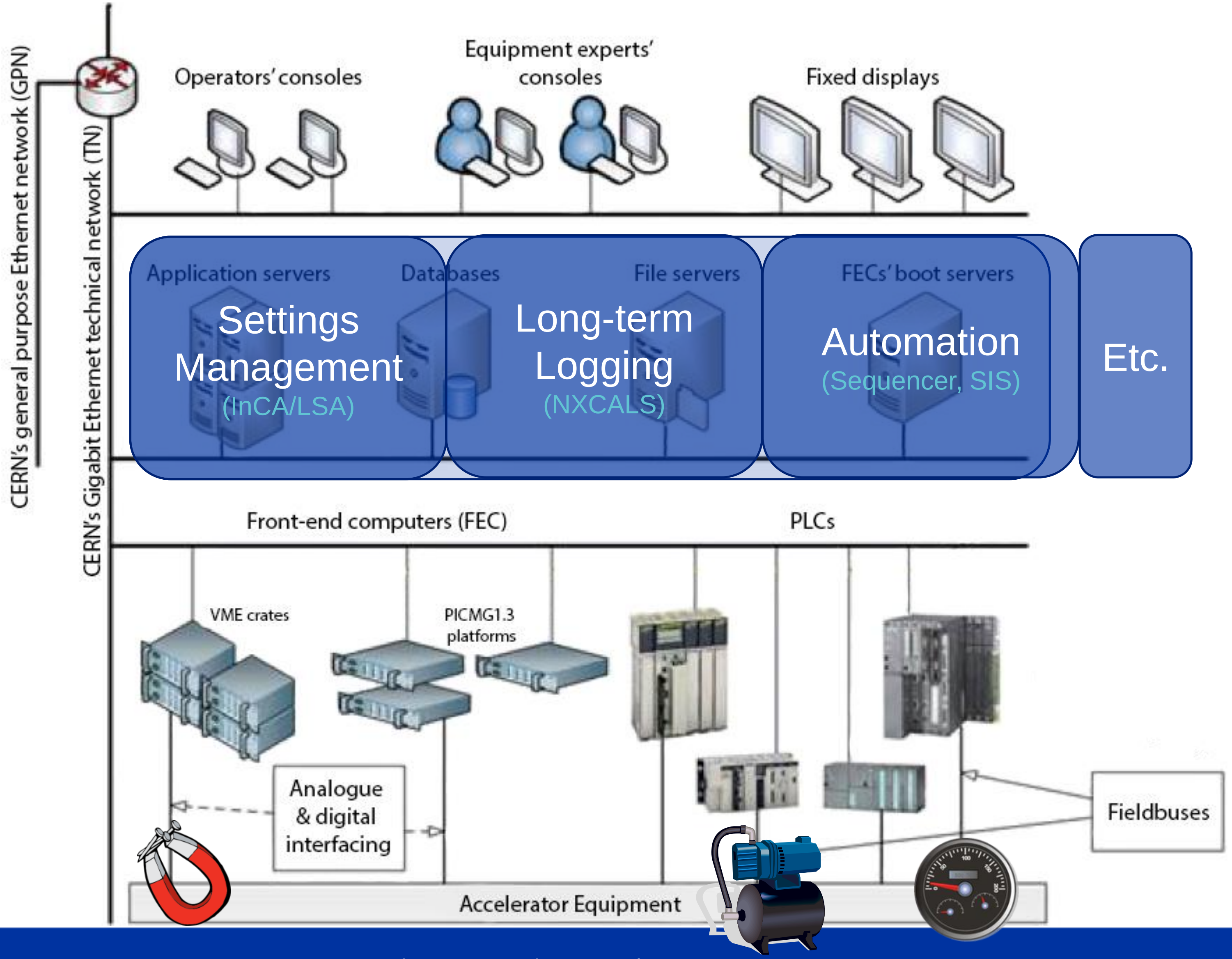
- Limited, local scope
- Fast reaction possible (interrupts)
- Limited computing power (compared to other tiers)
- Equipment processing to provides a high-level view of the hardware
- Real-time (RT) applications relies on frameworks, which capture the recuring aspects (react to events, publish new data, etc.) E.g. Front-End Software Architecture (FESA)
- Based on technologies closed to the hardware (C for drivers, C++ for RT, etc.)



High-Level Software Architecture

Business Tier
General purpose services & Specific business logic

- Broader scope; able to coordinate the entire accelerator
- Powerful computers
- Less reactive (network) and at a higher-level of abstraction
- Based on technologies that are better suited for high-level business logic (e.g. Java)



High-Level Software Architecture

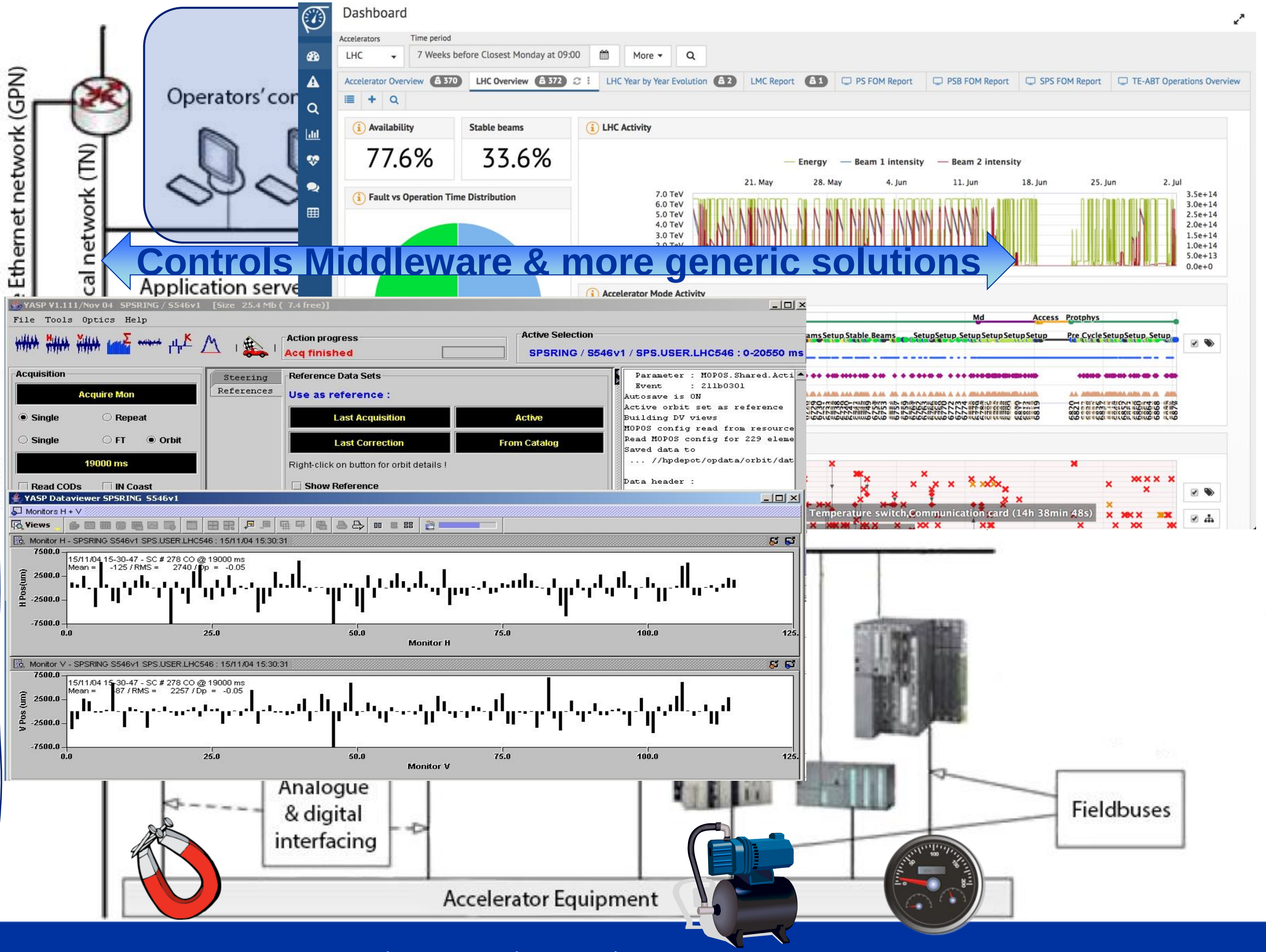
Presentation Tier
Graphical applications

Different technologies available
- Java Swing, Java FX
- Qt, PyQt
- Web ecosystem (Angular, View.js, etc.)

Keywords:
Graphical User Interface (GUI)
Command-line interface (CLI)

Communication

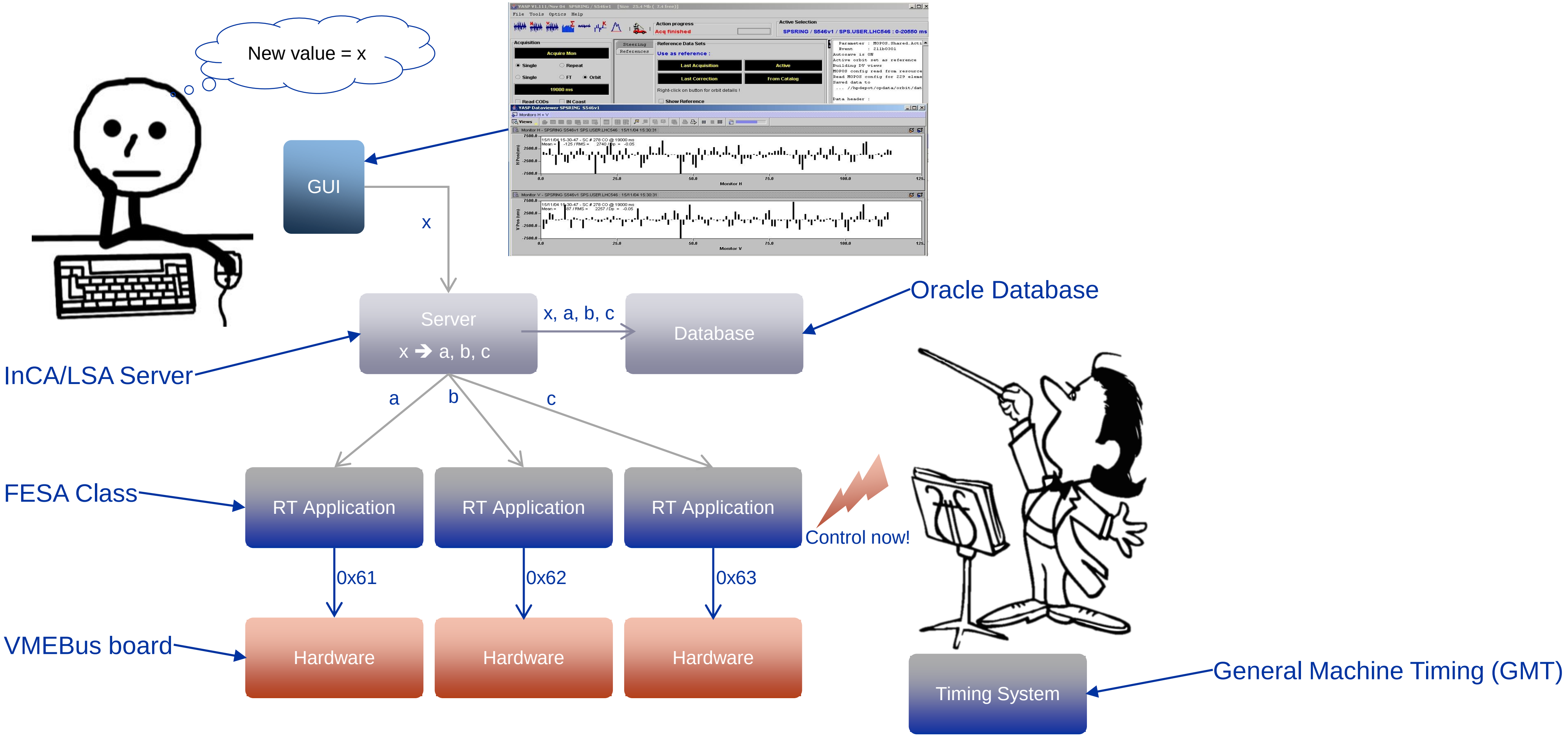
- Accelerator-specific protocols for the lower layers
  - Controls Middleware (CMW)
- Potentially, more generic technologies for the higher layers
  - RMI/JMS
  - REST API
  - gRPC
  - …



