HZB Helmholtz Zentrum Berlin

Role and impact of Control Systems in High-Energy Physics (HEP) Research Centers

EPICS Summer School 2024

Marcel Bajdel

bluesky EPICS

Introduction

- Nuclear power engineering graduate (nuclear physics at Warsaw University)
- PhD in Physics - “Development of the detector control system and instrumentation for the silicon tracking system in the Compressed Baryonic Matter experiment”
- Control system engineer at BESSY II beamlines department
  - ROCK-IT project
  - Deployment framework development
  - EPICS IOC development
  - Bluesky

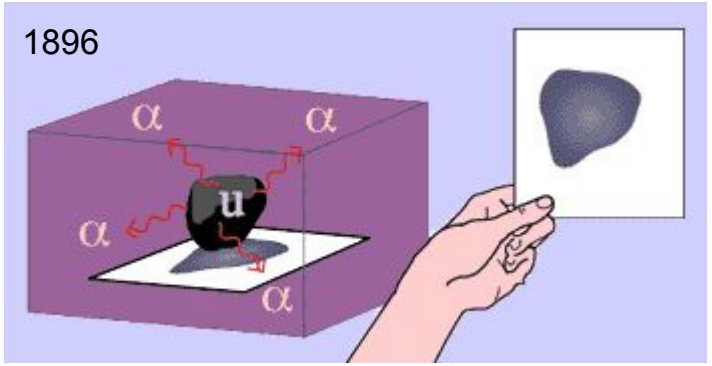
Overview

- History of the discoveries vs control systems
- What are high energy research centers?
- CERN - Large Hardon Collider (LHC)
- FAIR - SIS100
- FAIR - Compressed Baryonic Matter Experiment (CBM)
- Silicon Tracking System in the CBM
- Why do we need control systems?
- Experiment Control System
- Detector Control System

Shaping the Course of History

1895 - Röntgen discovered X-rays
1896 - Becquerel discovered radioactivity
1920s - Radioactive toothpaste produced in Berlin
1920s - Sir Arthur Eddington suggested that stars generate their energy by fusing hydrogen into helium
1938 - Otto Hahn discovered nuclear fission
1942 - Chicago Pile-I brought into operation
1986 - 4th reactor of the Chernobyl power plant melted down
2012 - discovery of Higgs Boson which takes part in giving mass to particles

First medical X-ray by Röntgen of his wife Anna Bertha Ludwig's hand



Becquerel's experiment that aimed at studying x-rays

wikipedia

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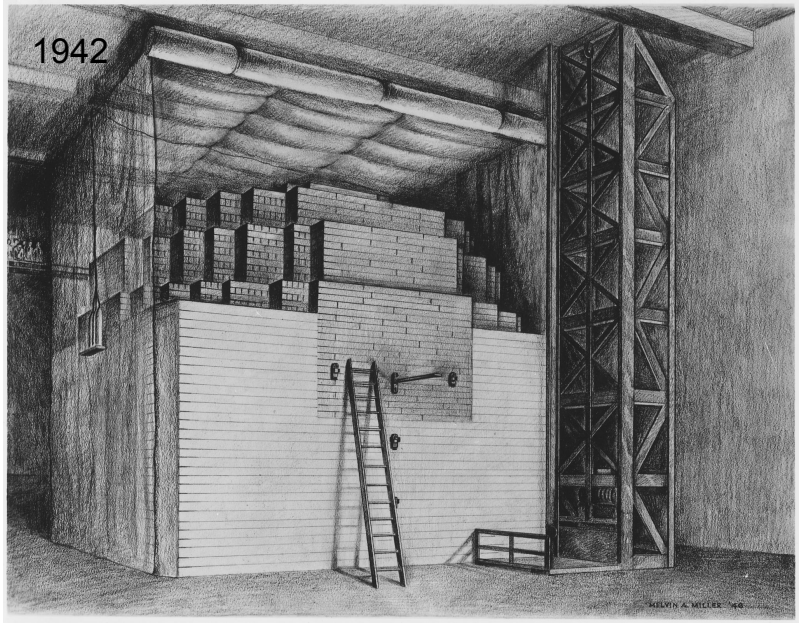

20m tall pile of graphite and uranium bricks with wooden rods covered with cadmium to slow down neutrons
Location:

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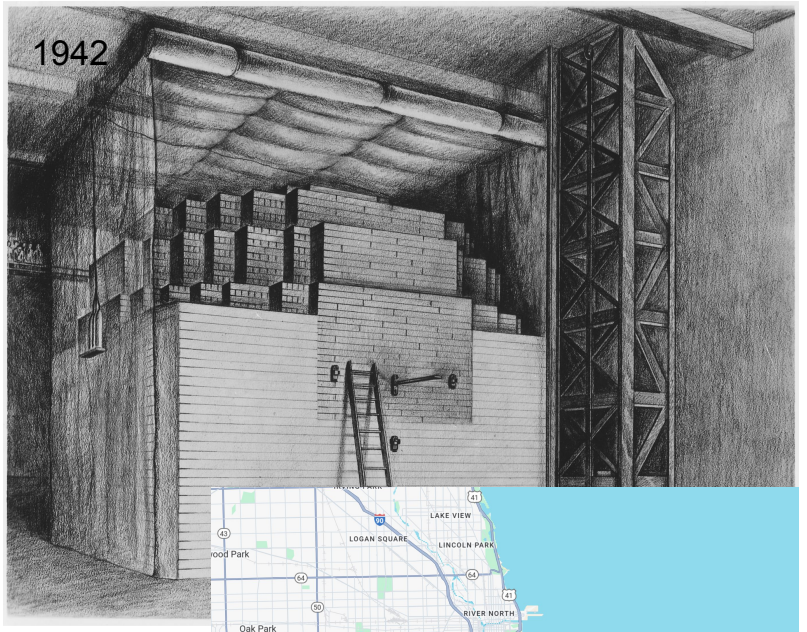
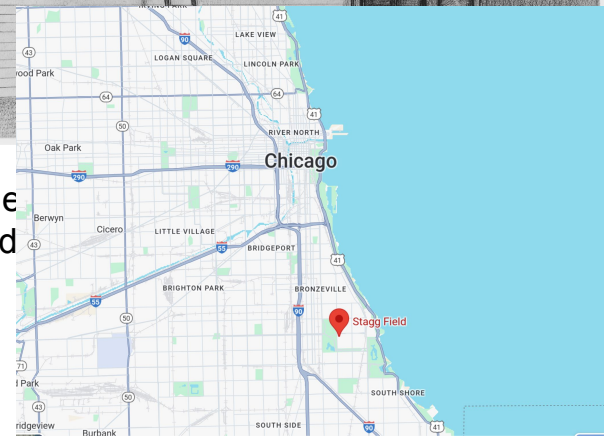


20m tall pile
wooden rod
neutrons
Location:



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3rd block control room

4th block control room

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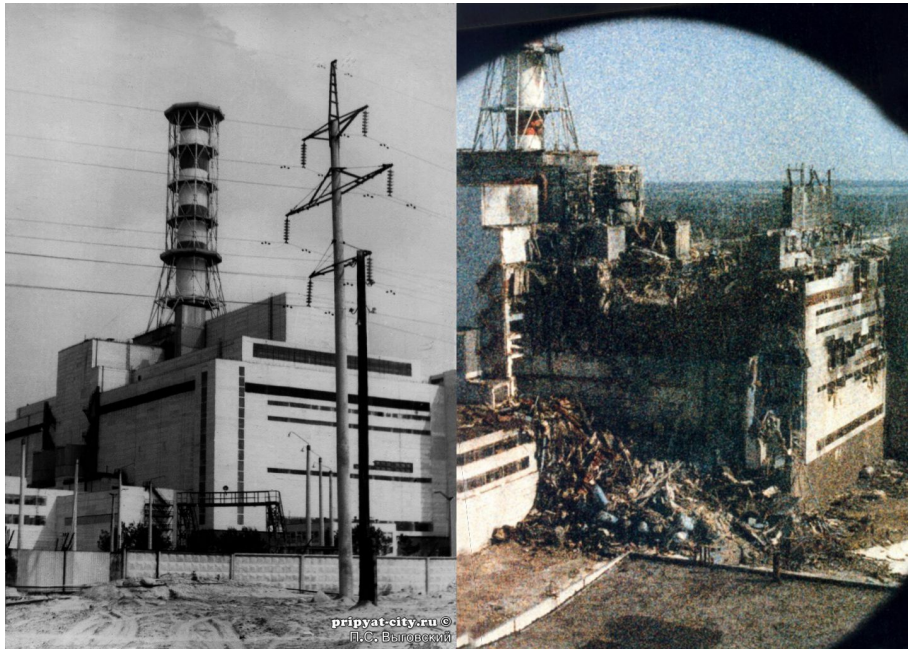
2017, view on the 4th reactor, photos from private excursion



