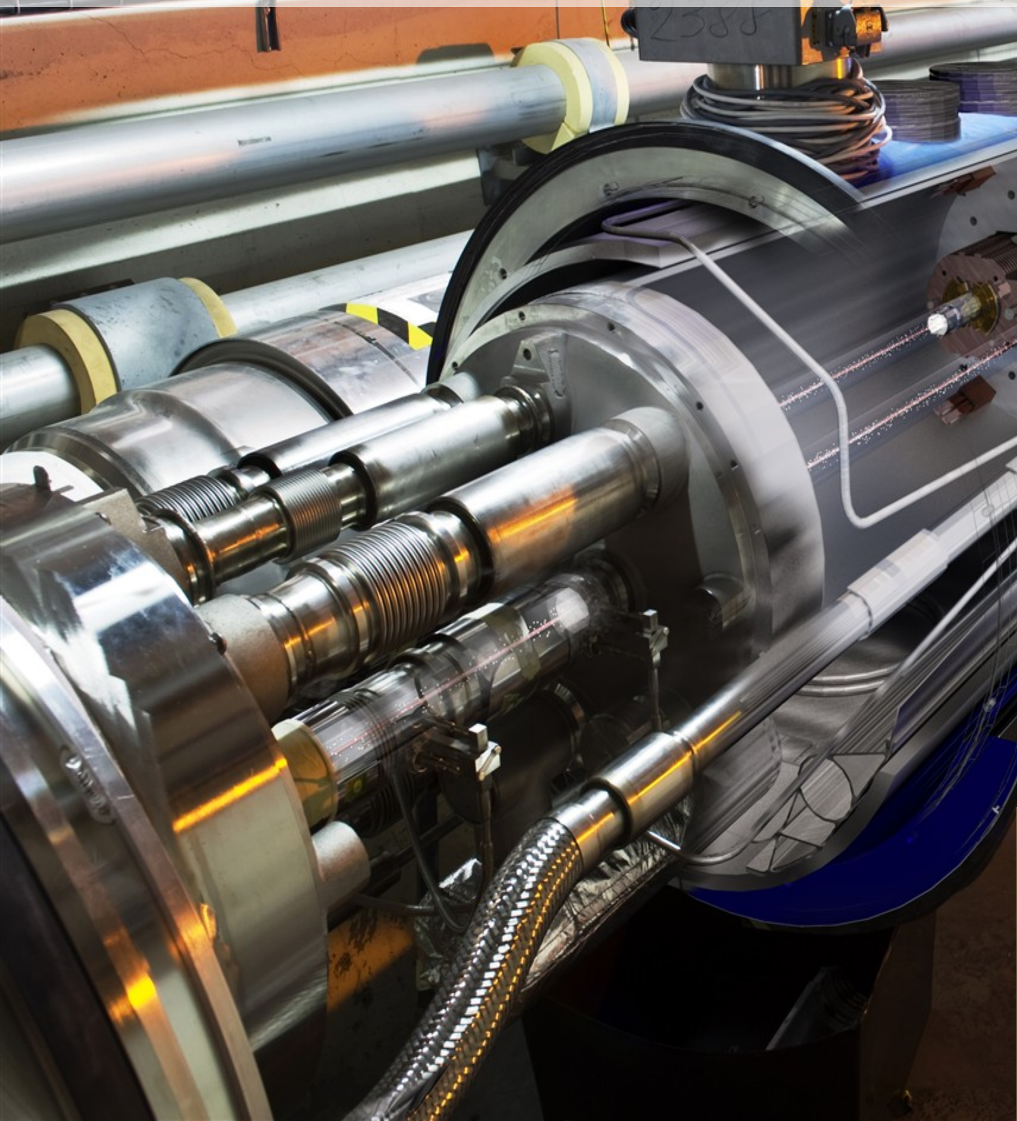
~~The LHC Control System~~

CERN Accelerators Control System



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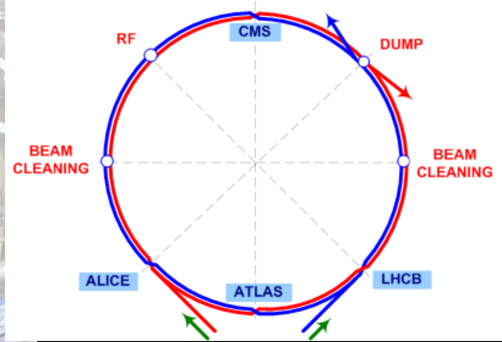
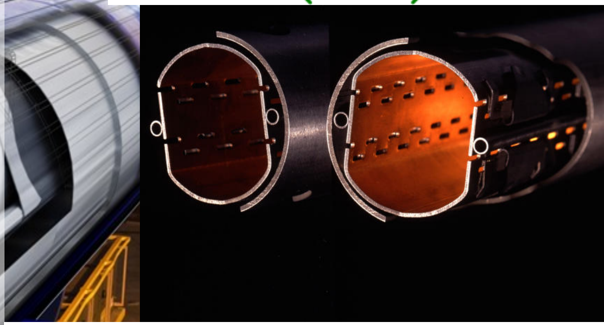
Accelerators and Technology Sector

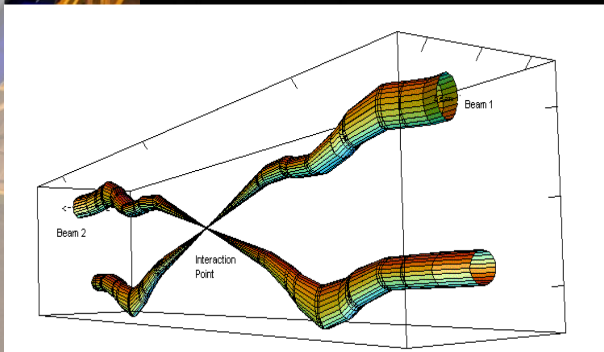
The Challenge

- Accelerate **2 beams of 2.2x10e14 high energy protons** in opposite directions around a 27km ring moving at 99.9999% of the speed of light
- Through **two very narrow, very cold tubes**
- Squeeze them down to **16 microns**
- Get them to and keep them colliding for **10-15 hours**
- Keeping **beam-losses** down to a **very low level**