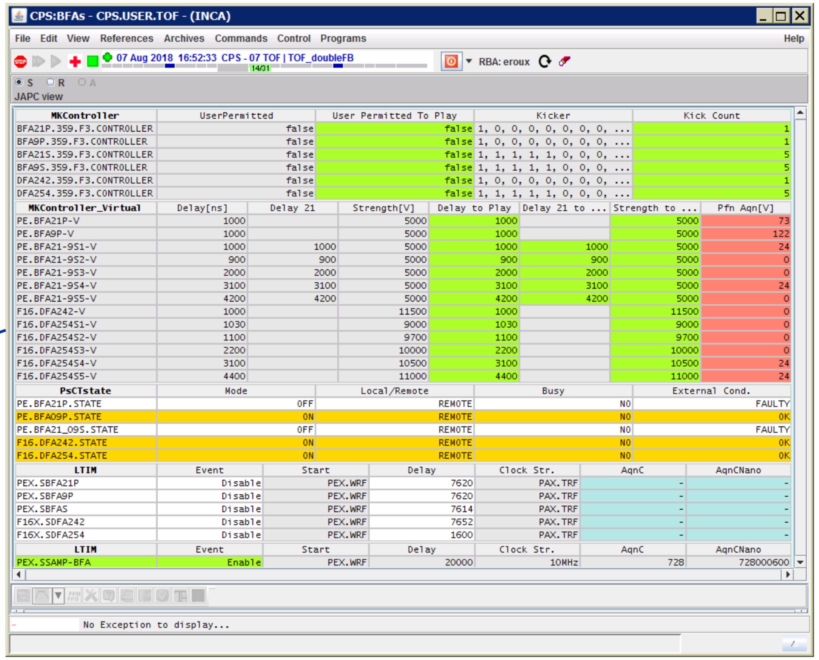
A few examples

And the key components used…

Example 1 – Control



Example 2 – Monitoring



CPS:BFAs - CPS.USER.TOF - (INCA)

File Edit View References Archives Commands Control Programs Help

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S R A

JAPC view

MKController	UserPermitted	User Permitted To Play	Kicker	Kick Count
BFA21P.359.F3.CONTROLLER	false	false	1, 0, 0, 0, 0, 0, 0, 0, ...	1
BFA9P.359.F3.CONTROLLER	false	false	1, 0, 0, 0, 0, 0, 0, 0, ...	1
BFA21S.359.F3.CONTROLLER	false	false	1, 1, 1, 1, 1, 0, 0, 0, ...	5
BFA9S.359.F3.CONTROLLER	false	false	1, 1, 1, 1, 1, 0, 0, 0, ...	5
DFA242.359.F3.CONTROLLER	false	false	1, 0, 0, 0, 0, 0, 0, 0, ...	1
DFA254.359.F3.CONTROLLER	false	false	1, 1, 1, 1, 1, 0, 0, 0, ...	5

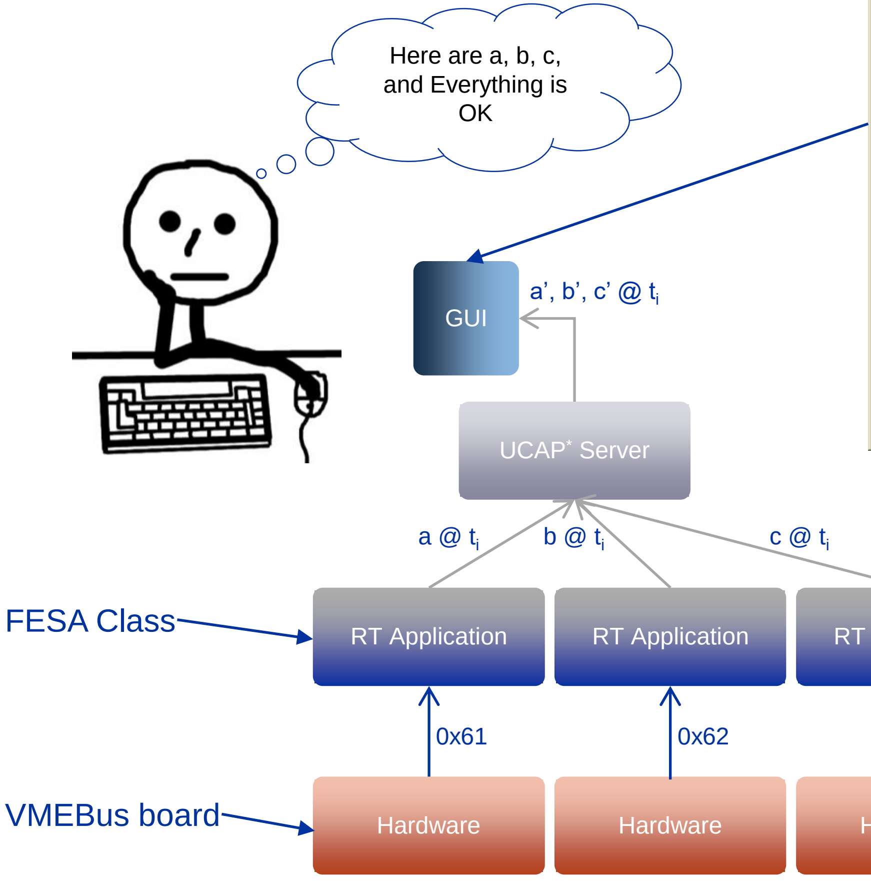
MKController_Virtual	Delay[ns]	Delay 21	Strength[V]	Delay to Play	Delay 21 to ...	Strength to ...	Pfn Aqn[V]
PE.BFA21P-V	1000		5000	1000		5000	73
PE.BFA9P-V	1000		5000	1000		5000	122
PE.BFA21-9S1-V	1000	1000	5000	1000	1000	5000	24
PE.BFA21-9S2-V	900	900	5000	900	900	5000	0
PE.BFA21-9S3-V	2000	2000	5000	2000	2000	5000	0
PE.BFA21-9S4-V	3100	3100	5000	3100	3100	5000	24
PE.BFA21-9S5-V	4200	4200	5000	4200	4200	5000	0
F16.DFA242-V	1000		11500	1000		11500	0
F16.DFA254S1-V	1030		9000	1030		9000	0
F16.DFA254S2-V	1100		9700	1100		9700	0
F16.DFA254S3-V	2200		10000	2200		10000	0
F16.DFA254S4-V	3100		10500	3100		10500	24
F16.DFA254S5-V	4400		11000	4400		11000	24

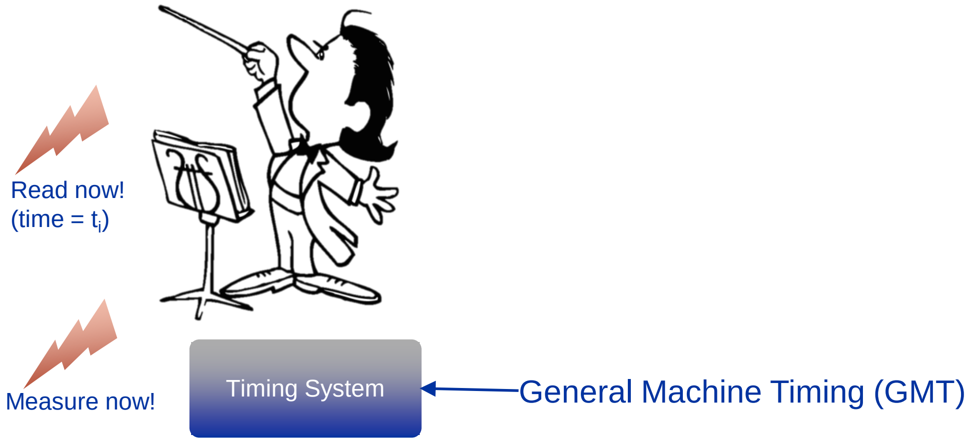
PsCTstate	Mode	Local/Remote	Busy	External Cond.
PE.BFA21P.STATE	OFF	REMOTE	NO	FAULTY
PE.BFA09P.STATE	ON	REMOTE	NO	OK
PE.BFA21_09S.STATE	OFF	REMOTE	NO	FAULTY
F16.DFA242.STATE	ON	REMOTE	NO	OK
F16.DFA254.STATE	ON	REMOTE	NO	OK

LTIM	Event	Start	Delay	Clock Str.	AqnC	AqnCNano
PEX.SBFA21P	Disable	PEX.WRF	7620	PAX.TRF	-	-
PEX.SBFA9P	Disable	PEX.WRF	7620	PAX.TRF	-	-
PEX.SBFAS	Disable	PEX.WRF	7614	PAX.TRF	-	-
F16X.SDFA242	Disable	PEX.WRF	7652	PAX.TRF	-	-
F16X.SDFA254	Disable	PEX.WRF	1600	PAX.TRF	-	-

LTIM	Event	Start	Delay	Clock Str.	AqnC	AqnCNano
PEX.SSAMP-BFA	Enable	PEX.WRF	20000	10MHz	728	728000600

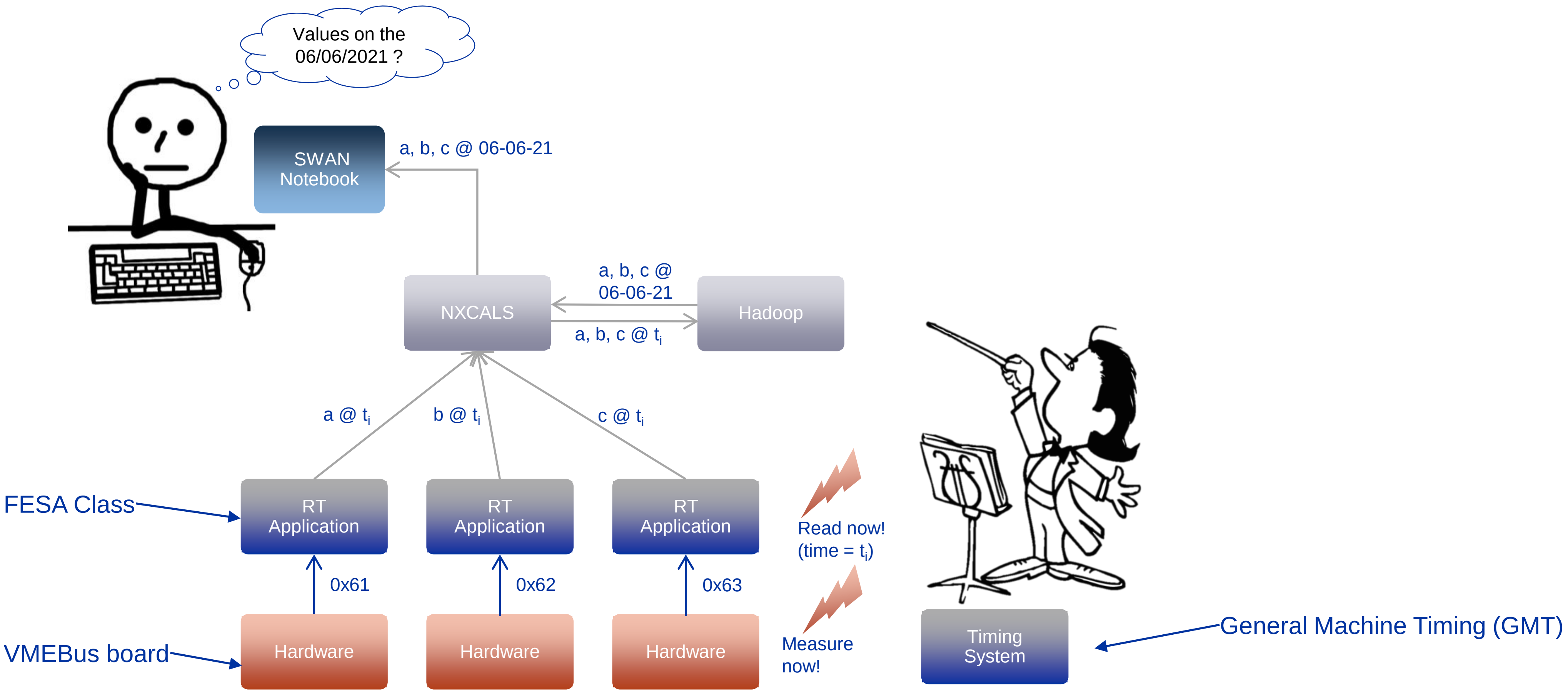
No Exception to display...