4th block of the power plant

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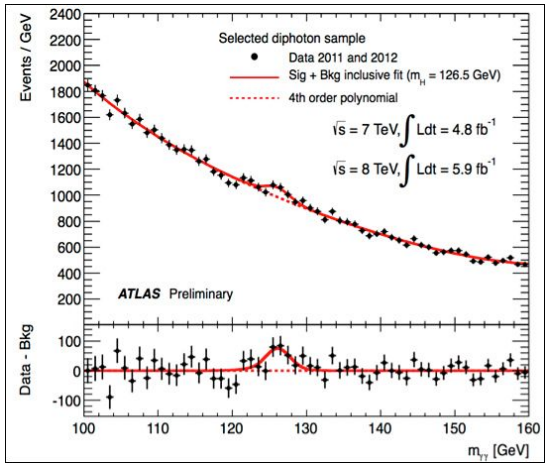
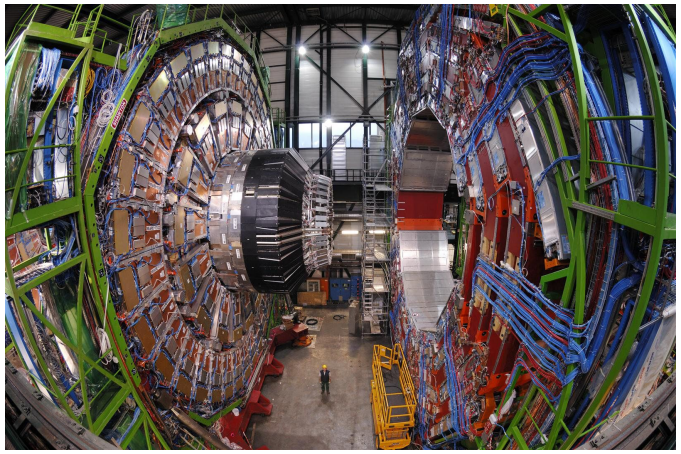


Atlas press release



Compact Muon Solenoid (CMS)

Large Hadron Collider control room (2008)

Shaping the Course of History - other system failures

1979 - Three Mile Island, partial melt down of the reactor

1986 - Blackout in Northeast United States and Canada

A major blackout affecting the northeastern United States and parts of Canada was partly caused by control system failures in the power grid. Software bugs in an alarm system prevented operators from receiving warnings about the system's instability, leading to a cascading failure.

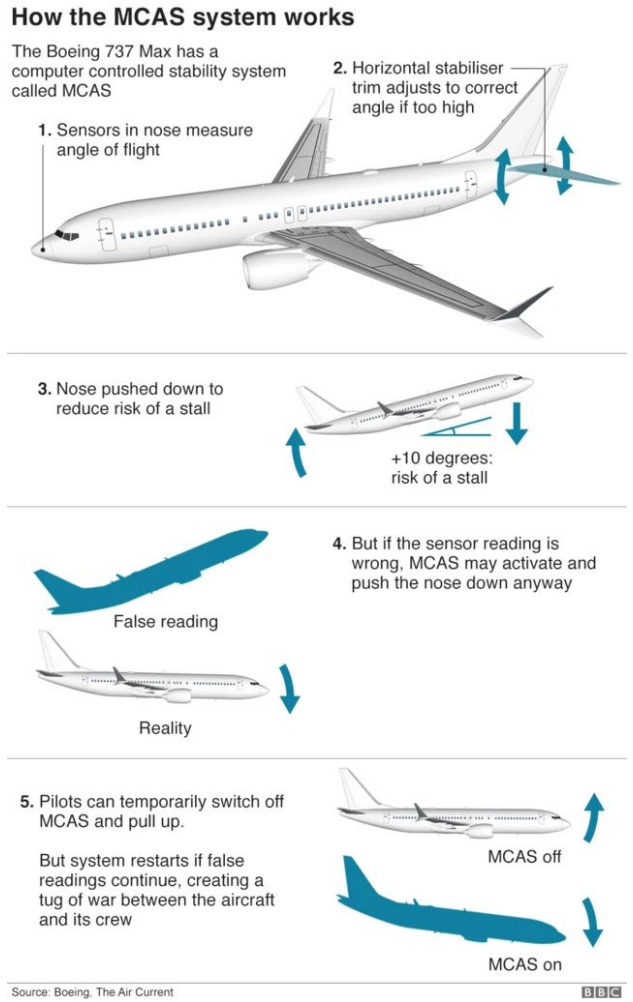
1896 - Ariane 5 Rocket Failure

The Ariane 5 rocket exploded 37 seconds after lift-off on its maiden flight due to a software error in the inertial reference system. The control system attempted to convert a 64-bit floating-point number to a 16-bit integer, causing an overflow and subsequent system failure.

1999 - Mars Climate Orbiter

NASA’s Mars Climate Orbiter disintegrated upon entering Mars' atmosphere due to a units conversion error in its control system. One part of the software used metric units while another used imperial units, causing the spacecraft to deviate from its intended path.

2020s - Boeing 737 MAX



Shaping the Course of History

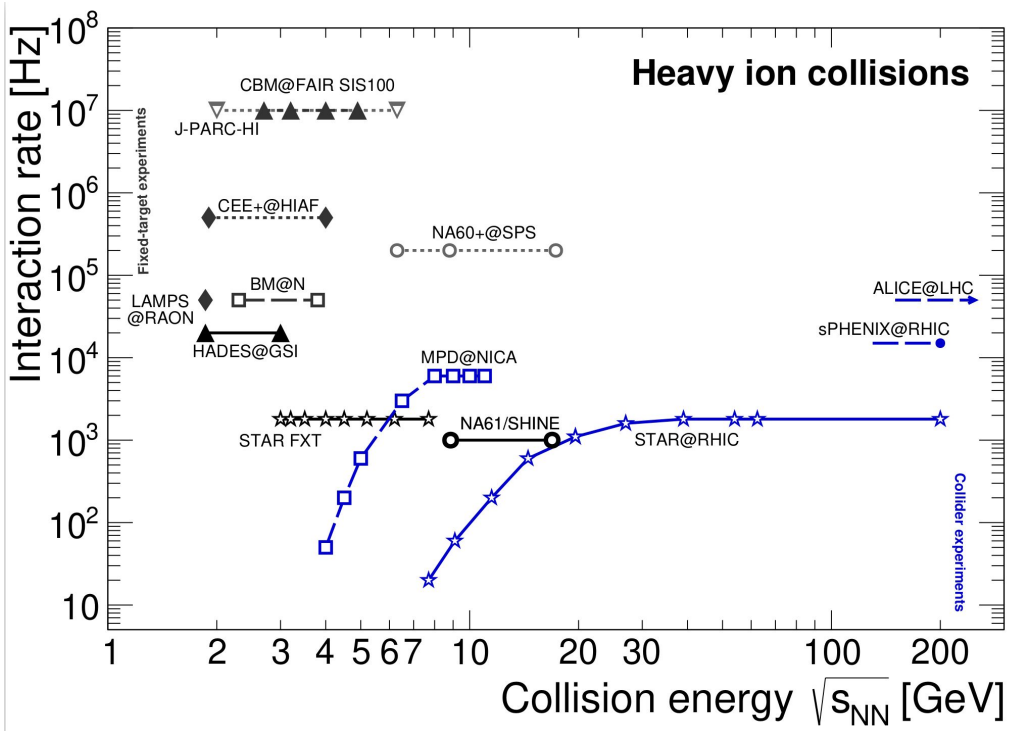
Aspect	1980s	Now
Technology	Analog components, mechanical relays	Digital tech, microcontrollers, advanced sensors
Computation Power	Limited, basic microprocessors	Powerful processors, AI algorithms
Communication	Hard-wired, limited networking	Ethernet, wireless, IIoT connectivity
Software	Low-level programming	High-level languages, simulation tools
Integration	Standalone systems	Integrated with enterprise systems, Industry 4.0
User Interface	Basic displays, physical buttons	Touchscreens, graphical HMIs, mobile access
Reliability	Less reliable, reactive maintenance	High reliability, predictive maintenance
Cost	Expensive, less accessible	More affordable, widely accessible

Table 1: Differences Between Control Systems (1980 vs. Now)

What are High-Energy Research Centers?

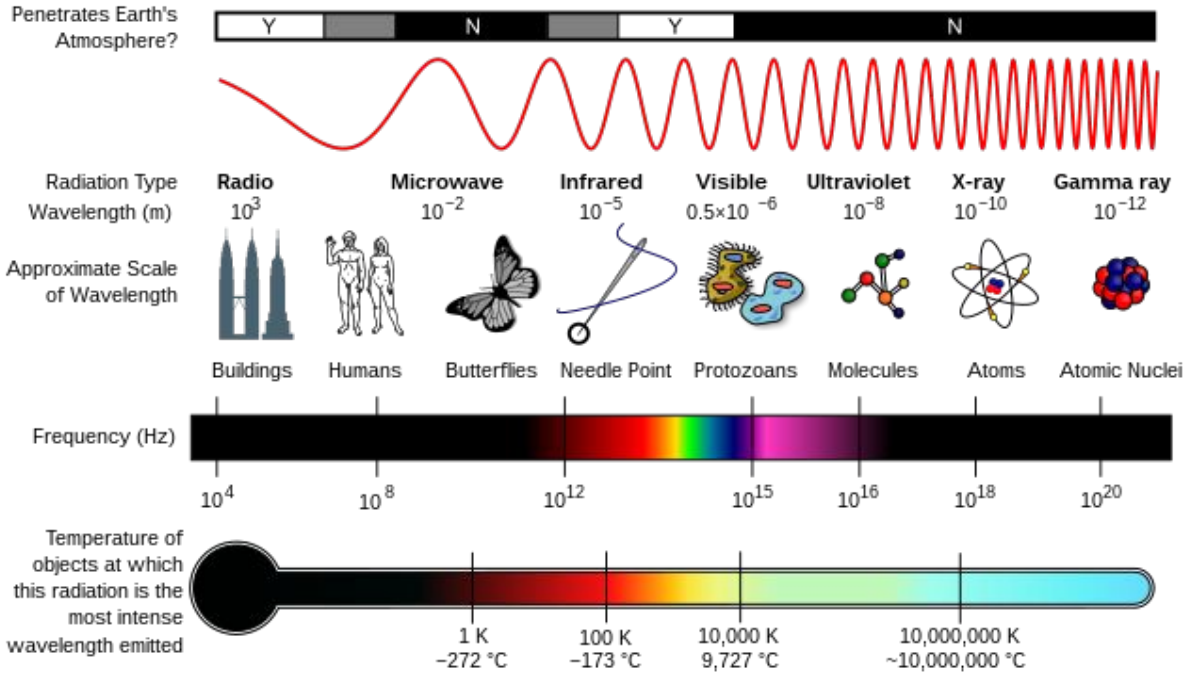
Particle physics or **high-energy physics** is the study of fundamental particles and forces that constitute matter and radiation.