THIS HAS TO BE DONE WITH THE CONTROL SYSTEM

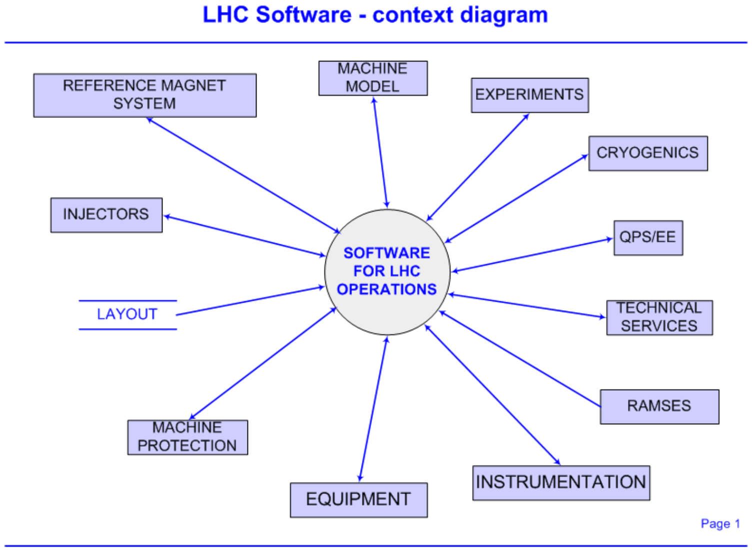






Relative beam sizes around IP1 (Atlas) in collision

The Controls' Challenge



- EQUIPMENT
  - Collimators/TDI/TCDQ etc.
  - Beam Dump
  - Power converters,
  - Kickers
  - RF, TFB, LFB
  - Spectrometers & compensation
- INSTRUMENTATION
  - Distributed systems:
    - BLMs, BPMs,
  - Standalone:
    - BCT, BTV, AGM, BIPM, BWS, Schottky..
  - Tune, Chromaticity, Coupling
  - Luminosity monitors
  - Radiation Monitors
- MAGNETS – RMS, errors
- MACHINE PROTECTION
- VACUUM, CRYOGENICS, QPS, EE
- EXPERIMENTS

⊗

Settings, functions, monitoring, display, post mortem, control, acquisition, concentration, archiving, alarms, interlocks

⊗

Driving the machine through the cycle

Magnet errors, crossing angles, snapback, ramping, squeezing, colliding, orbit, parameter control, optimisation etc. etc.

High Level Control System Requirements

- Provide **controls** to operators **to act and affect changes** to the accelerator (settings management, measurements, acquisitions, ..)
- **Automatic process control, feedback** and **sequence control**

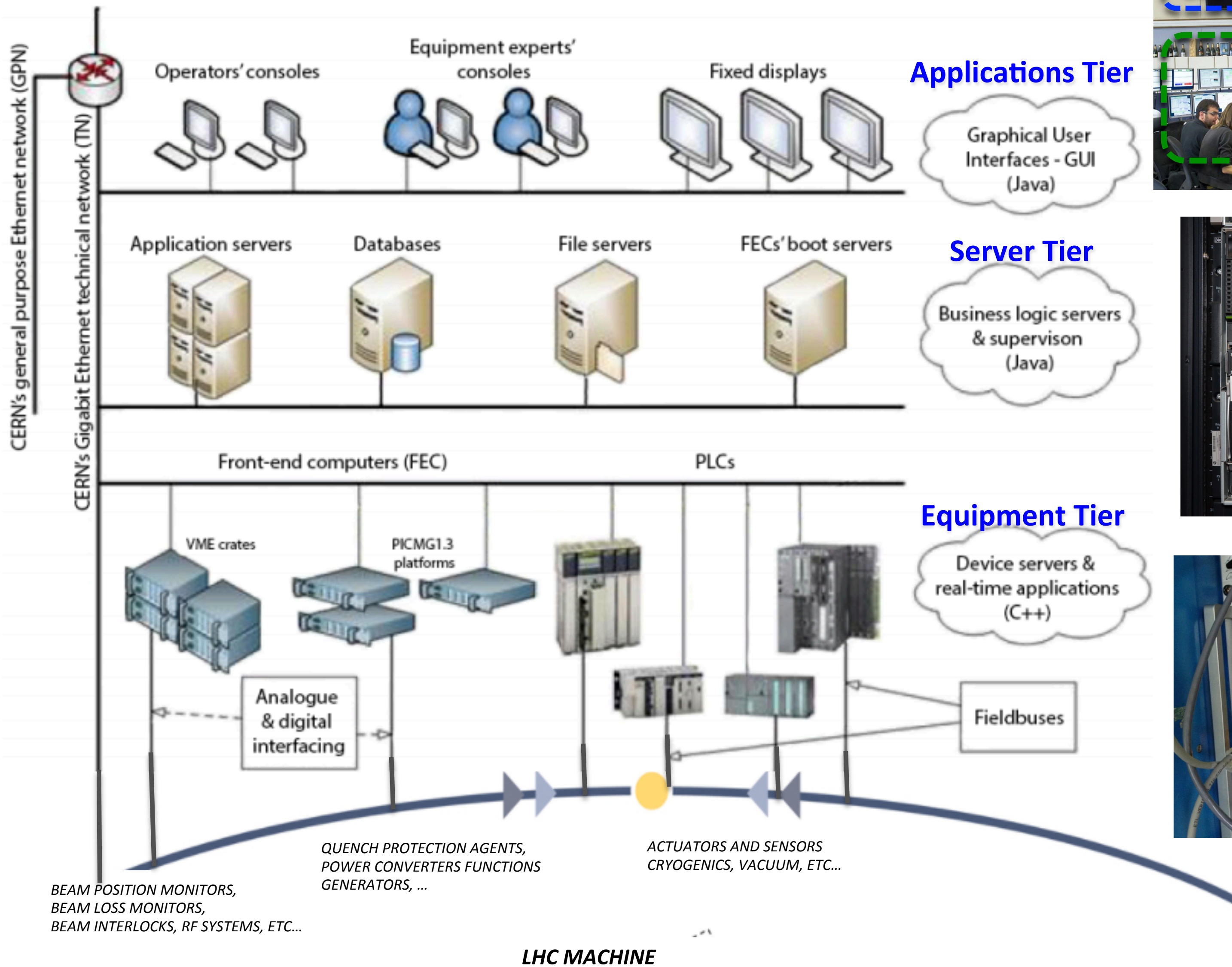
- **Display** of operator information regarding the accelerator status and beam parameters
- **Monitoring, recording and logging** of accelerator status and process parameters