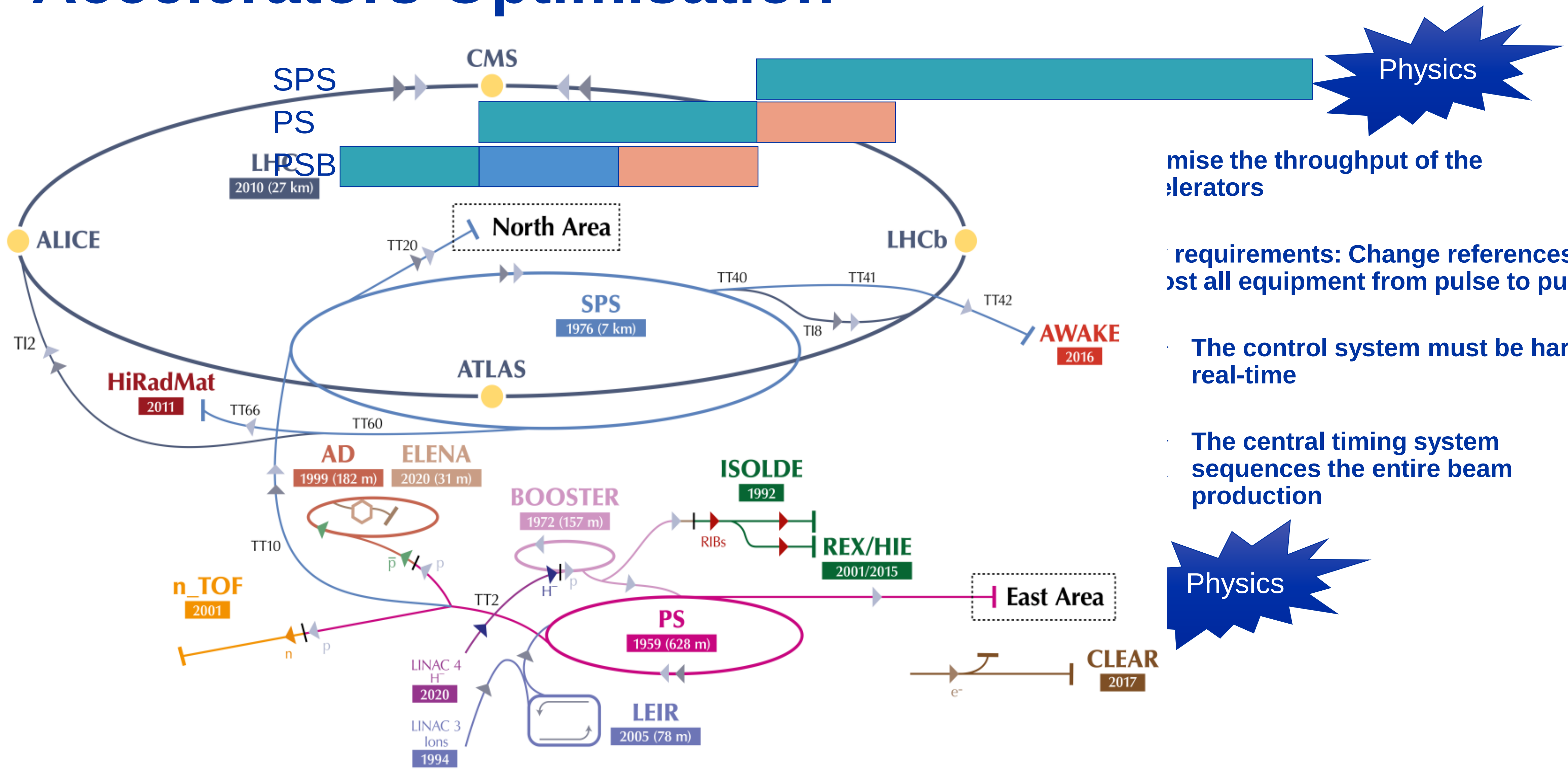
*UCAP: Unified Controls Acquisition & Processing framework

Example 3 – Logging



*SWAN: Service for Web based ANalysis

Accelerators Optimisation



mise the throughput of the
elerators

requirements: Change references of
ost all equipment from pulse to pulse

- The control system must be hard real-time
- The central timing system sequences the entire beam production

Program for Tomorrow…

- **Review the examples but looking at the technical implementation details**
  - Which technologies
  - Workflows
  - Design choices
  - Etc.

- **If possible, review**
  - The high-level architecture (get used to the names)
  - The examples
  - The timing system

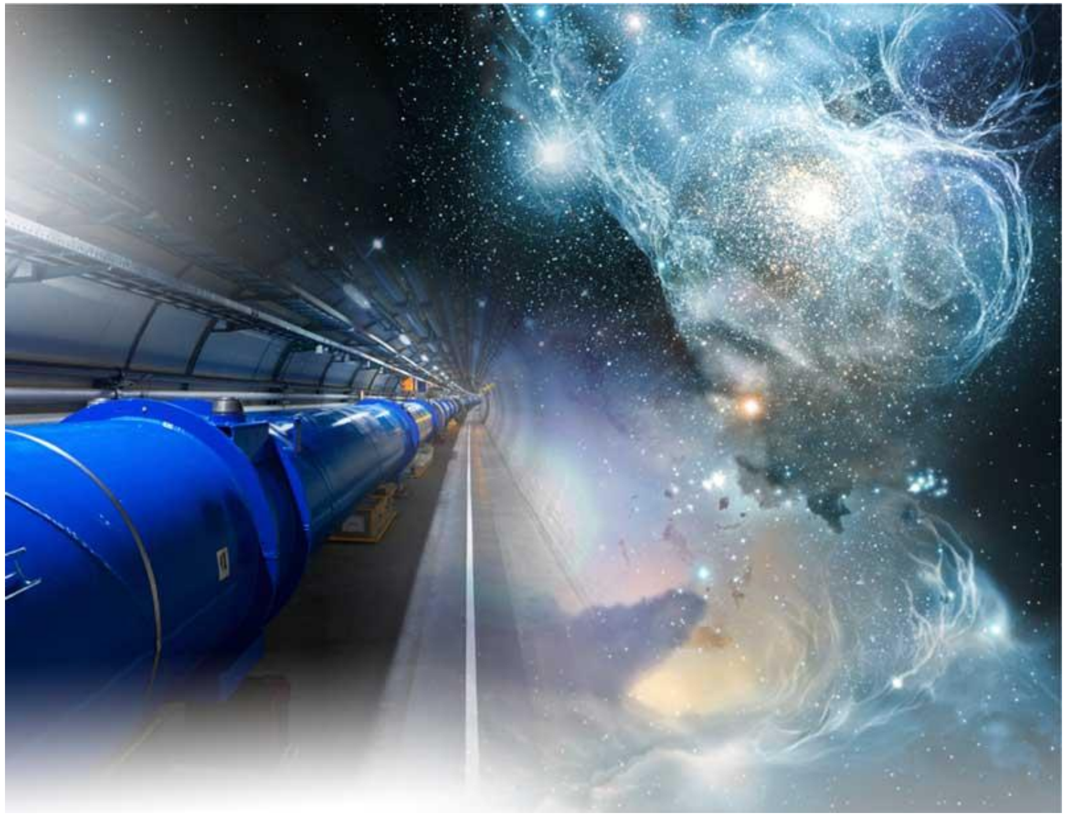
Want to know more?

CERN Beams Department (https://beams.cern/)

Introduction to BE-CO Control System, 2019 Edition, S. Deghaye & E. Fortescue, CERN, 2020. (https://cds.cern.ch/record/2748122)

Tango Controls (https://www.tango-controls.org/)

EPICS (https://epics-controls.org/)



Day 2

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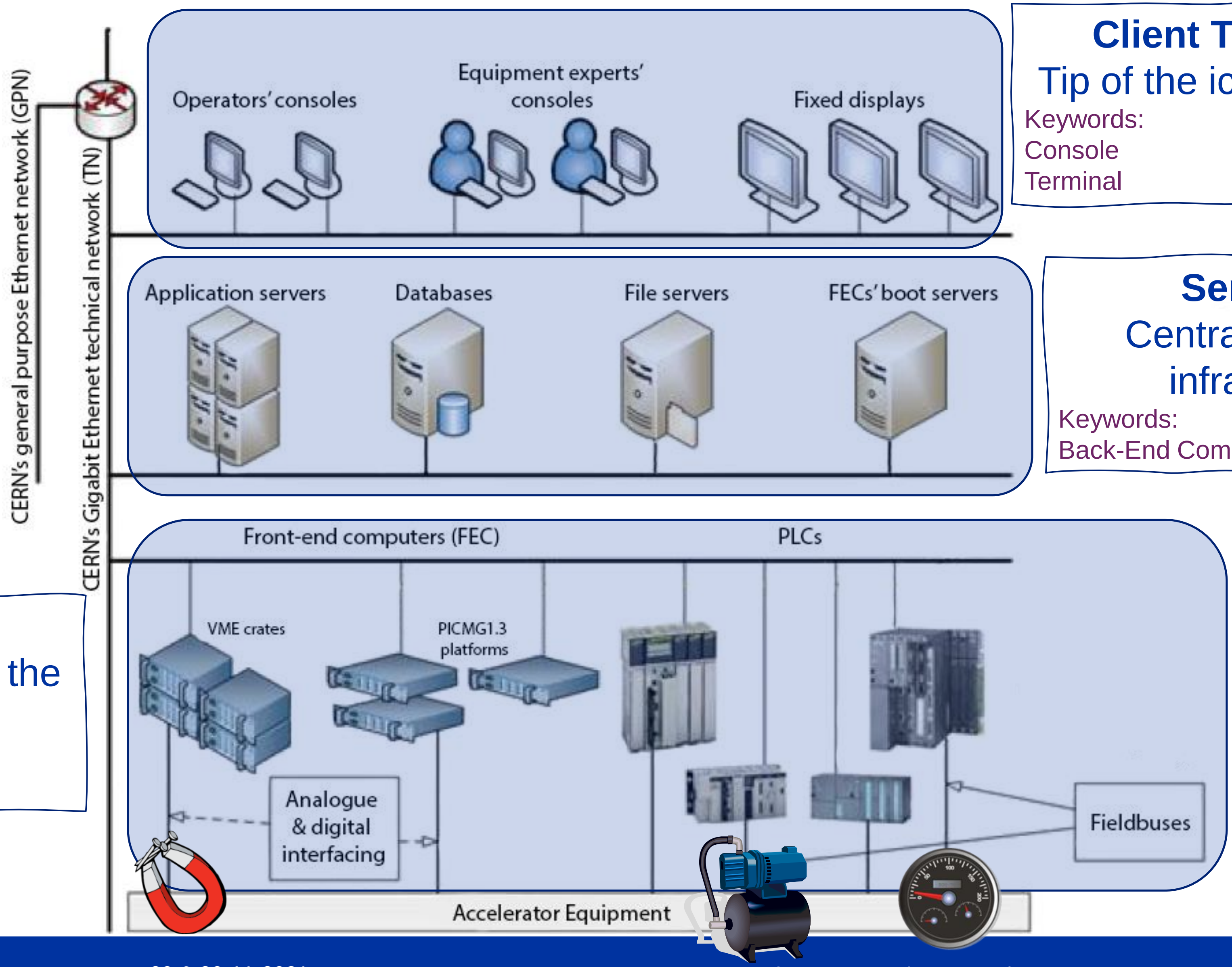
High-Level Hardware Architecture

Recap



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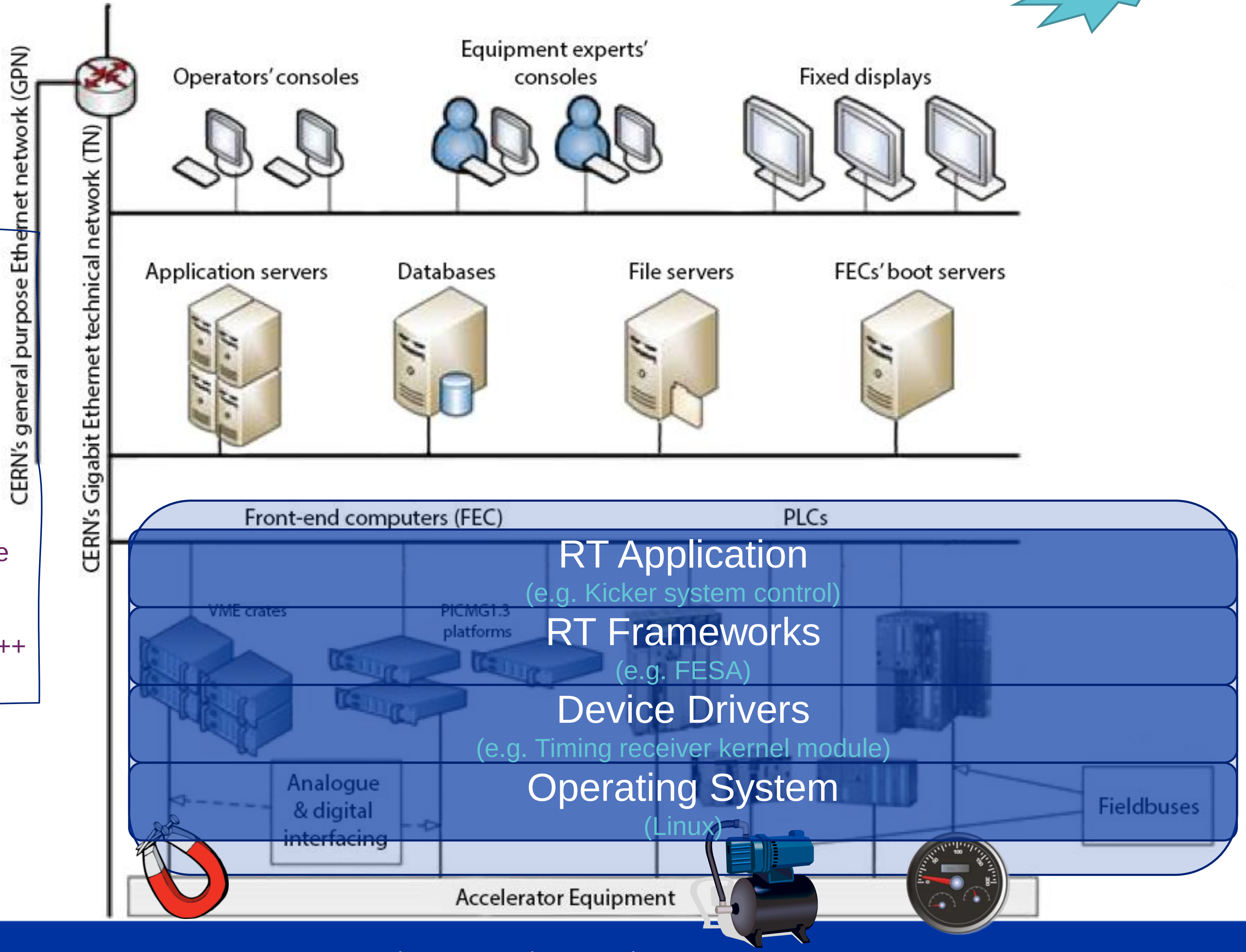