- GSI/FAIR heavy ions in GeV energies
- CERN particles collision energy TeV



BESSY II EM energy range in eV - keV

X-rays are ideally suited for probing the structural arrangement of atoms and molecules in a wide range of materials



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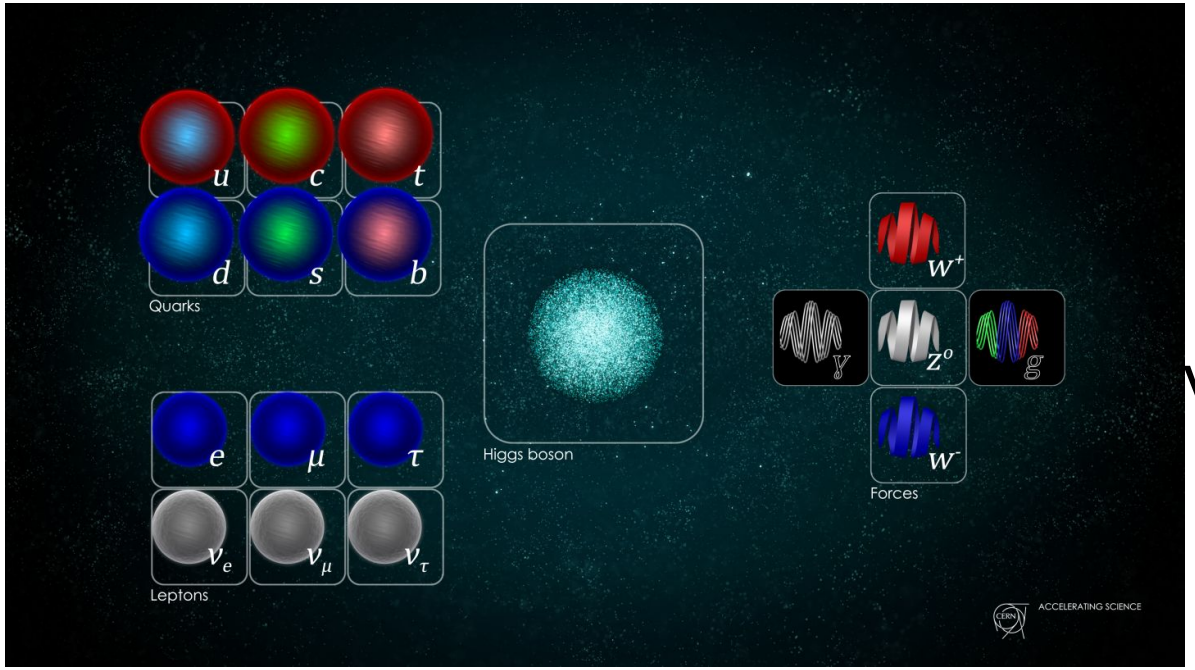
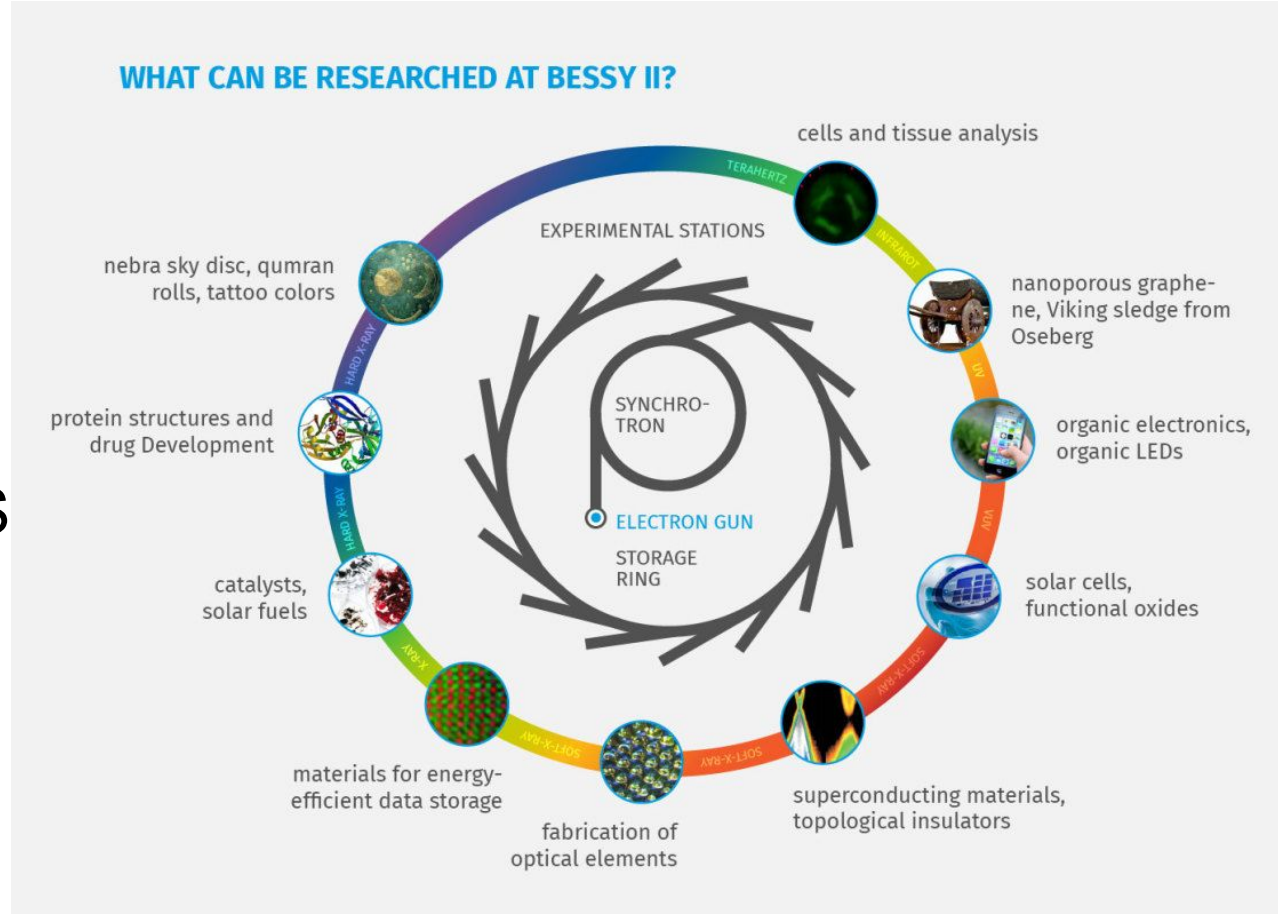
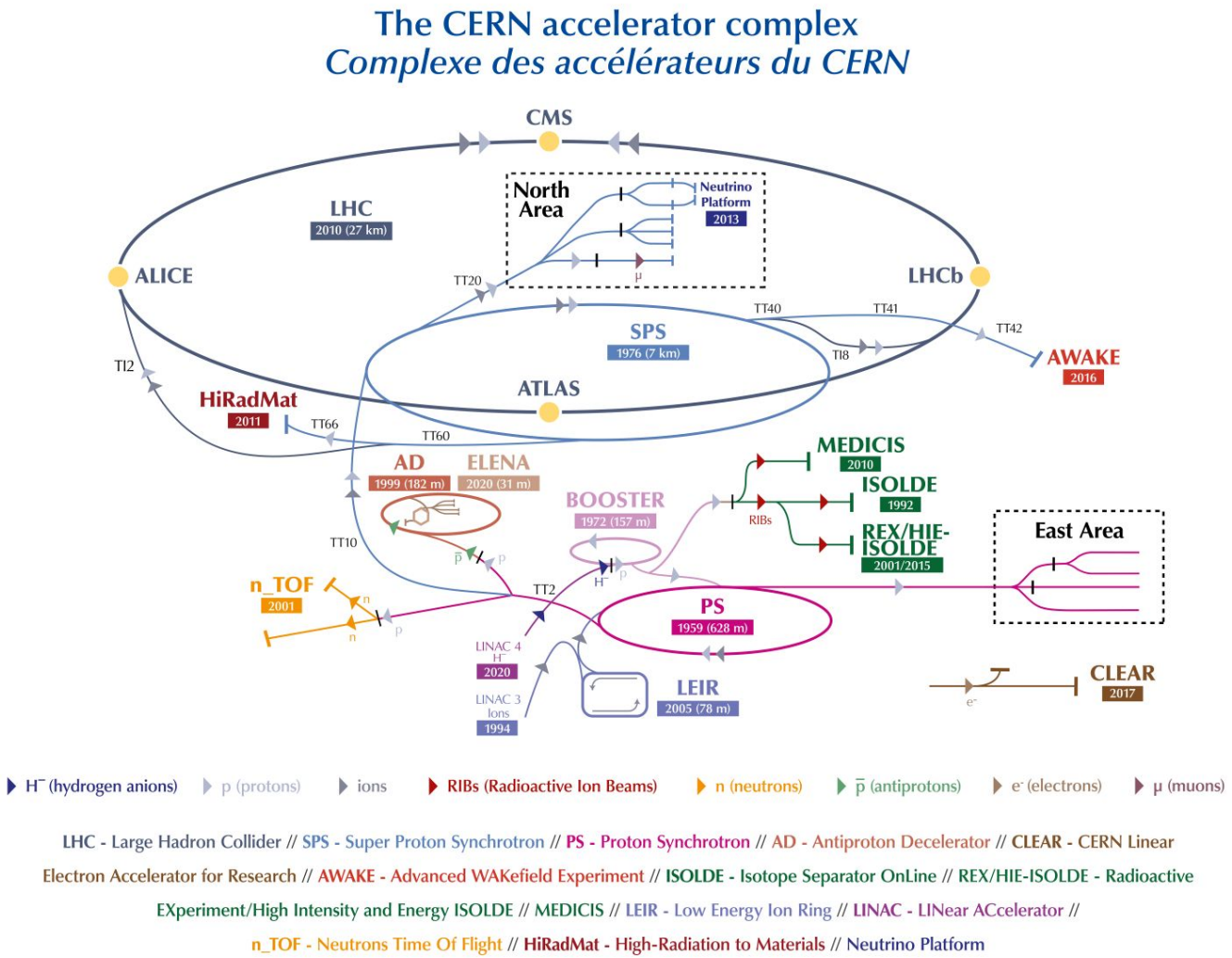