- **Prevention of automatic or manual control actions which might initiate a hazard**
- **Fault diagnostics and recovery**

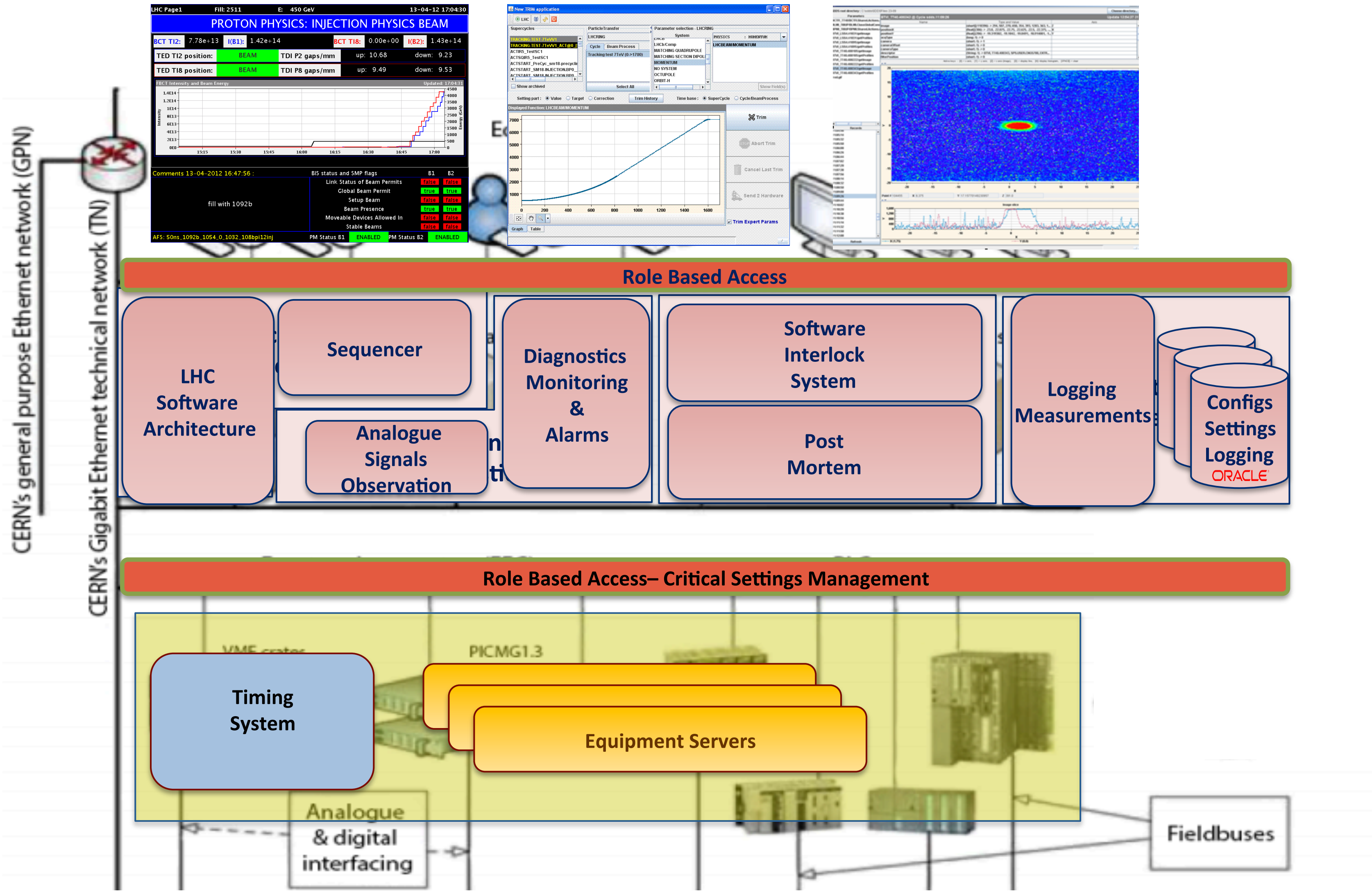
- **Machine protection - Detection of onset of hazard and automatic hazard termination (i.e. dump the beam), or mitigation (i.e. control within safe operating limits)**

- **Must cover** all **operational scenarios**
  - Commissioning (preparation, testing)
  - Physics (proton-proton, proton-ion, ion-ion)
  - Machine Development (experimenting, tuning)