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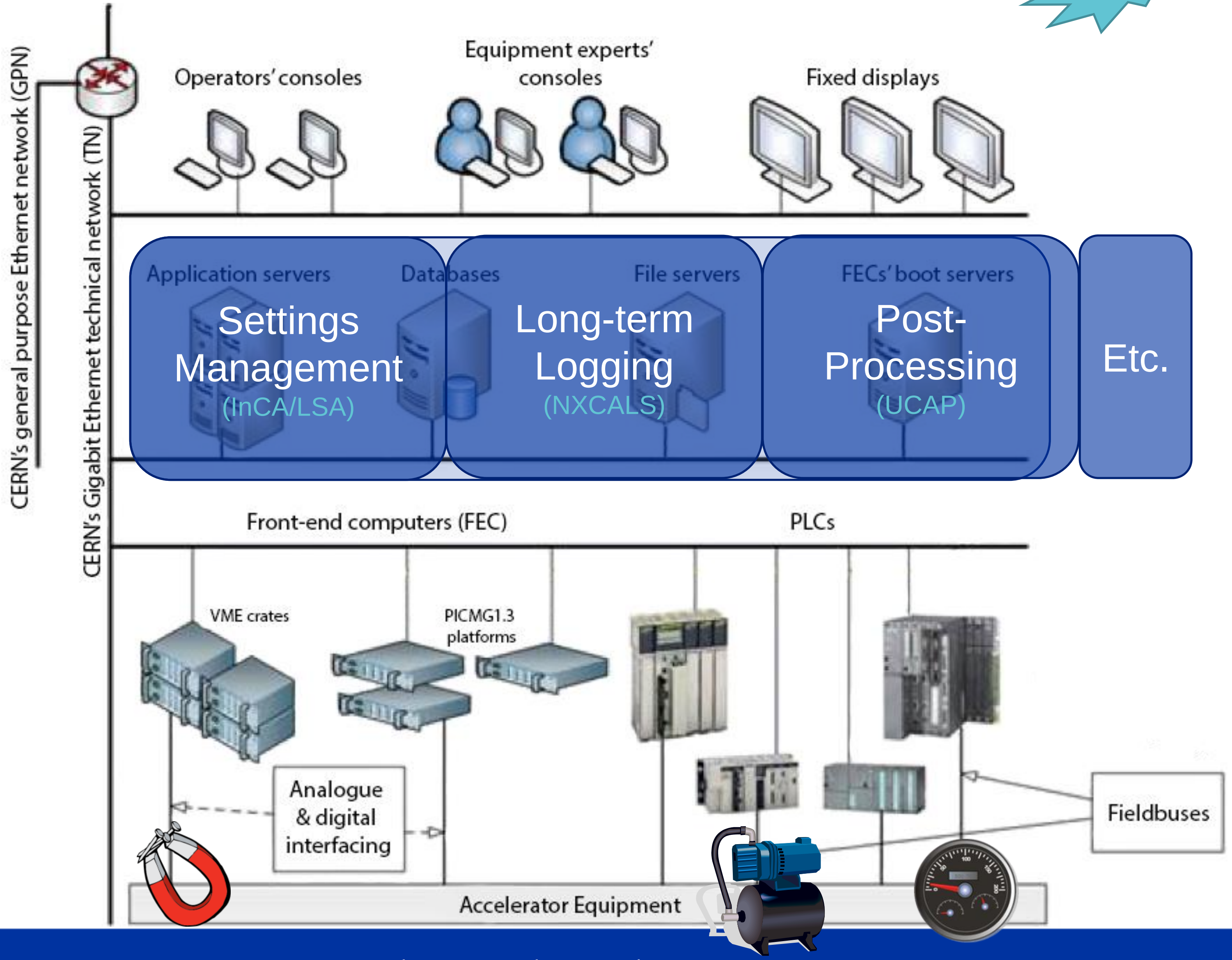
- Powerful computers
- Less reactive (network) and at a higher-level of abstraction
- Based on technologies that are better suited for high-level business logic (e.g. Java)



High-Level Software Architecture

Recap

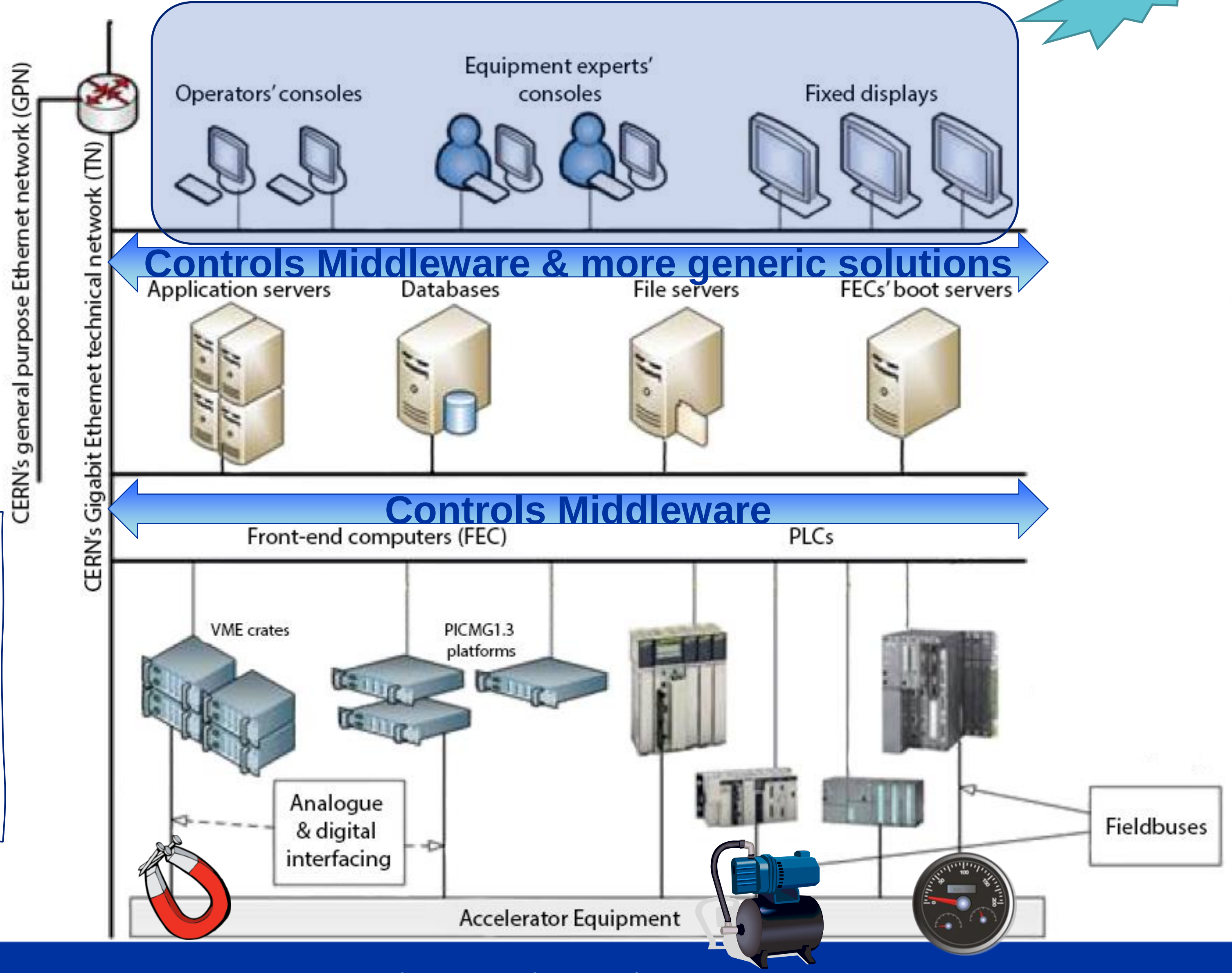
Presentation Tier
Graphical applications

Different technologies available
- Java Swing, Java FX
- Qt, PyQt
- Web ecosystem (Angular, View.js, etc.)

Keywords:
Graphical User Interface (GUI)
Command-line interface (CLI)

Communication

- Accelerator-specific protocols for the lower layers
  - Controls Middleware (CMW)
- Potentially, more generic technologies for the higher layers
  - RMI/JMS
  - REST API
  - gRPC
  - …