The Standard Model of particle physics. The W, Z and Higgs bosons were discovered at CERN (Image: Daniel Dominguez/CERN)

VS



CERN - LHC vs FAIR - SIS100

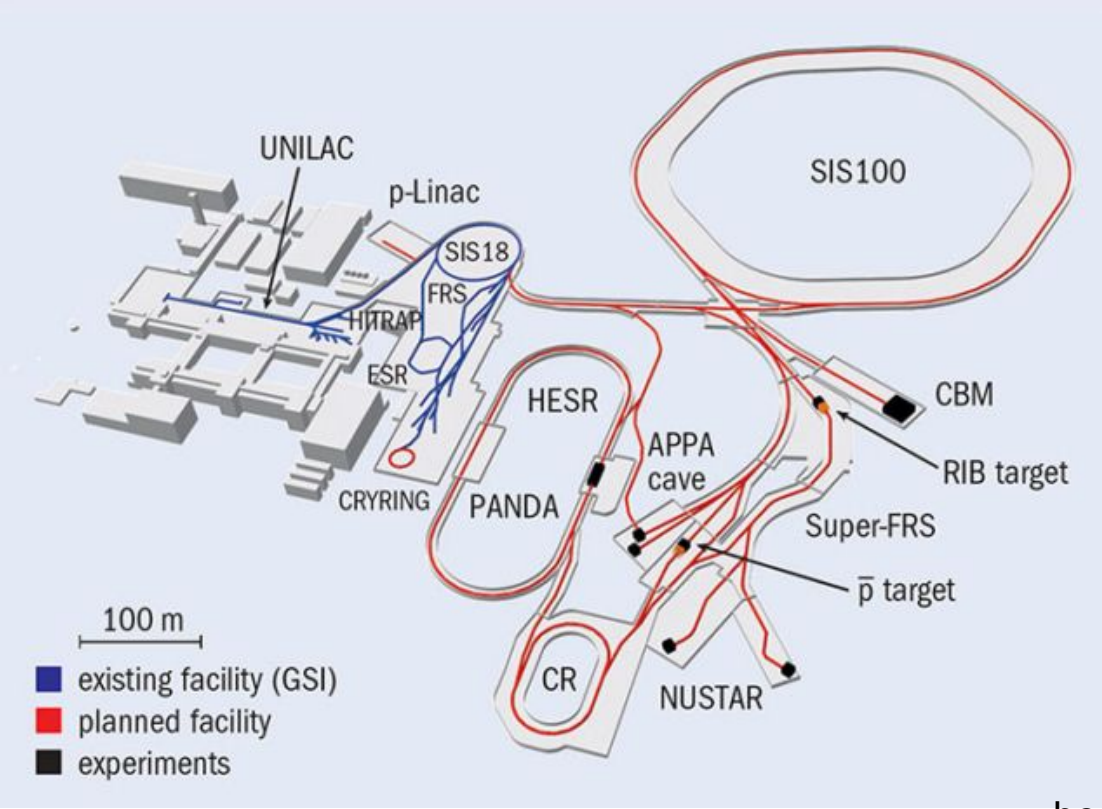


Large Hadron Collider (LHC)

- World largest and highest-energy collider with two directed beams of particles
- Scientists analyze the byproducts of the collisions to study the structure of subatomic world and the laws of nature governing it
- Many byproducts are extremely short-lived, making them nearly impossible to study
- 10000 superconducting magnets operating at 1.9K
- Producing around 15 petabytes of data per year ~ 340 millions HD movies per year ~ 340 years to watch them all

ALICE specializes in heavy-ion collisions to study quark-gluon plasma.
ATLAS and **CMS** are general-purpose detectors focused on a wide array of physics goals, including the search for new particles and precision measurements of known phenomena.
LHCb focuses on the behavior of particles containing beauty quarks to investigate matter-antimatter asymmetry.

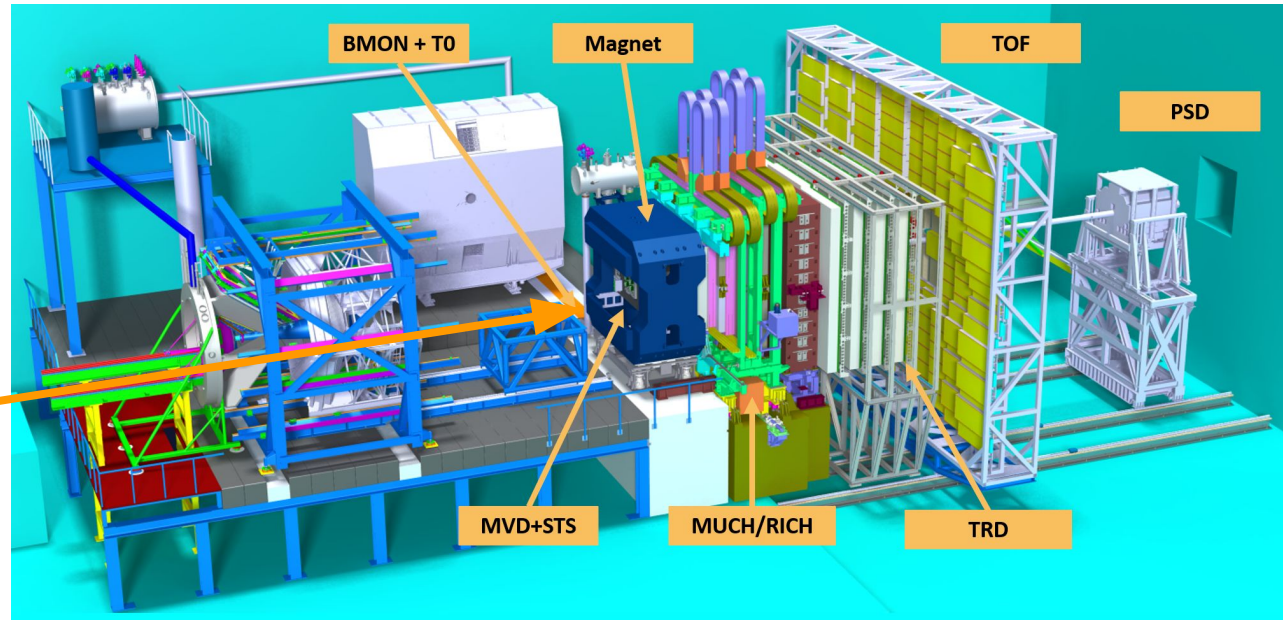
CERN - LHC vs FAIR - SIS100



https://cerncourier.com/a/fair-forges-its-future/

Schwerionensynchrotron 100

- the facility is still under construction, but it will study the properties of nuclear matter at high densities and temperatures, relevant to astrophysical processes and fundamental nuclear physics.
- lower energies of the beams up to 2.7 GeV/u
- only Compressed Baryonic Matter Experiment (CBM) could produce up to 10 exabytes of data per year!