Control System Architecture



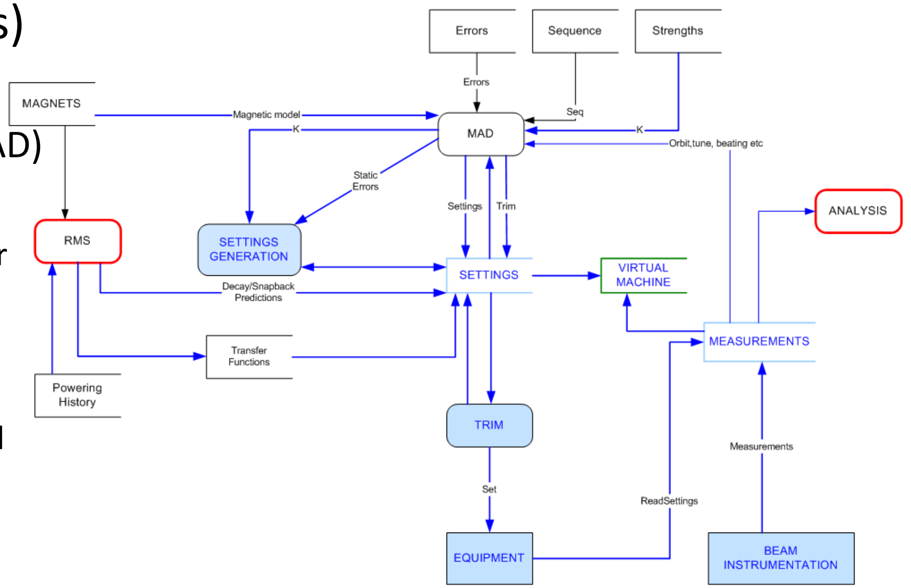
Control Software Architecture



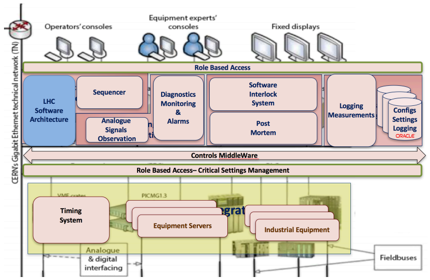
LHC Settings and Cycles

- The LHC is **Event Driven** and not Timing Driven
  - The Injector Complex is timing driven (repetition of cycle with pre-defined length)
  - The LHC cycle contains **Beam Processes** (pre-cycle, injection, ramp, squeeze, etc.) that are in principle not time limited
  - Each Beam Process contains **settings** for all devices and all beam processes are linked
  - **The Sequencer** walks efficiently and securely through all steps in the beam processes and execute the pre-defined commands and checks

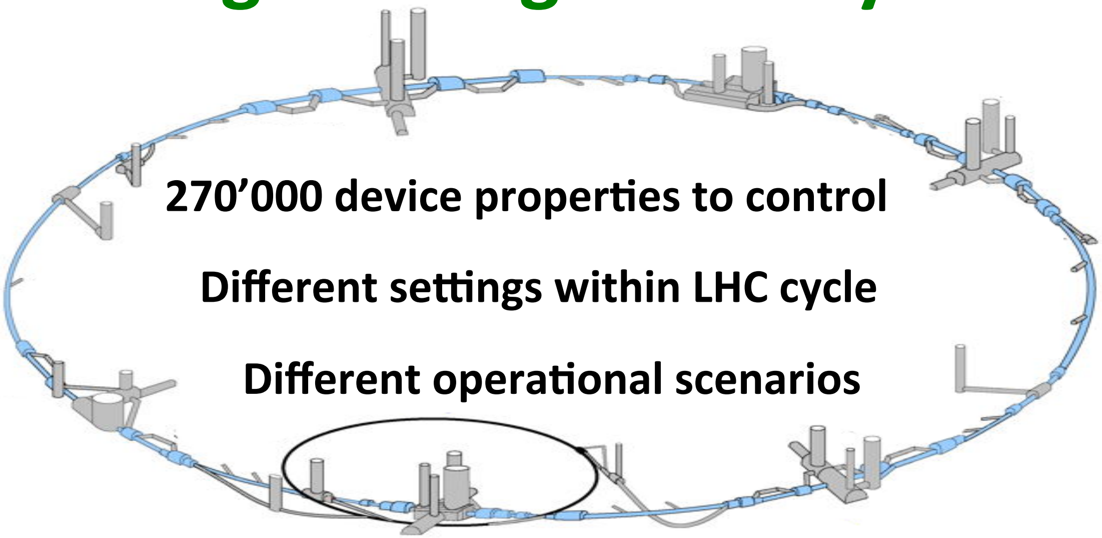
- The LHC is Model Using High Level (physics) Parameters
  - **Settings Generation** from theoretical model (MAD)
  - **Setting Management** is done:
    - Through **dedicated application software** (single or multiple parameters/hierarchies)
    - **Semi-automatic** through feed-forward (FIDEL) and feedback (e.g. orbit, tune)
    - **Protected** through **Role Based Access Control** and **Critical Setting management** to minimize undesired/mistakenly parameter changes



LHC Software Architecture
(LSA)