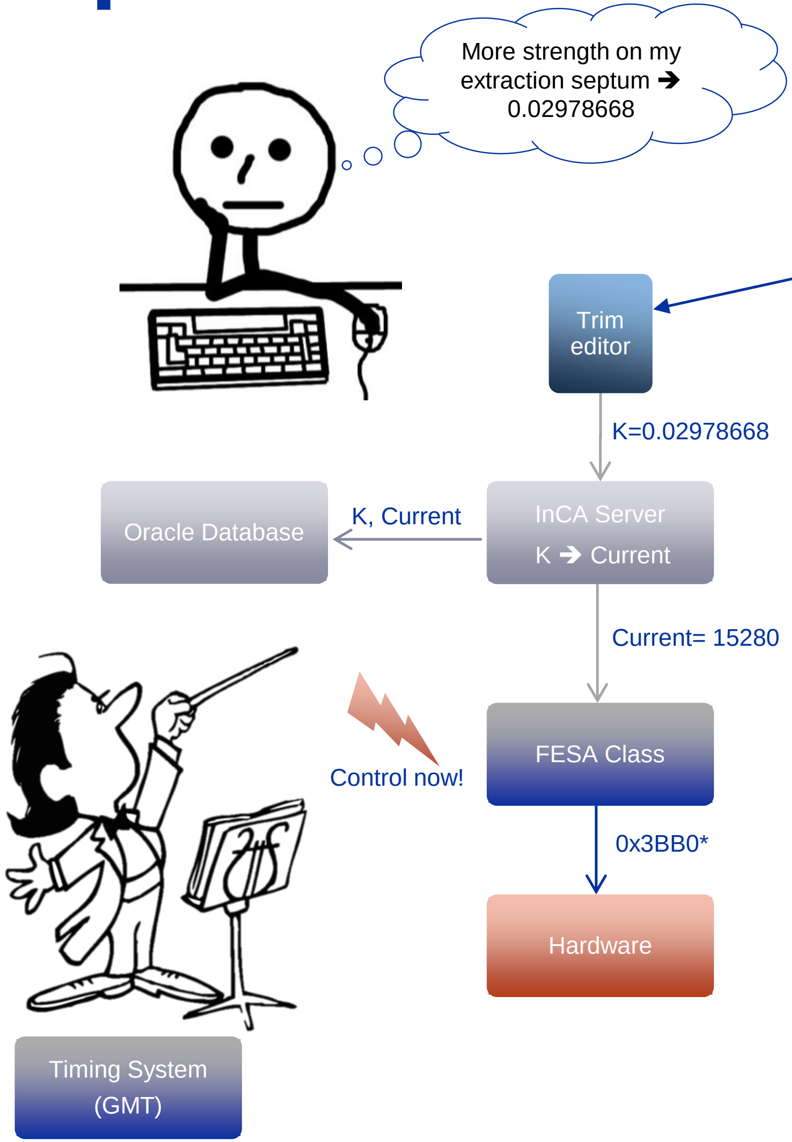


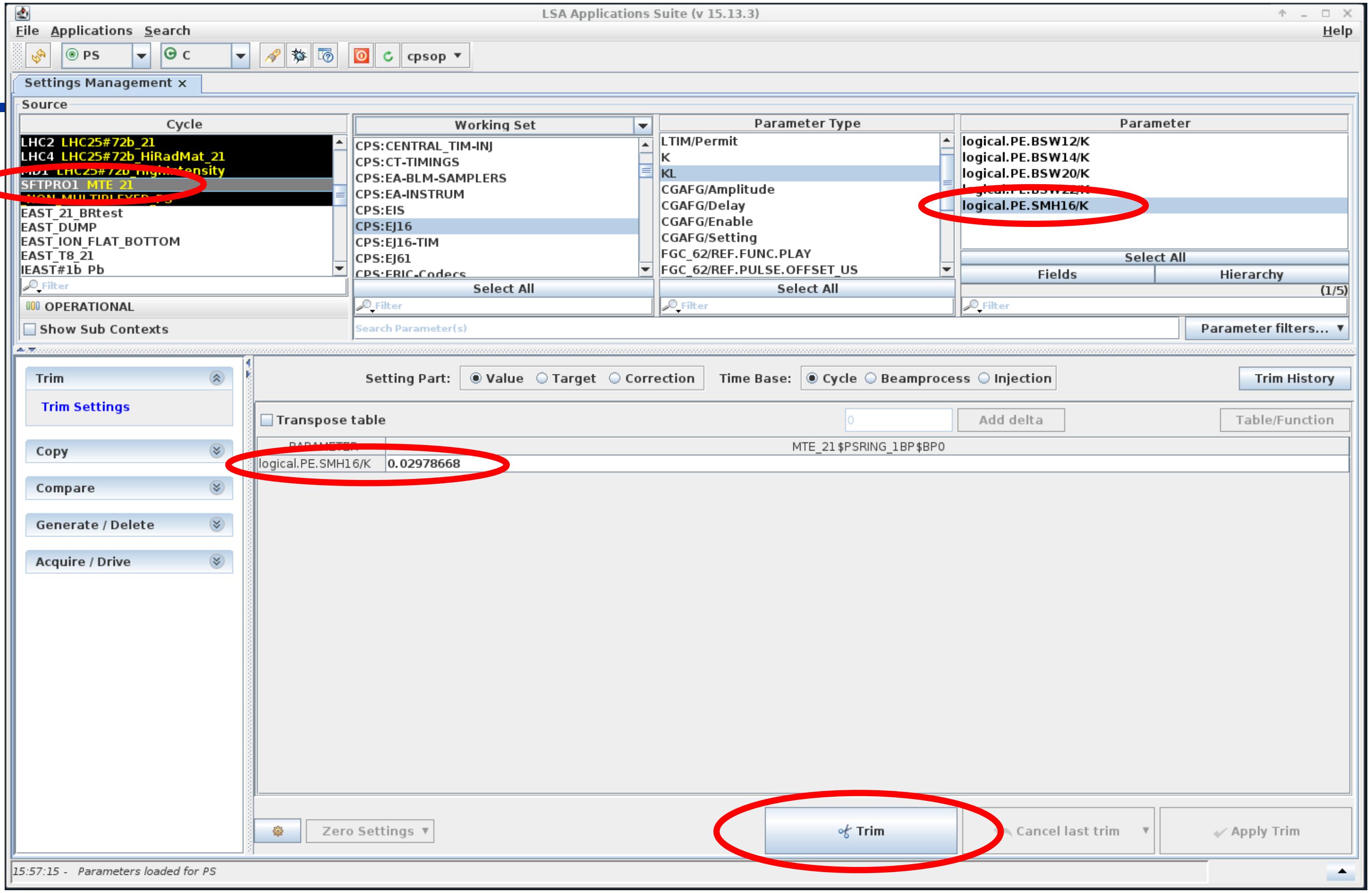
Use Case 1: Control

- **Who:** PS operator
- **What:** Change the strength of the extraction septum towards the SPS for the Fixed Target beam
- **Involved controls components:**
  - InCA/LSA (Setting management)
  - CMW (Controls Middleware)
  - FESA (Real-time hardware control)
  - Timing (Synchronisation)

In all the examples, we assume all the configuration is already done and we focus on the run-time aspects

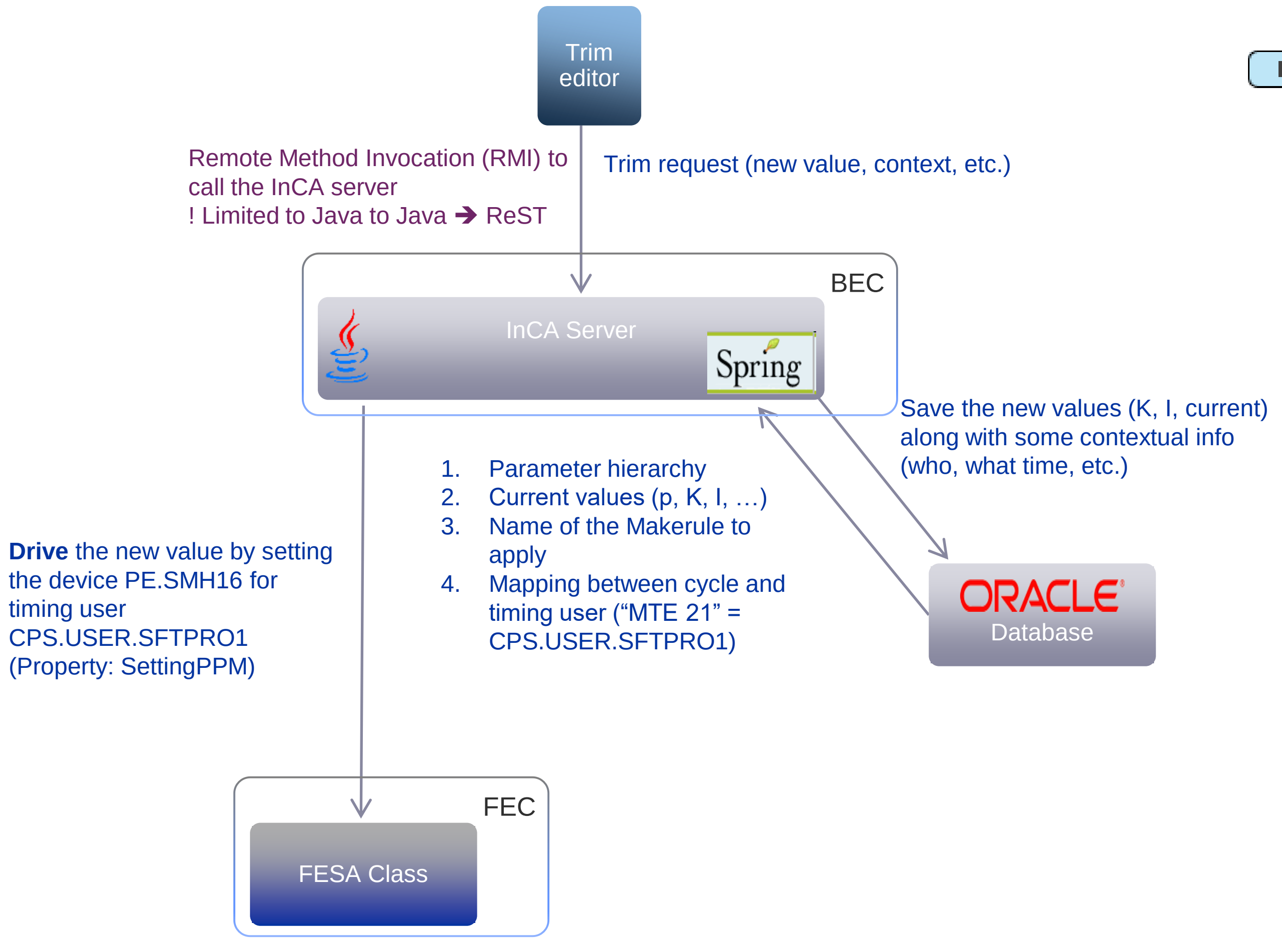
Example 1 – Control –

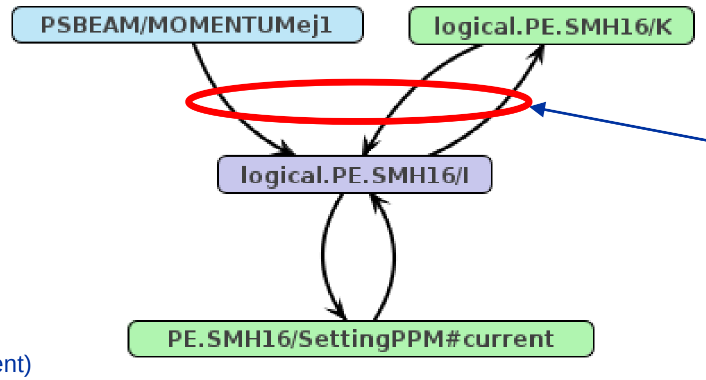




*not a real value

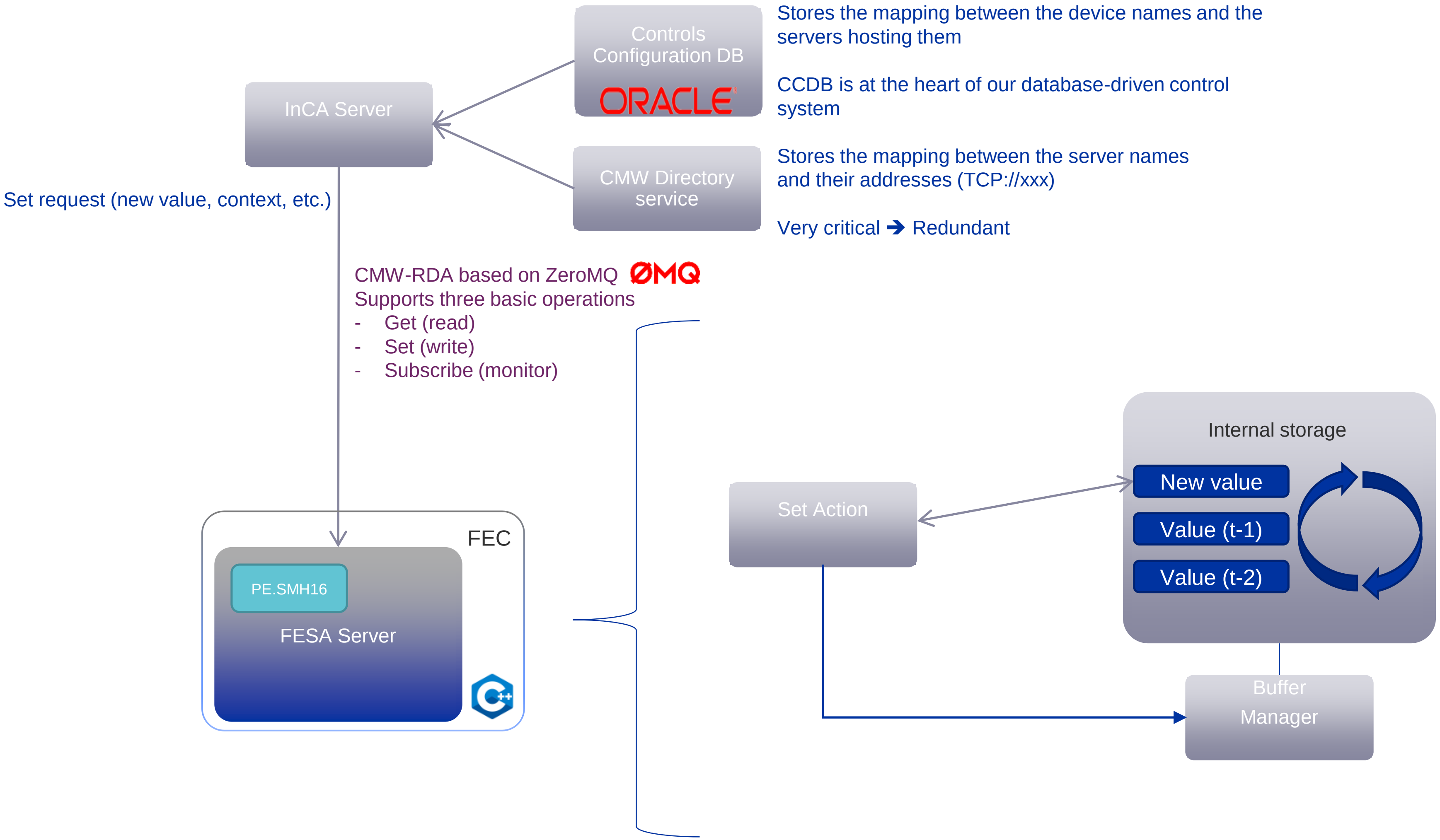
Example 1 – Control - Communication





Makerule: Java class to compute parameters based on other parameters, hardware characteristics (calibration curve) and cycle specific values