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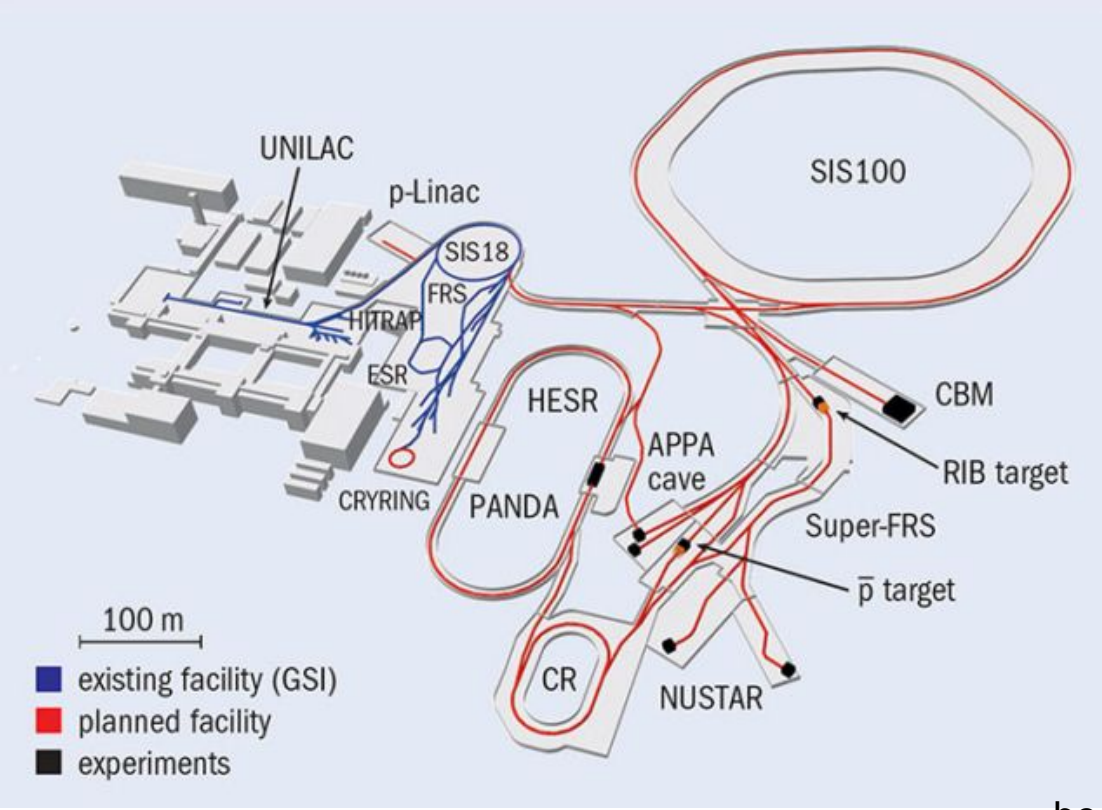

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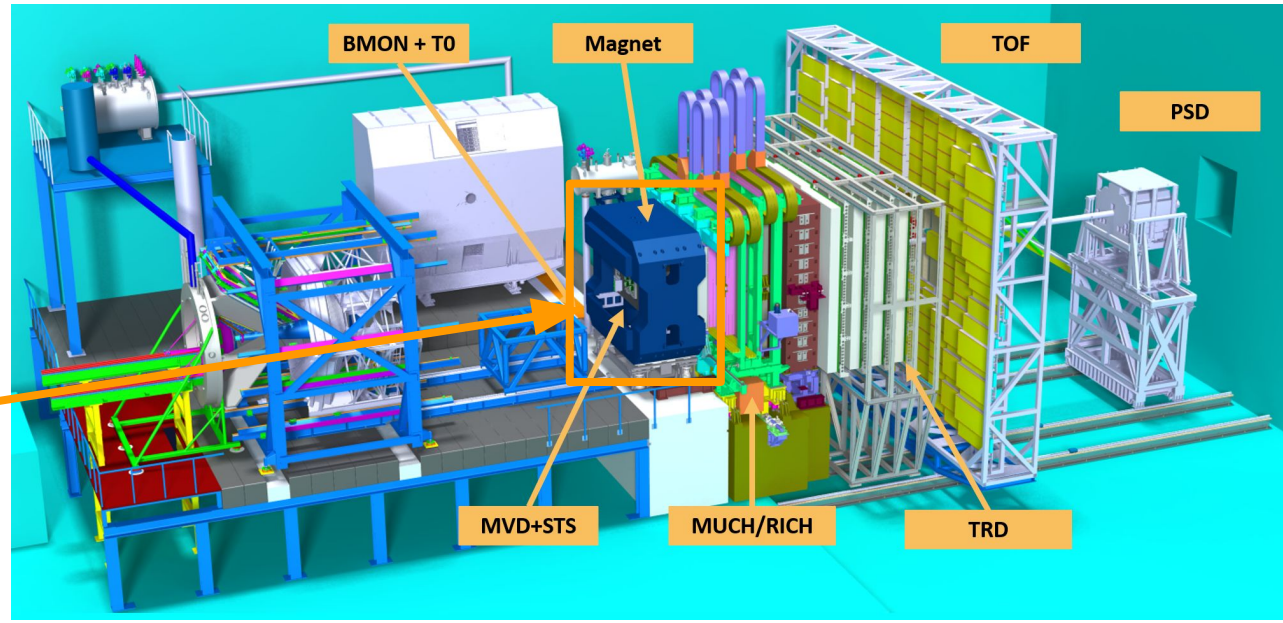
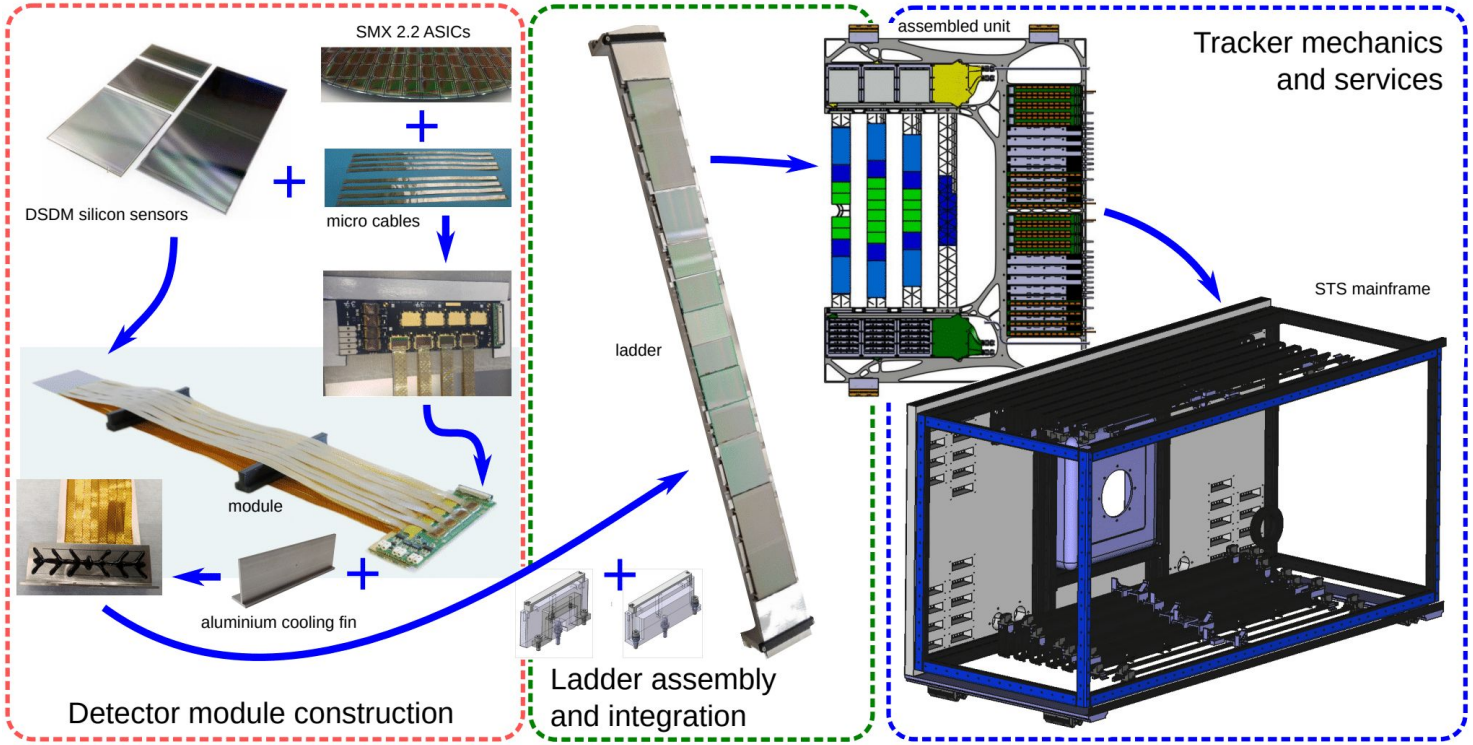