Settings Management System



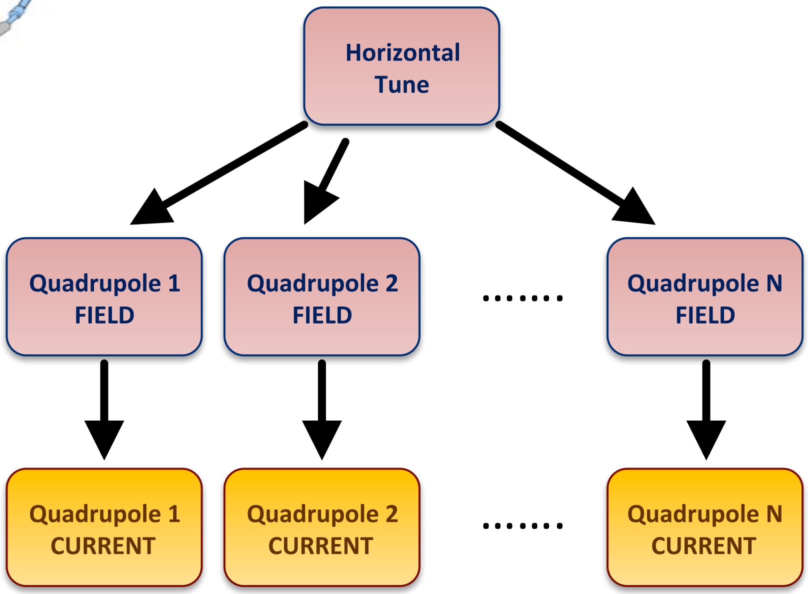
270’000 device properties to control

Different settings within LHC cycle

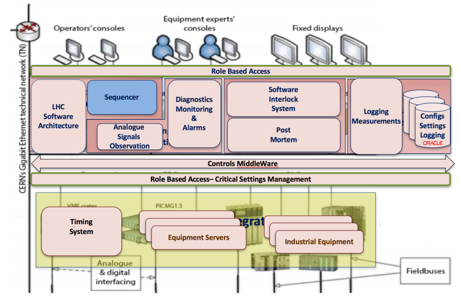
Different operational scenarios

- Used in 6 accelerators:
- LHC, SPS, LEIR, PS, PSB, ISOLDE
  - **Exportable**: used in GSI
- > ~150 M of settings
- ~ 1M lines of code

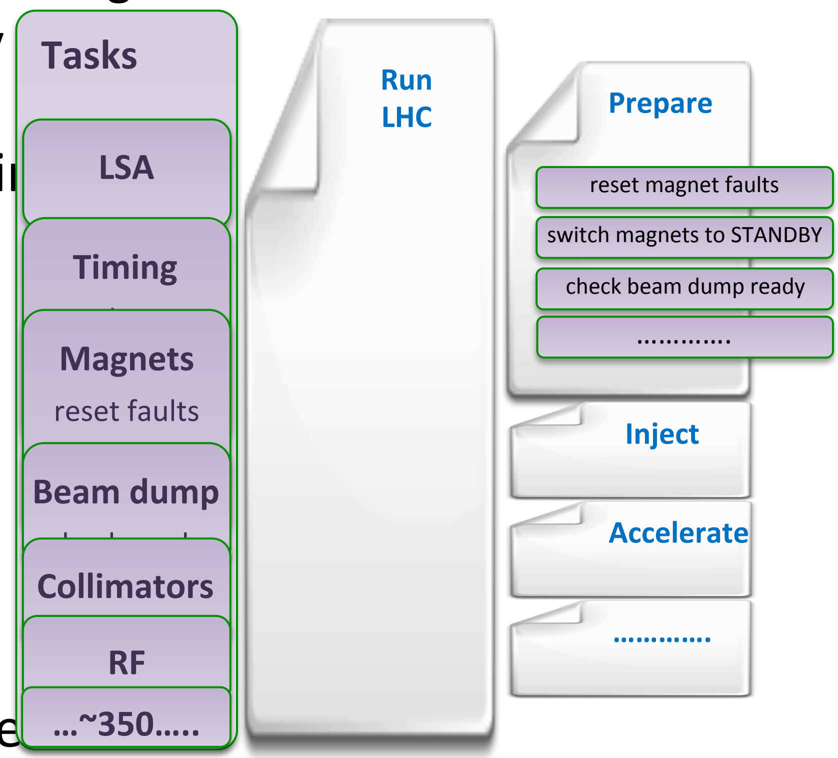
Translation of high-level accelerator parameters to low-level device properties



Sequencer



- **Automates** execution of **sequences of tasks**
  - Check the values of devices
  - Ask the control system to load the settings
  - Wait for the equipment to be ready
- **Operators** memory
- **Reliable** execution and error reporti
- **Safe** mode
  - run-through automatically
  - run until task
  - step task-by-task
- **Expert** mode
  - skip task
  - jump to task

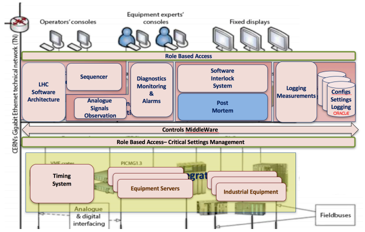


- ~ 1250 sequences for LHC Beam Ope
- ~ 350 tasks types
- LHC main sequence: ~1100 tasks in total

LHC Machine Protection

- LHC relies on an Important and **Complex Machine Protection System** (MPS)
  - Protect machine against damage from power of the beams
  - In case MPS is triggered, efficient diagnostics through post-mortem data analysis is of prime importance