Example 1 – Control – Low-level



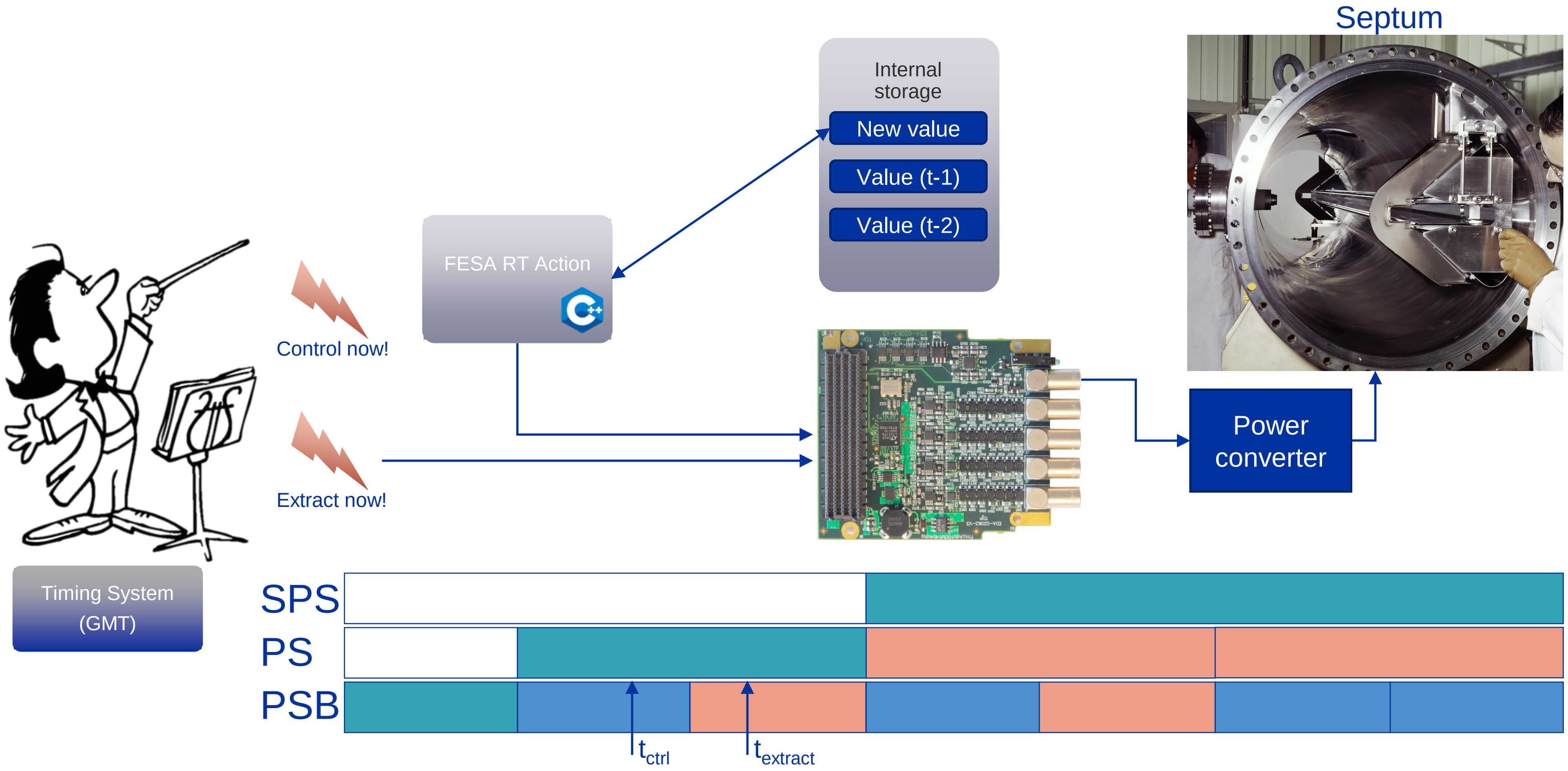
Stores the mapping between the device names and the servers hosting them

CCDB is at the heart of our database-driven control system

Stores the mapping between the server names and their addresses (TCP://xxx)

Very critical ➔ Redundant

Example 1 – Control – Beam production

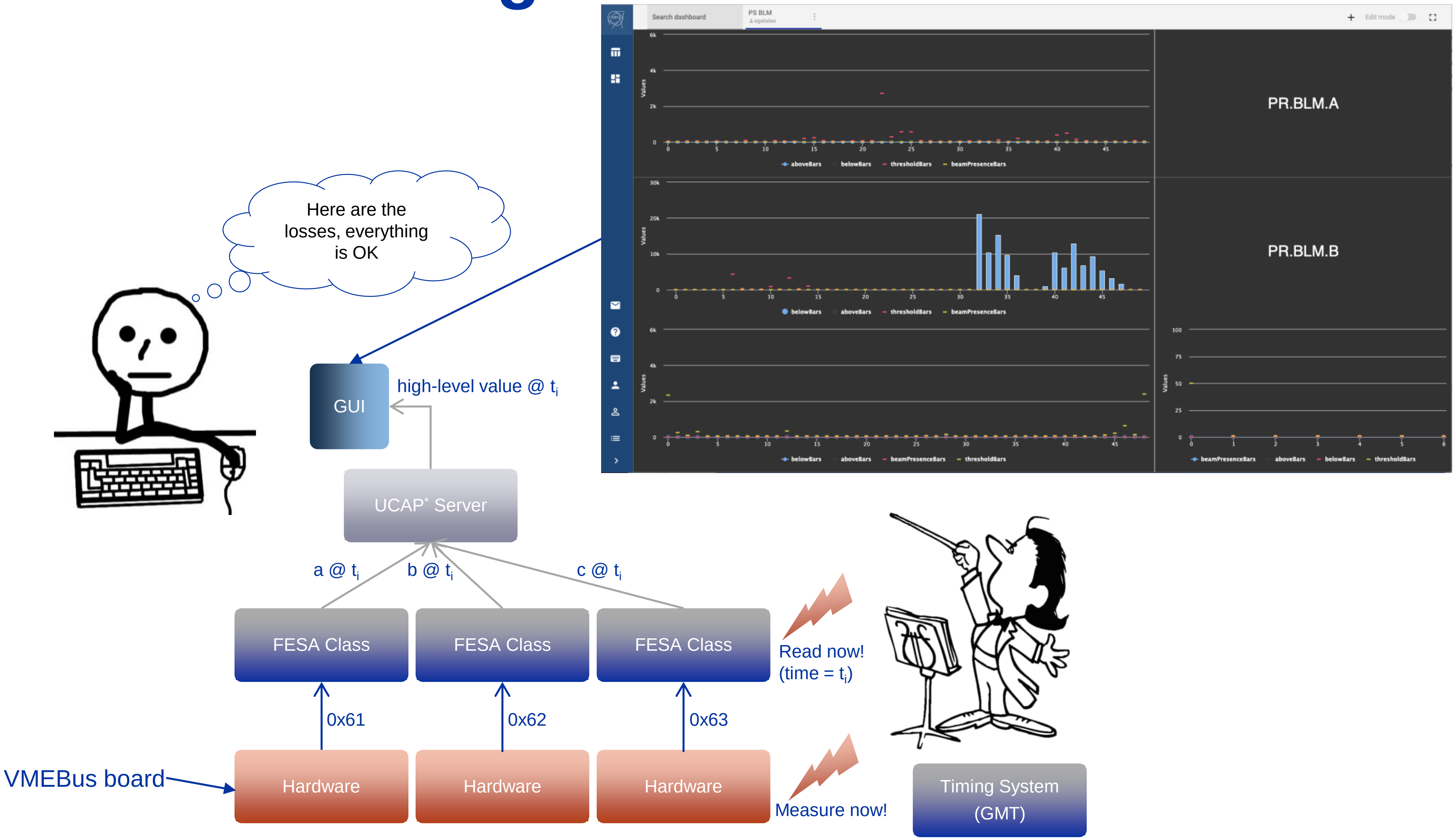


Use Case 2: Acquisition

- **Who:** PS operator
- **What:** Keep an eye on acquisition values of many control devices. The low-level data needs post-processing and will be displayed as a graph in a web page
- **Involved controls components:**
  - Timing (Synchronisation)
  - FESA (Real-time hardware control)
  - CMW (Controls Middleware)
  - UCAP (Unified Controls Acquisition & Processing)
  - WRAP (Web Rapid Application Platform)

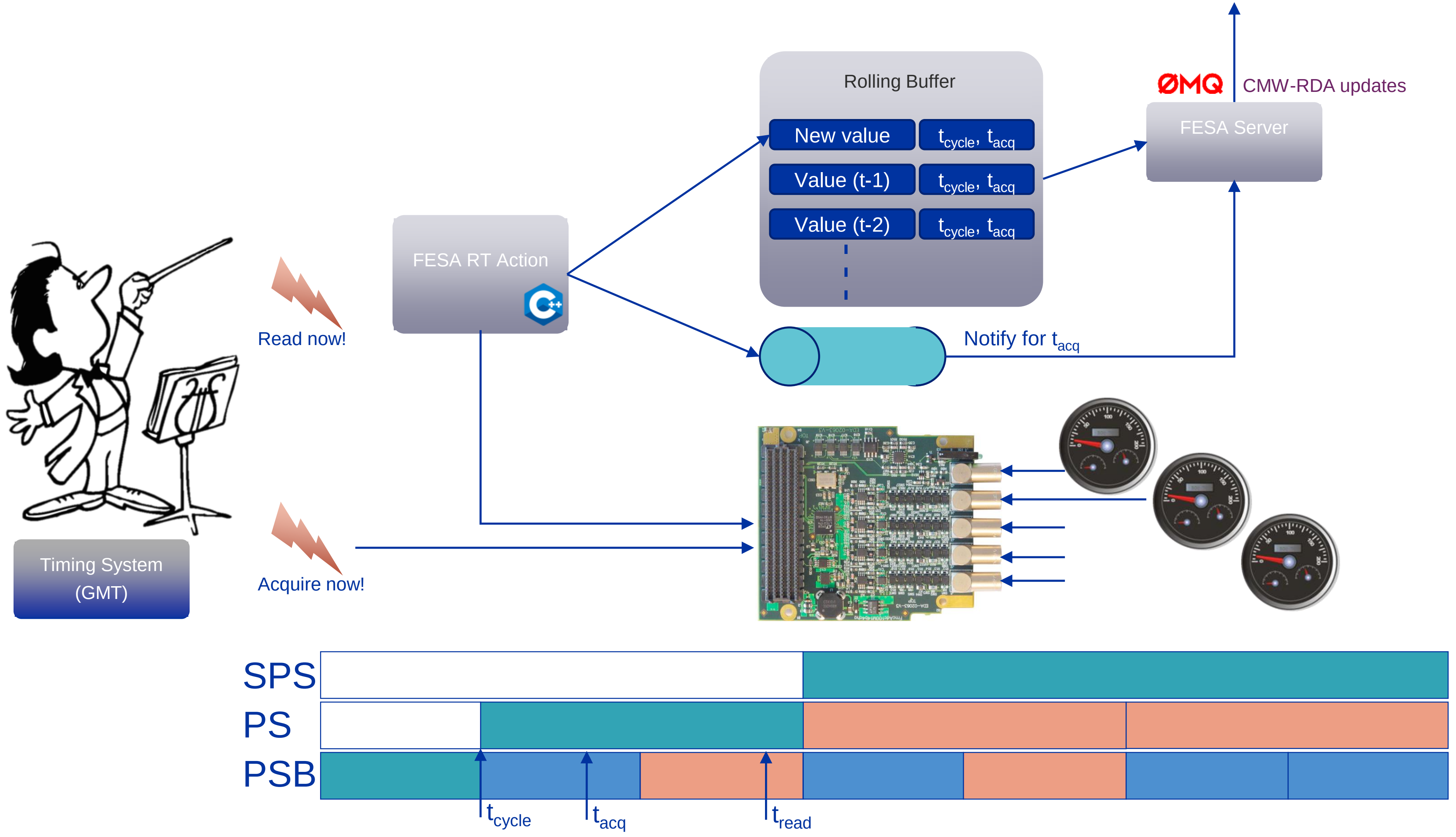
In all the examples, we assume all the configuration is already done and we focus on the run-time aspects