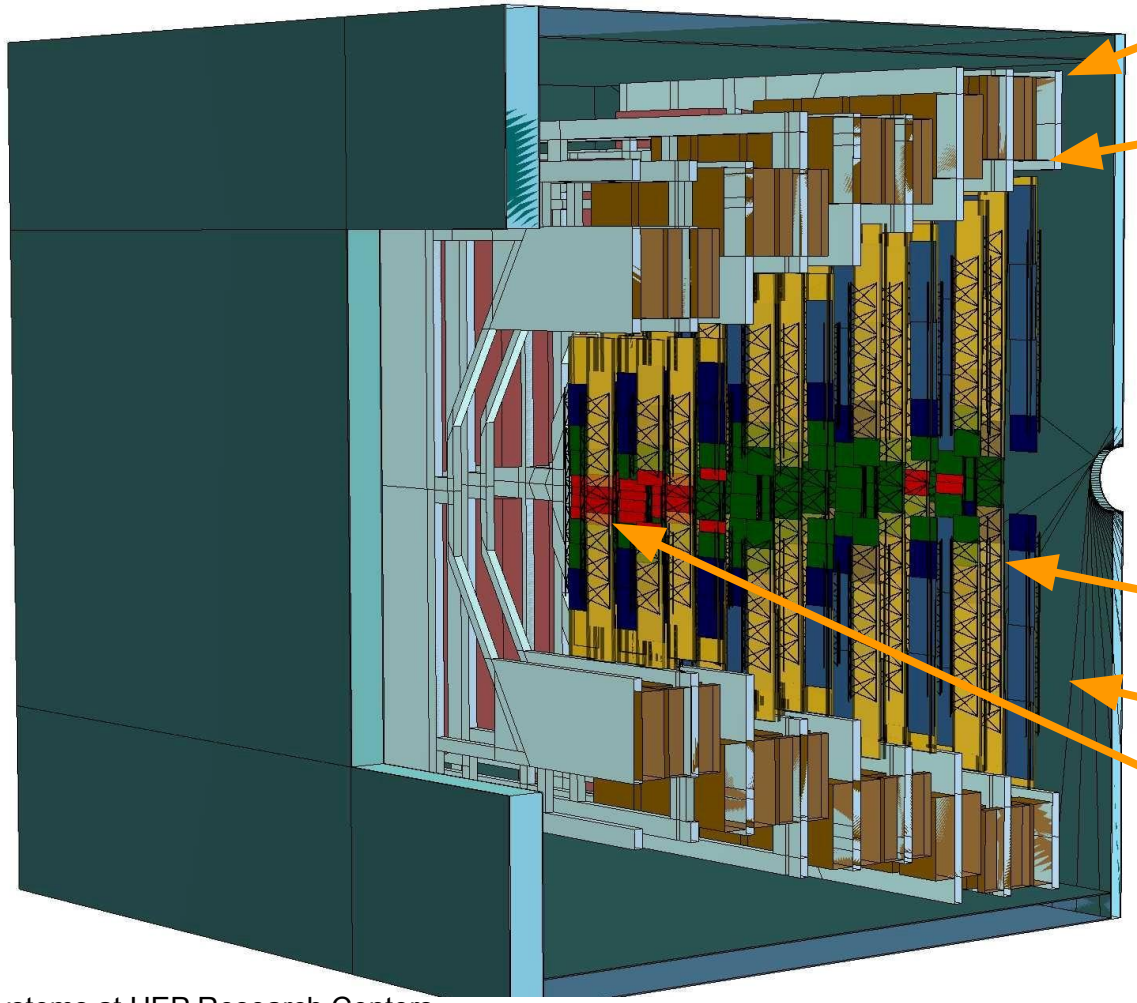
Silicon Tracking System in the CBM experiment

- track reconstruction and momentum determination for the charged particles
- one collision of gold on a gold target can result in up to 700 tracks, with interaction rate of 10^7/s

- cover polar angles from 2º to 25º
- minimize material budget of the system
- radiation hard components (12 kGy)
- evacuate the excess heat from inside the enclosure

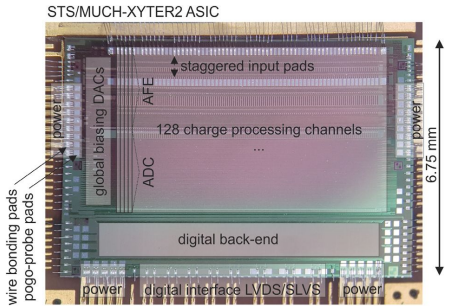


Silicon Tracking System



Cooling system with a dedicated cooling plant

Front End Boards (part of DAQ, low voltage around 2500 channels powering around 14000 Application-specific integrated circuits)



Silicon strip sensors (high voltage for the bias around 1800 channels)

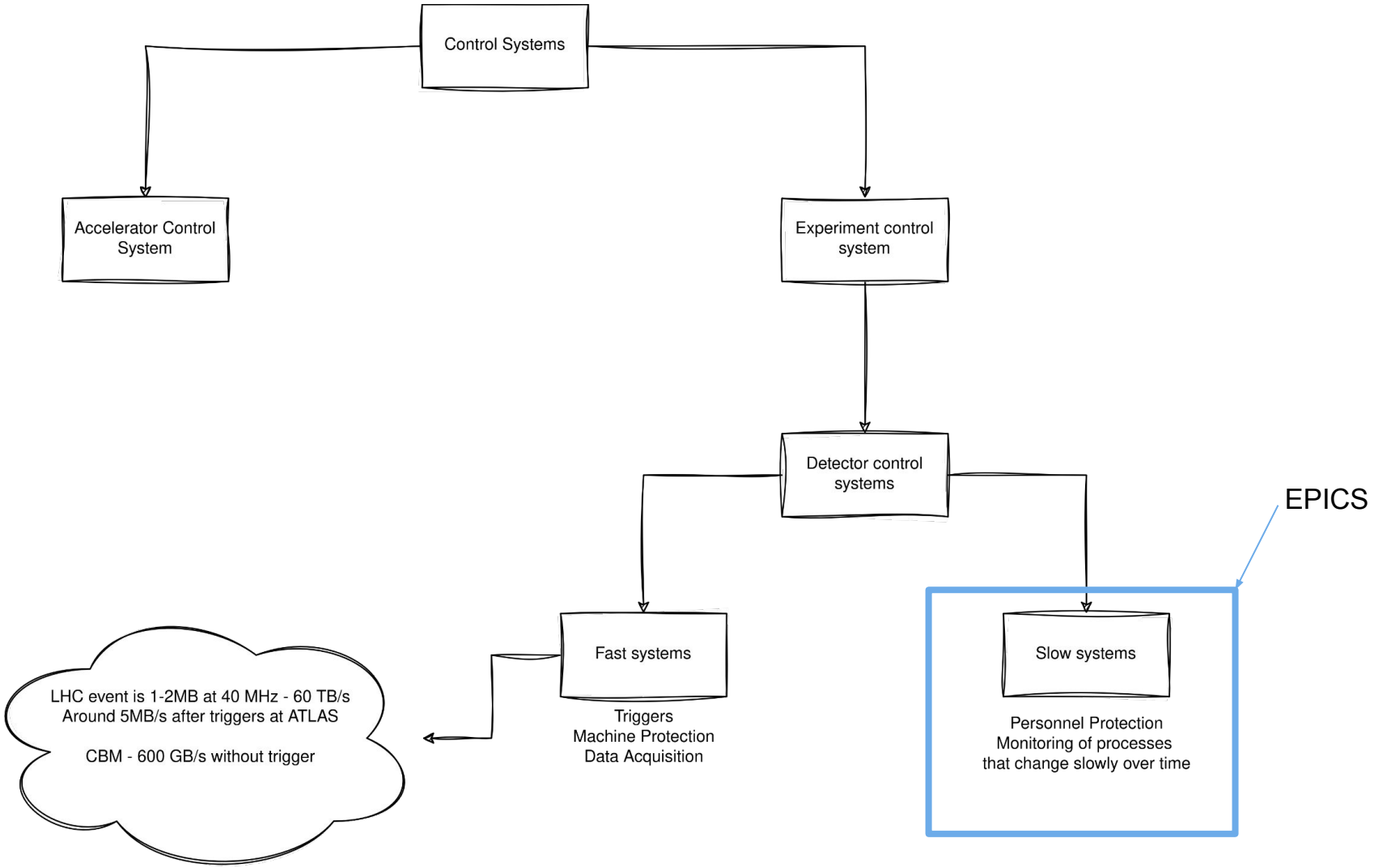
Temperature, humidity and pressure sensors

Gas cooling system

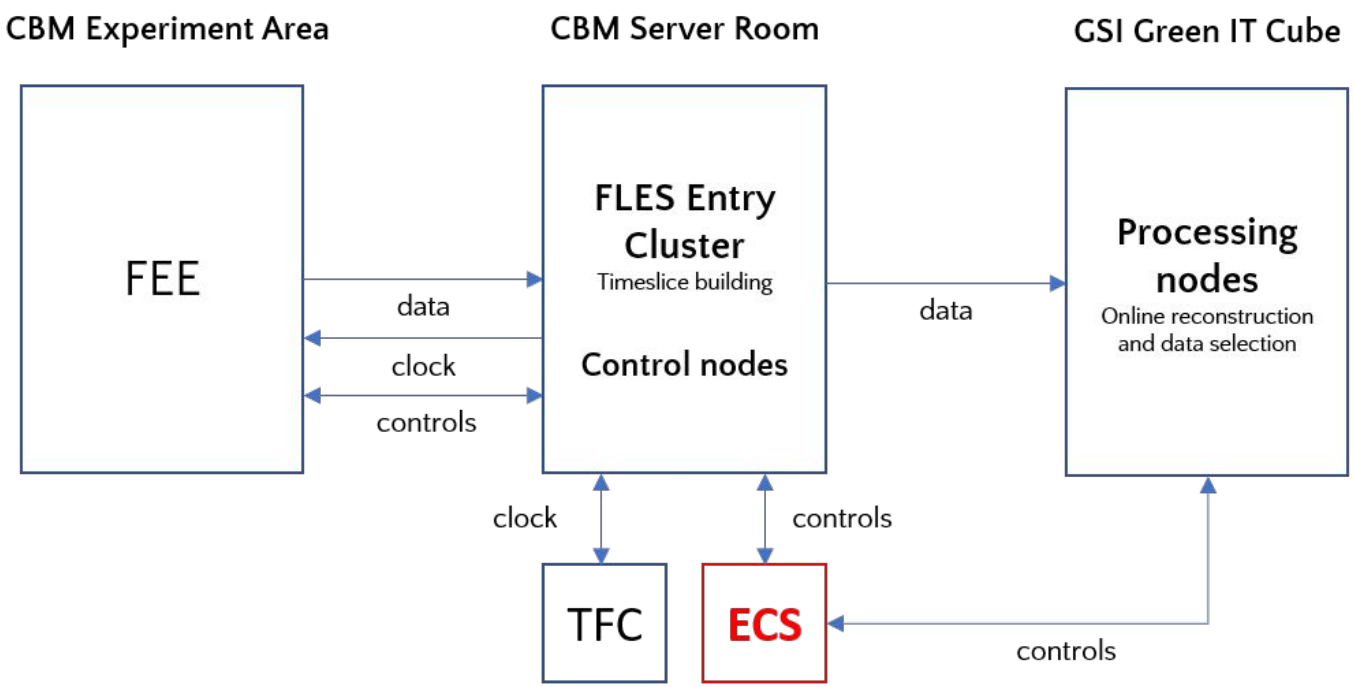
Why is a control system needed?