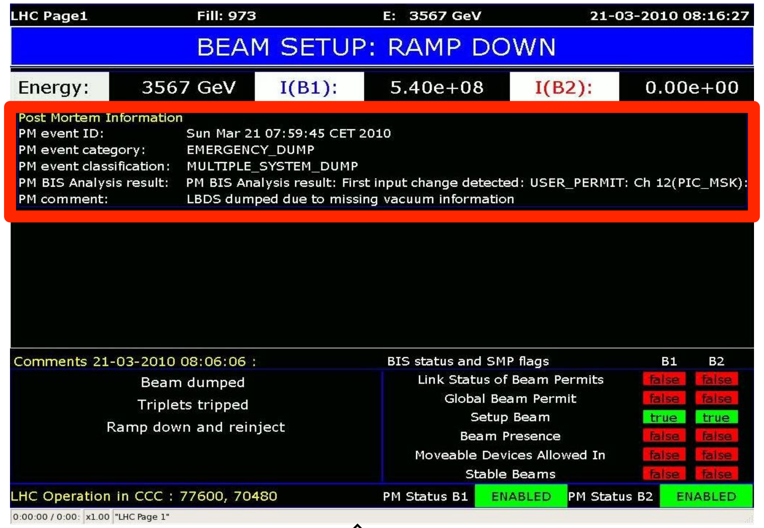
Post-Mortem Analysis

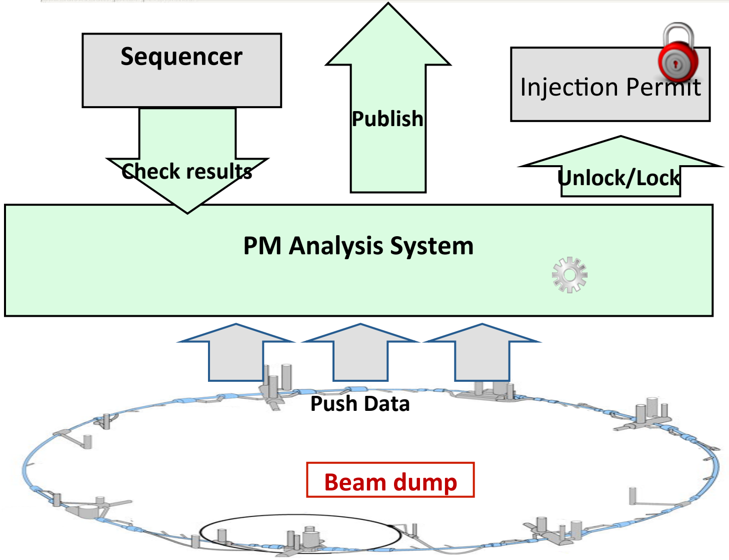


- Part of overall **Machine Protection**
- Detects the cause of the beam dump
- Checks if all the protection equipment behaved as expected
- Decides if it safe to continue the operations
- Blocks the next injection otherwise

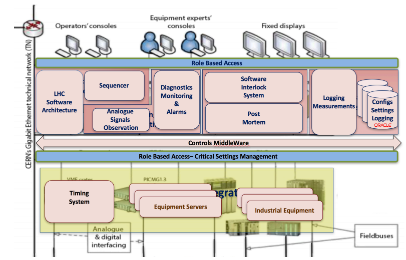
- 4 mission critical LHC applications
  - LHC Beam Dump Analysis
  - External Post-Operational Check
  - Injection Quality Check
  - Powering Event Analysis

- 2 GB per LHC Beam Dump



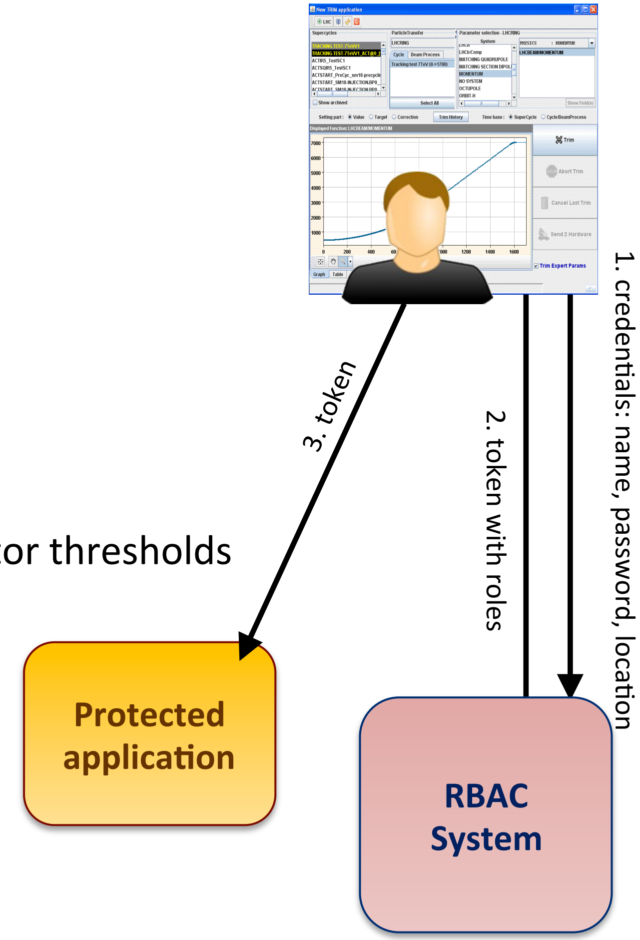


Role Based Access & Critical Settings



- **Role Based Access**
  - **Protects the action (**unauthorized access), not the value
  - Authentication & Authorization
  - Permission definitions
    - Who, what, when, from where
  - RBAC protects all the LHC equipment
  - ~500’000 permission definitions
  - ~500 users

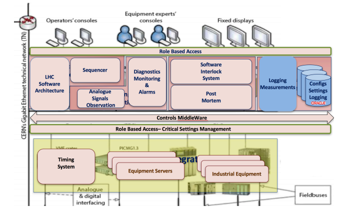
- **Critical Setting Management**
  - **Protects the value**, not the action, ex. BLM, BPM, collimator thresholds
  - Only experts can modify the value
  - Digitally signed values
  - 100 critical value types => 1500 properties