Example 2 – Monitoring

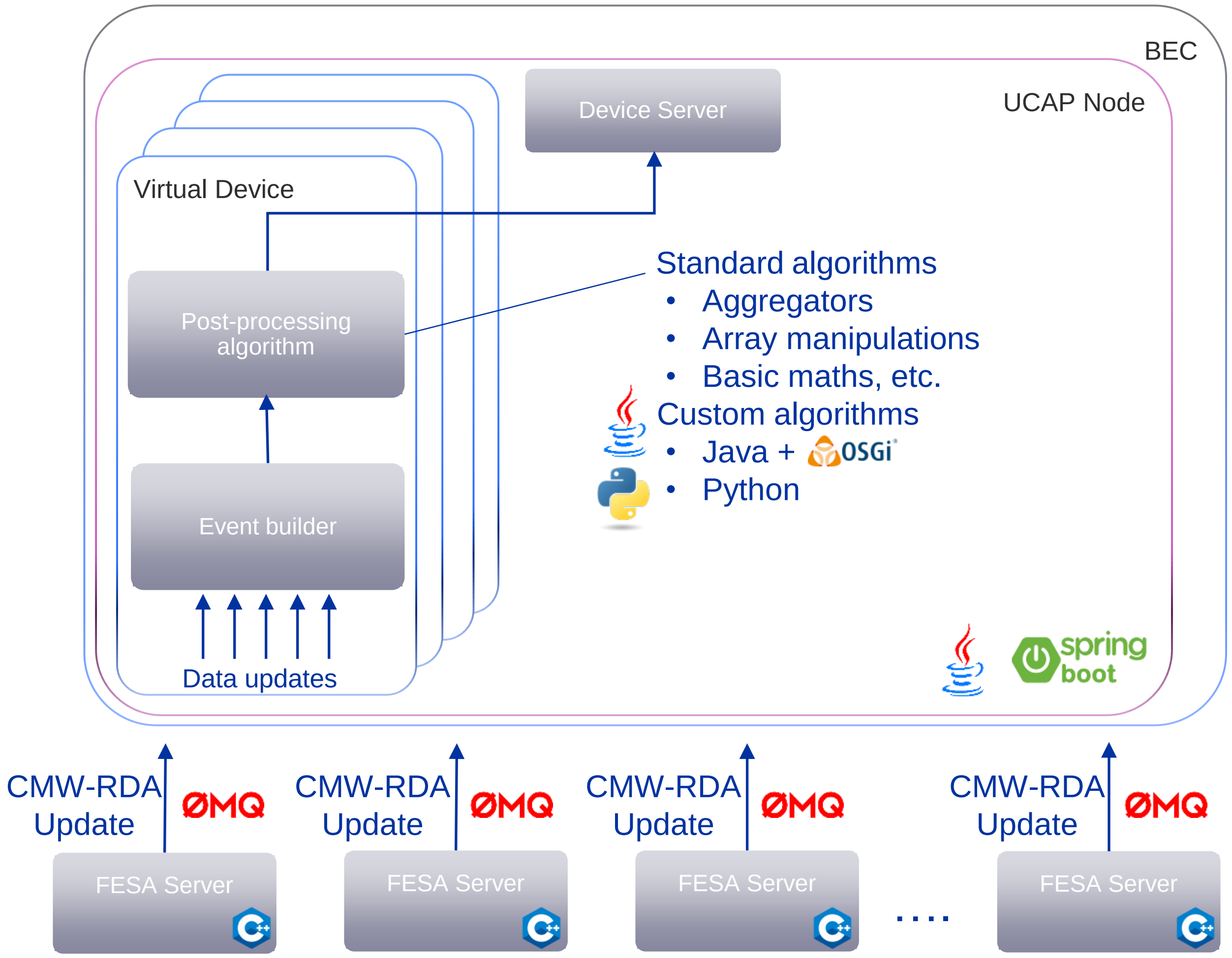


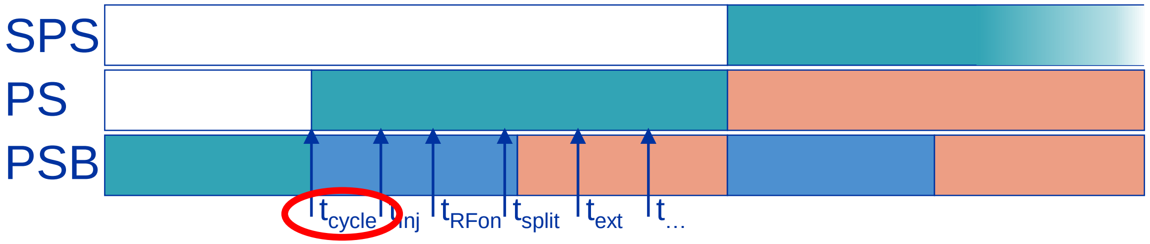
*UCAP: Unified Controls Acquisition & Processing framework

Example 2 – Monitoring – Low-level acquisition



Example 2 – Monitoring – Post-processing



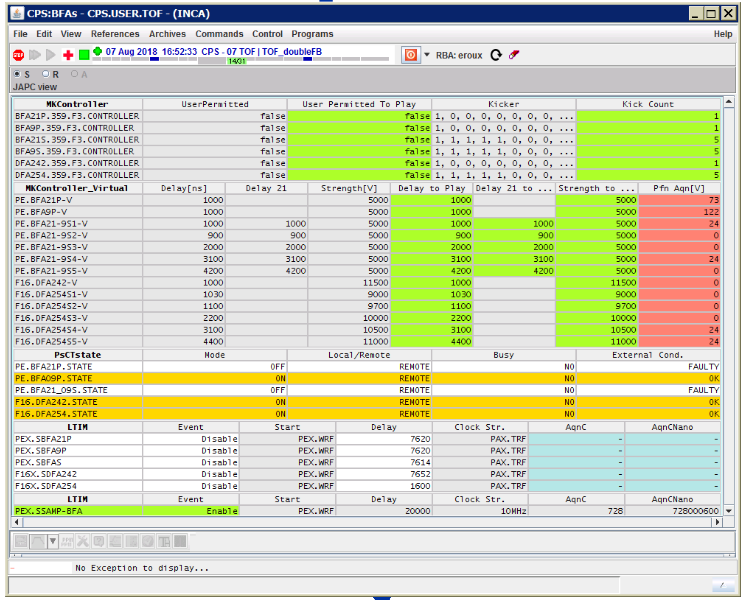


- How to group the incoming data?
  ➔ Start Cycle timestamp (AKA cyclestamp)
- When to trigger the post-processing?
  ➔ Once all the data is there or after a time-out
- How long to wait for late comers?
  ➔ Configurable time-out
- What to do if no data is published?
  ➔ Out-of-the-box monitoring

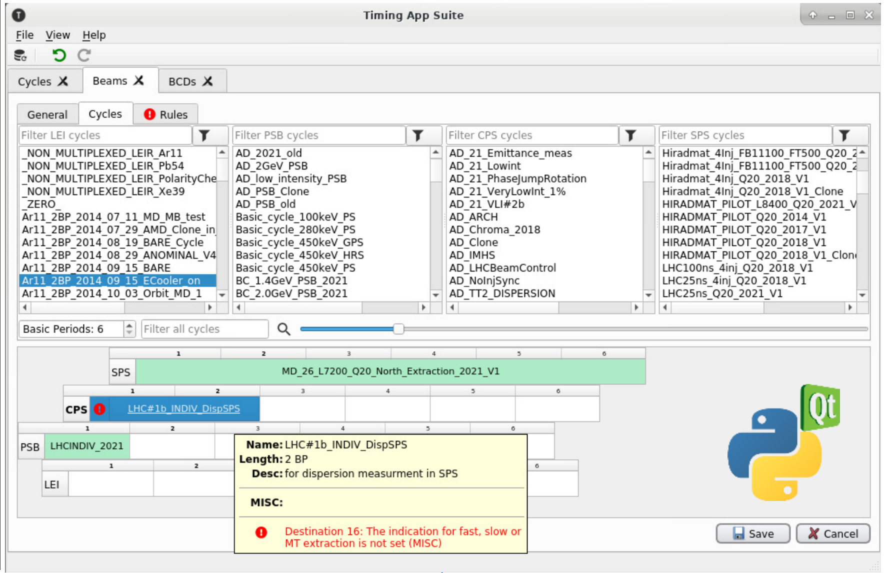
Grafana Prometheus

Example 2 – Monitoring – Diagnostics

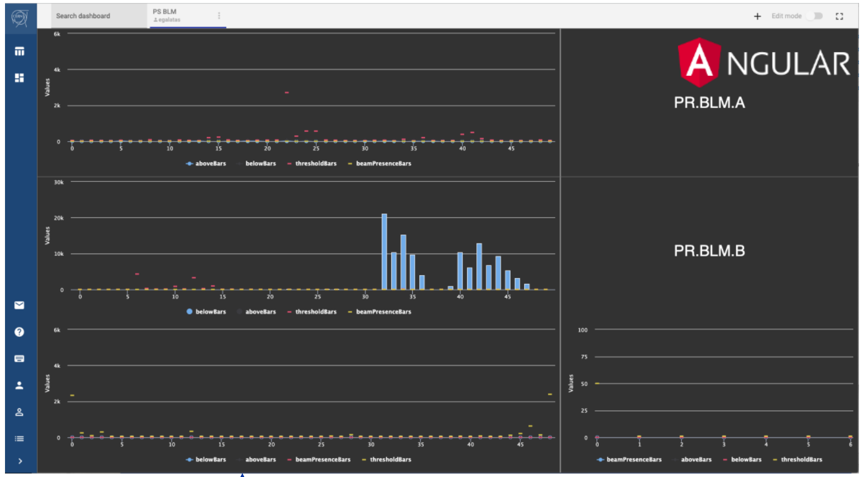
Example 2 – Monitoring – Graphical User Interface



SWING



WRAP



Simplified flow

REST for command/response
HTTP/2 push events for live updates

Controls Configuration DB
ORACLE

Stores the configurations of the web dashboards

BEC

Web back-end server

spring boot

UCAP Node

Device Server

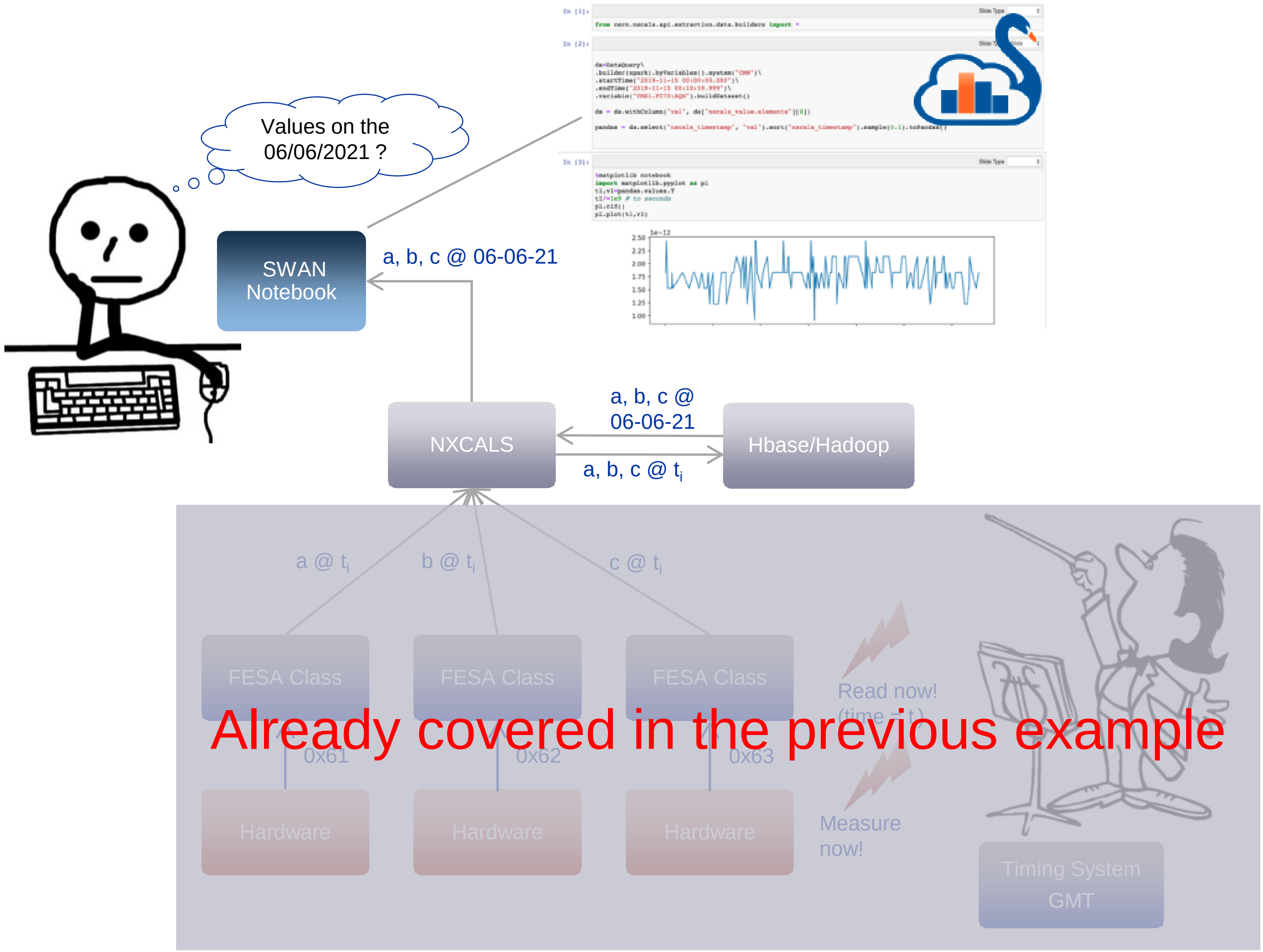
CMW-RDA updates
ØMQ

Use Case 3: Logging

- **Who:** Accelerator physicist
- **What:** Store acquisition values of many control devices long-term and perform analysis
- **Involved controls components:**
  - Timing (Synchronisation)
  - FESA (Real-time hardware control)
  - CMW (Controls Middleware)
  - NXCALS (Data Logging)
  - SWAN (Web-based analysis tool)