- the detector will operate in temperatures below 0°C - temperature and humidity monitoring is crucial to avoid condensation on electronics
- stable operation of low voltage and high voltage is crucial for the quality of data - low voltage is supplied to all Front-End Electronics and high voltage is delivered to the silicon sensors
- entering the experiment cave is prohibited during the data taking - need for remote operation
- cooling system has to react to the changes in the detector and also work reliably during the detector lifetime (fallback cooling system to avoid damage to the sensors)
- the detector will work with slight overpressure, therefore monitoring the pressure inside the enclosure can provide information about the potential unsealing

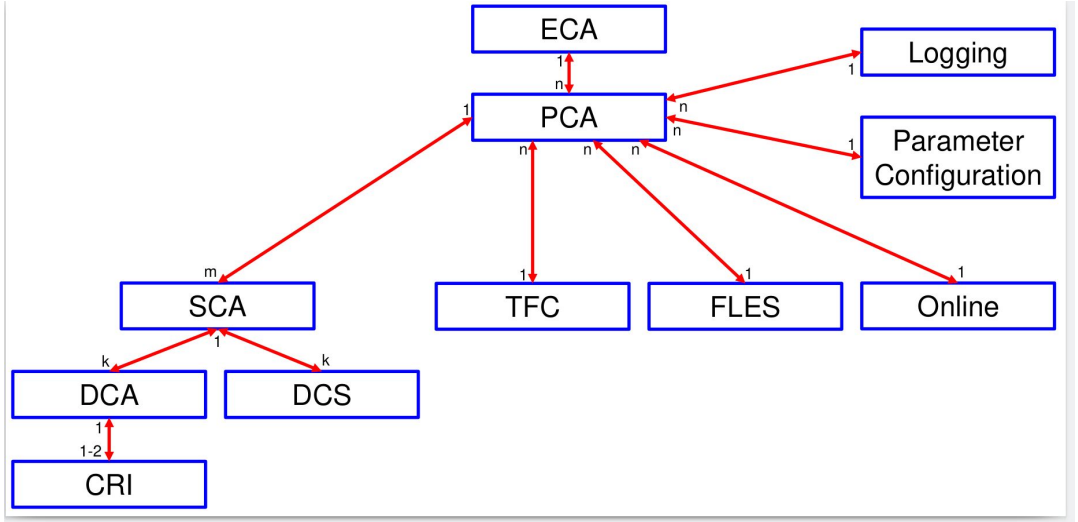
Control systems in HEP facility



Experiment Control System

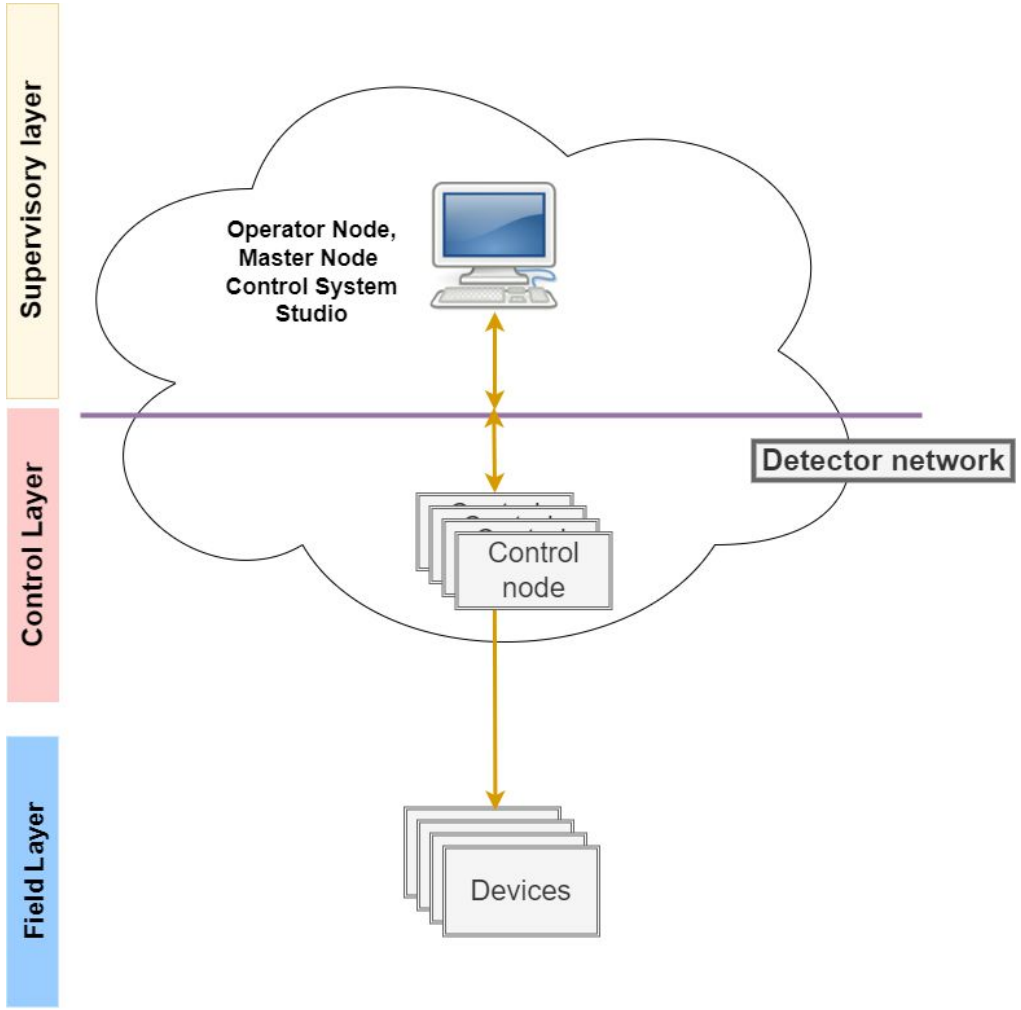


Software agents for the ECS



TFC - time and fast control
FLES - First Level Event Selector
PCA - Partition Control Agent
SCA - System Control Agent
DCA - Device Control Agent
CRI - Common Readout Interface

Detector Control System - slow control



General Tasks

- Environmental Monitoring (temperature, radiation, humidity)
- Equipment Stability (HV, LV, biasing voltage)
- Calibration and Alignment
- Safety and Risk Management (alarms, procedures)
- Data Logging and Trend Analysis
- Integration with Fast Control Systems
- Remote Monitoring and Control
- Long-term Experiment Operation
- System Diagnostics and Maintenance
- Cost Efficiency

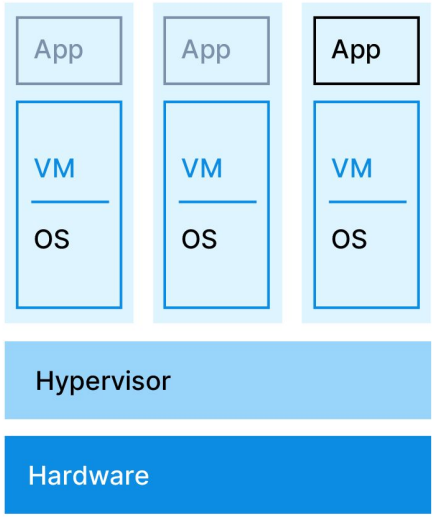
EPICS for CBM experiment

Experimental Physics and Industrial Control System (EPICS) was chosen as the software platform to implement the CBM DCS. Basic attributes are:

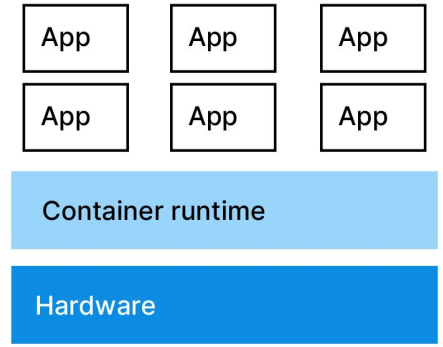
- **Tool based**: Minimizes the need for custom coding.
- **Distributed**: Supports an arbitrary number of IOCs and OPIs, as long as the network does not saturate.
- **Event driven**: Designed to be event-driven to the maximum extent possible.
- **High performance, robust**
- **Scalable**
- **Under constant development**

Containerized approach - what does it mean?

A container is a standard unit of software that packages up code and all its dependencies so the application runs quickly and reliably from one computing environment to another.