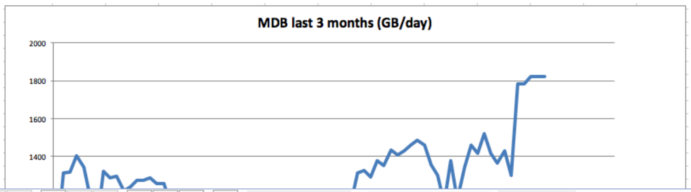
Understanding the LHC

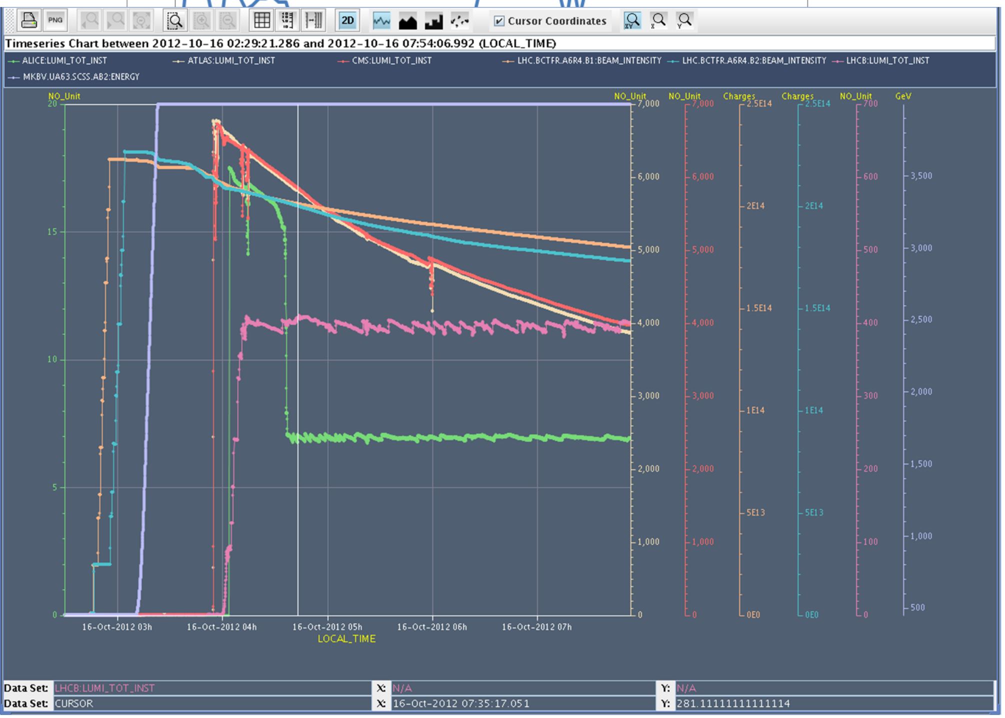
- LHC operation relies heavily on **Logging** and **Post-Mortem** data
  - For trouble shooting
  - For machine performance analysis
  - To enhance machine performance and to understand beam dynamics issues, high volume data observation systems (ADT/ObsBox data) provide valuable input
  - For data analysis, long-term storage and efficient retrieval of data are key

Measurement & Logging System



- **Storage** for beam & equipment data beyond LHC lifetime
  - No experiments' data





~ 1000 clients
~ 5 million extraction requests/day

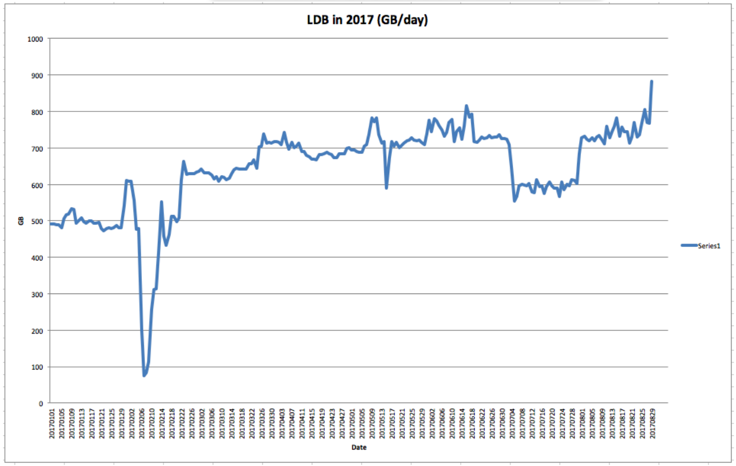
Measurement DB
7 days of raw data
ORACLE

Filter ~ 95 % reduction

Logging DB
>20 years of filtered data
ORACLE

~ 11TB / week (1.5TB/day)
~ 71e9 data points/day (4e9 in 2014)

~ 1.5M signals archived
~ 20k device properties
~ 1 TB/day
~ 1 PB of archived data



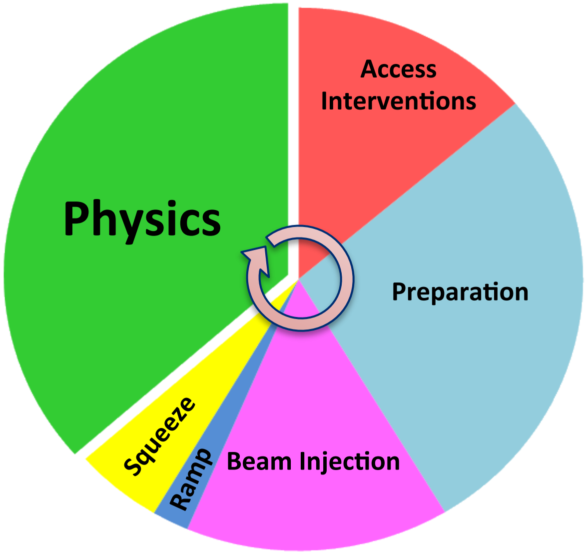
- Allows **analysis of accelerator behaviour** over **long periods of time**

Towards LHC Performance Improvement

“Integrated Luminosity is important, hence machine/beam availability is key”

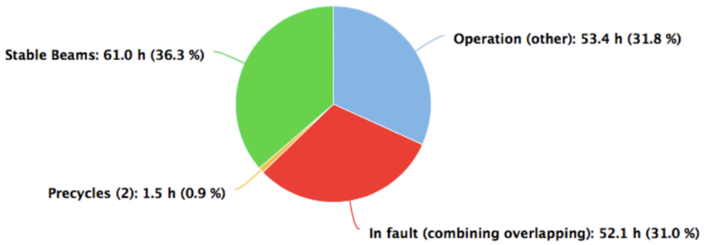
Physics time maximization

- LHC procedures optimization through better tools
    - Recent automation of Hardware Commissioning steps and validation have made this process much more efficient **(~ 1 months → 2 weeks)**