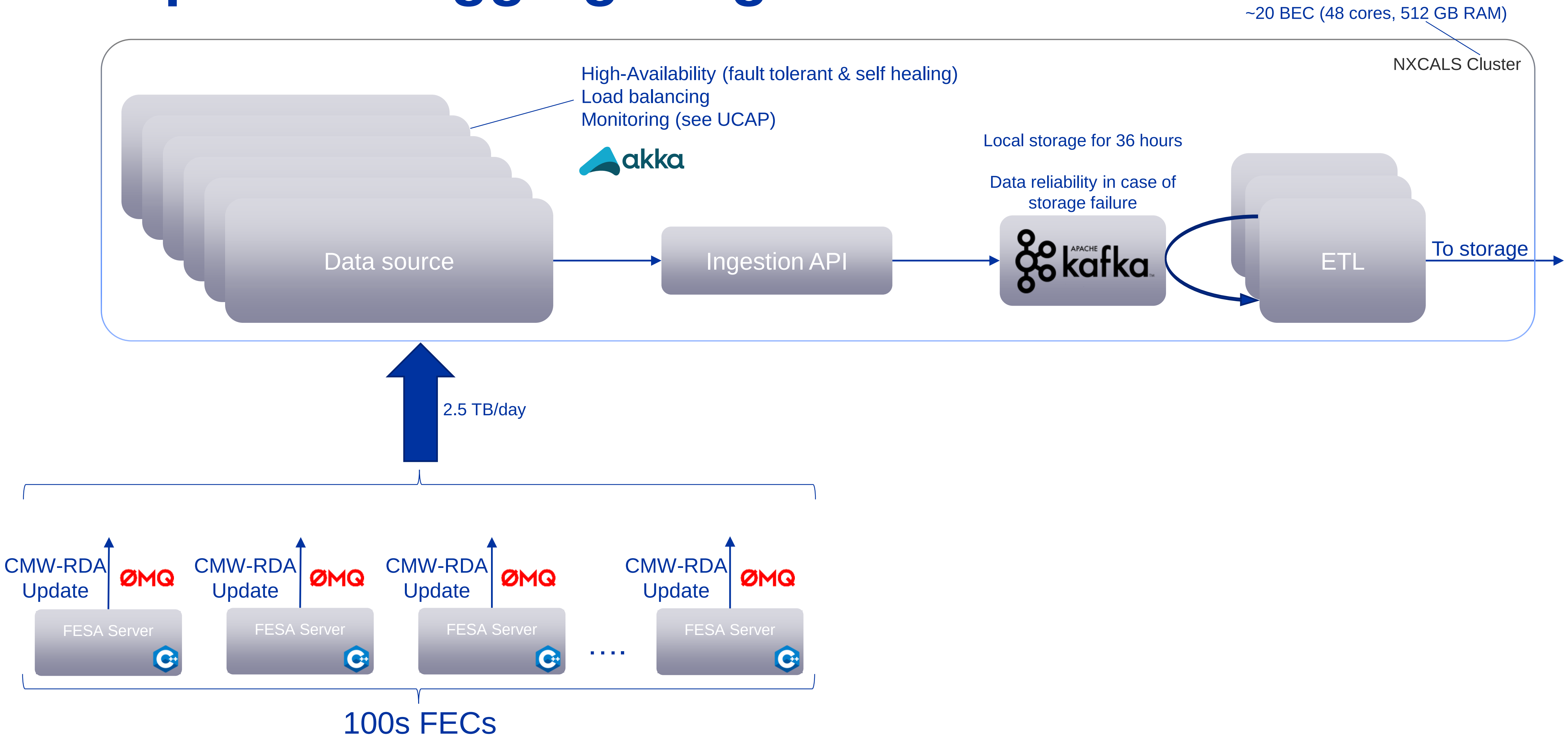
In all the examples, we assume all the configuration is already done and we focus on the run-time aspects

Example 3 – Logging

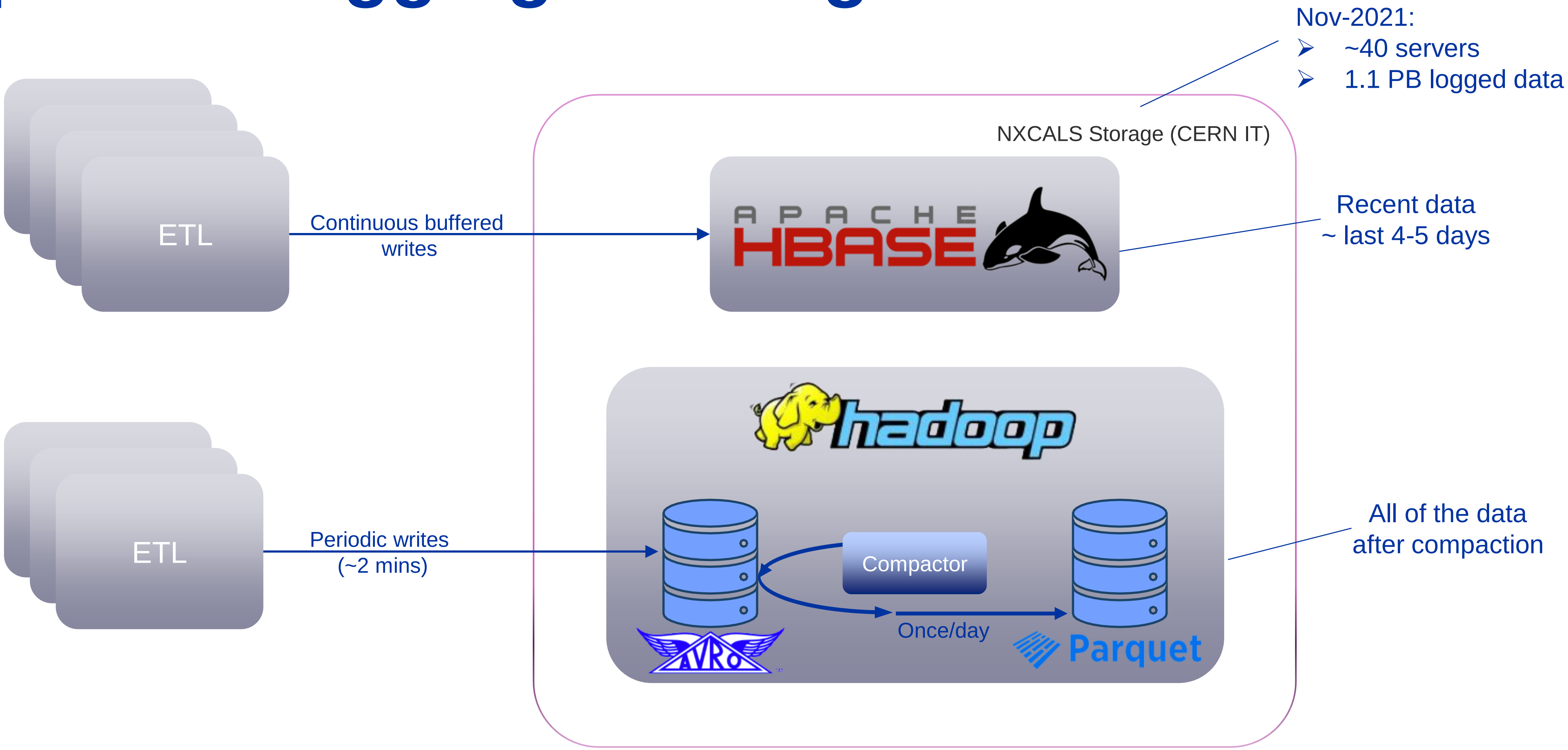


*SWAN: Service for Web-based ANalysis

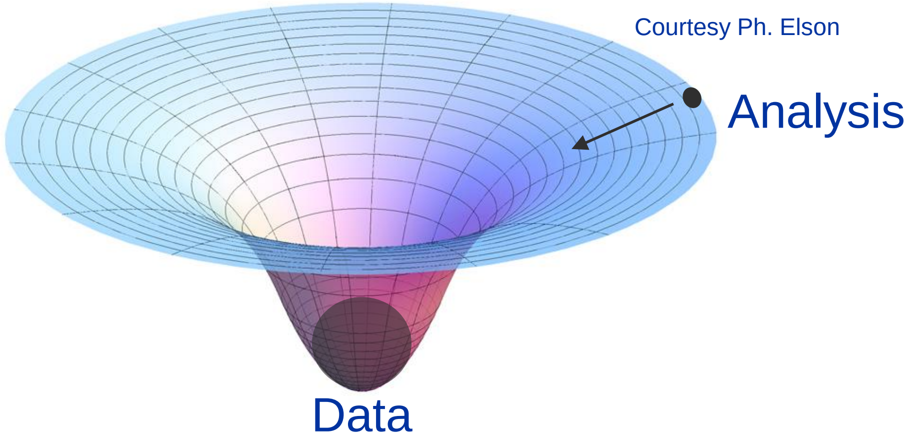
Example 3 – Logging - Ingestion

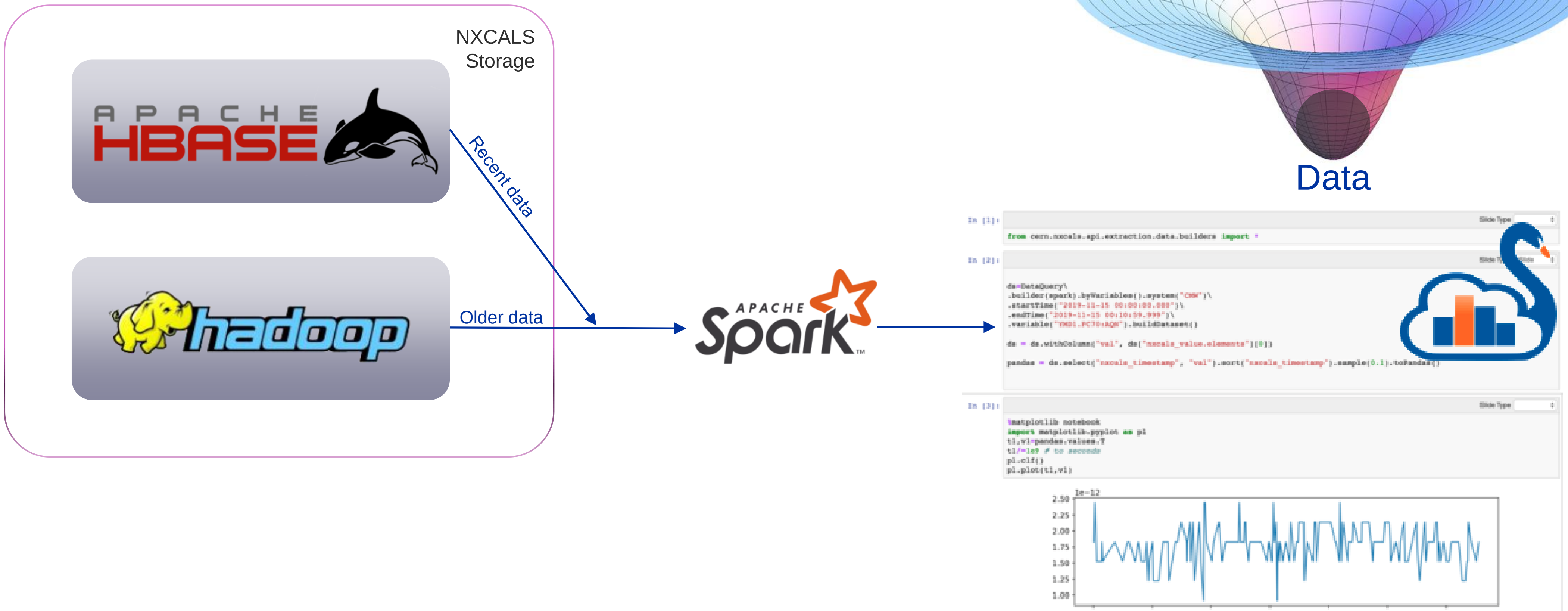


Example 3 – Logging - Storage



Example 3 – Logging - extraction





Want to know more?

CERN Beams Department (https://beams.cern/)

Introduction to BE-CO Control System, 2019 Edition, S. Deghaye & E. Fortescue, CERN, 2020. (https://cds.cern.ch/record/2748122)

Tango Controls (https://www.tango-controls.org/)

EPICS (https://epics-controls.org/)