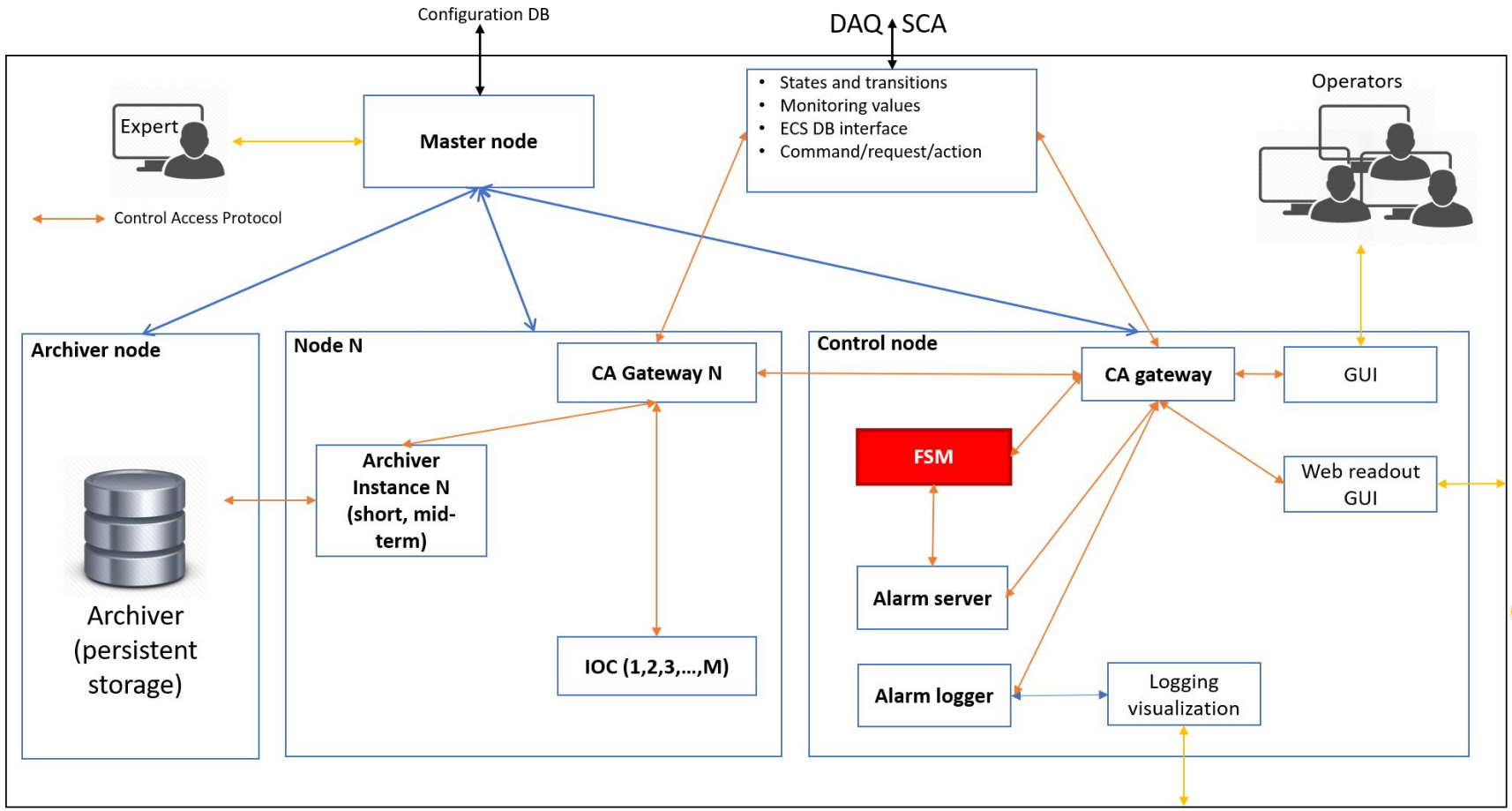


Traditional virtualization

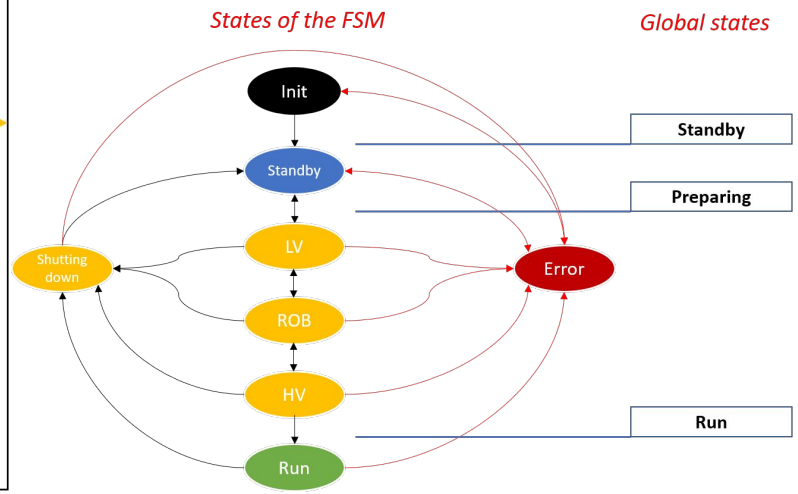


Microservices

Detector Control System - slow control

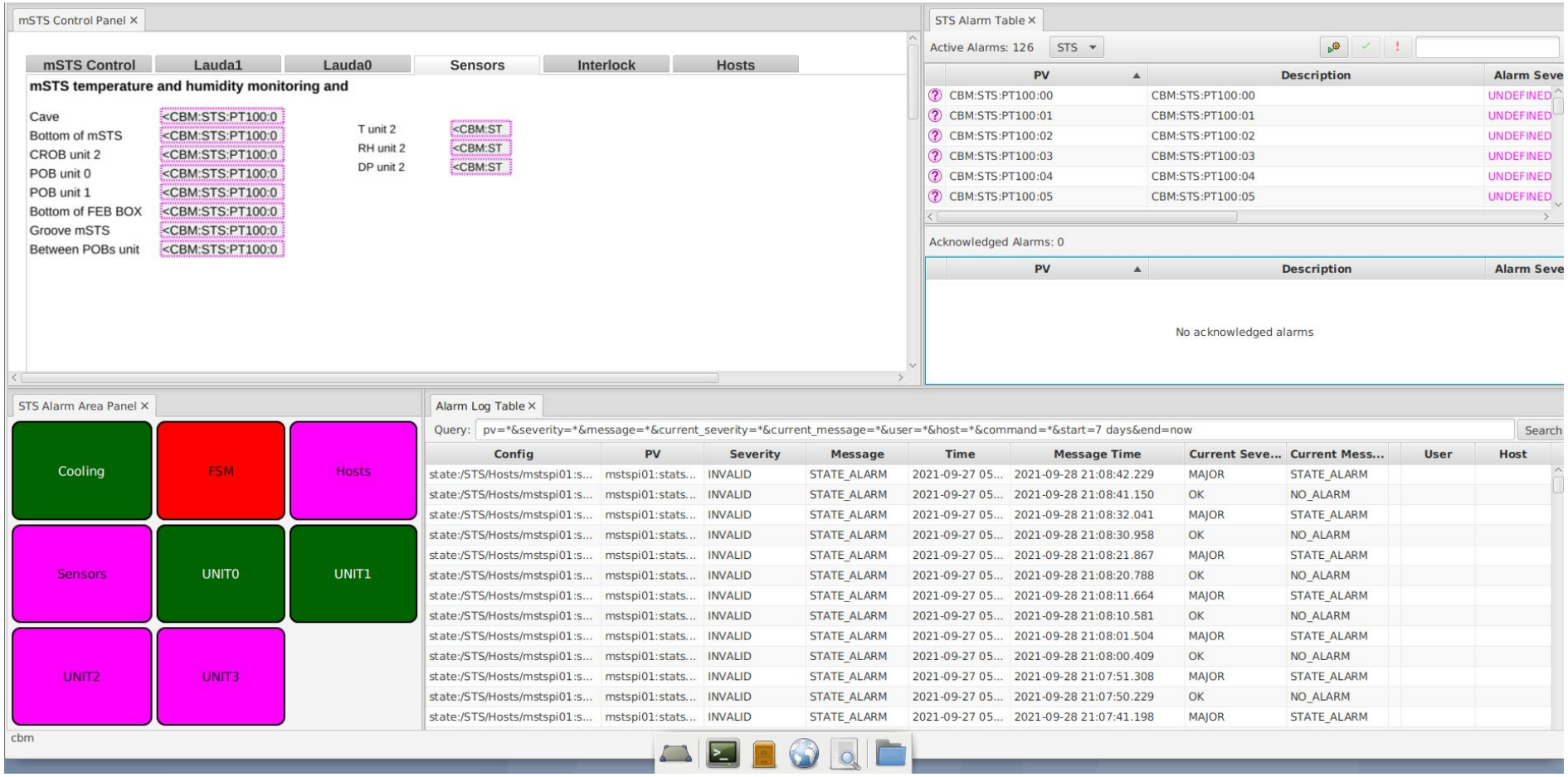


A **finite state machine** (sometimes called a finite state automaton) is a computation model that can be implemented with hardware or software and can be used to simulate sequential logic and some computer programs. Finite state machines can be used to model problems in many fields including mathematics, artificial intelligence, games, and linguistics.



User interface for the STS prototype - phoebus

A framework and set of tools to monitor and operate large scale control systems, such as the ones in the accelerator community.

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