- Control System fault minimization

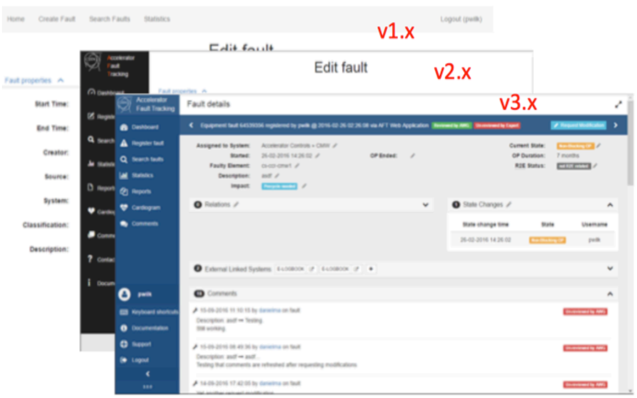
Time distribution

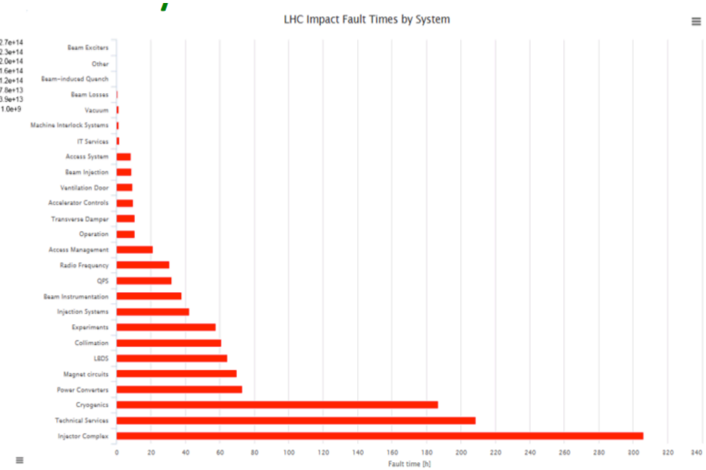


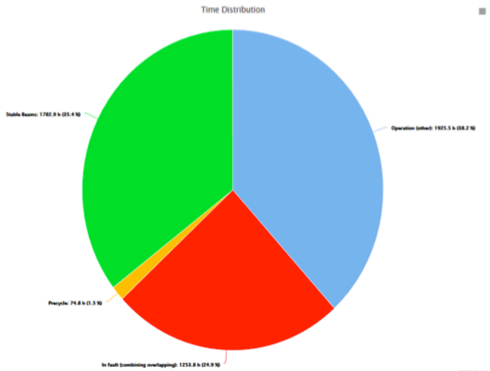
Accelerator Fault Tracking

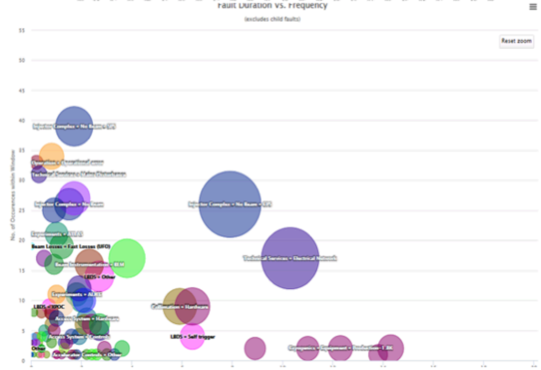
"Why are we not doing Physics when we should be?"
"What can we do to increase machine availability?"

- Coherent data capture: 830 faults recorded for LHC helping areas for improvements
- Detailed fault classification and analysis for equipment groups
- Covers CERN's entire injector complex



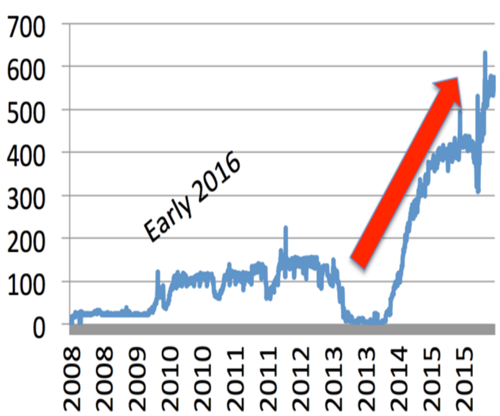


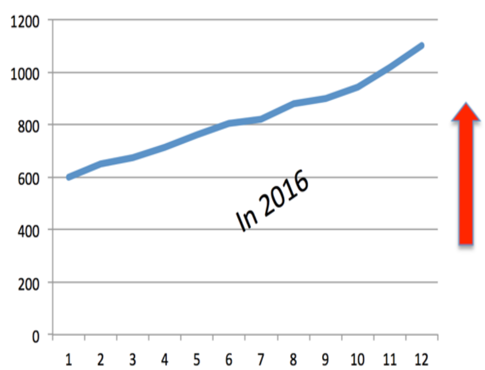


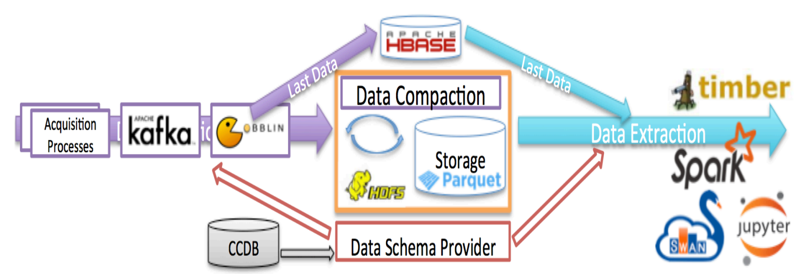


Towards BIG Data

- Current data throughput rates in the existing Logging system approach 1 TB / day and are expected to continue to increase in the coming years
- The next generation Logging System is being developed
- Based on modern "Big Data" technologies (Hadoop, Kafka, Spark)
- Built on open source components and libraries
- Aims to answer the needs to store more data, & to be able to efficiently analyse it using the languages of choice by data experts







The LHC has a very Modular Distributed Control System

- Performs **mission-critical tasks**
  - 70'000 equipment processes on ~2000 front ends machines
  - ~2000 programs running on 550 servers
  - 500 different GUIs and ~300 server programs
  - **Developed by ~100 people from 16 different groups**
  - 1100 Java executable
  - **~10M lines of code**
  - **1PB of archived data**
- Big (>1000) user community
- It **evolves** constantly

BACK UP SLIDES

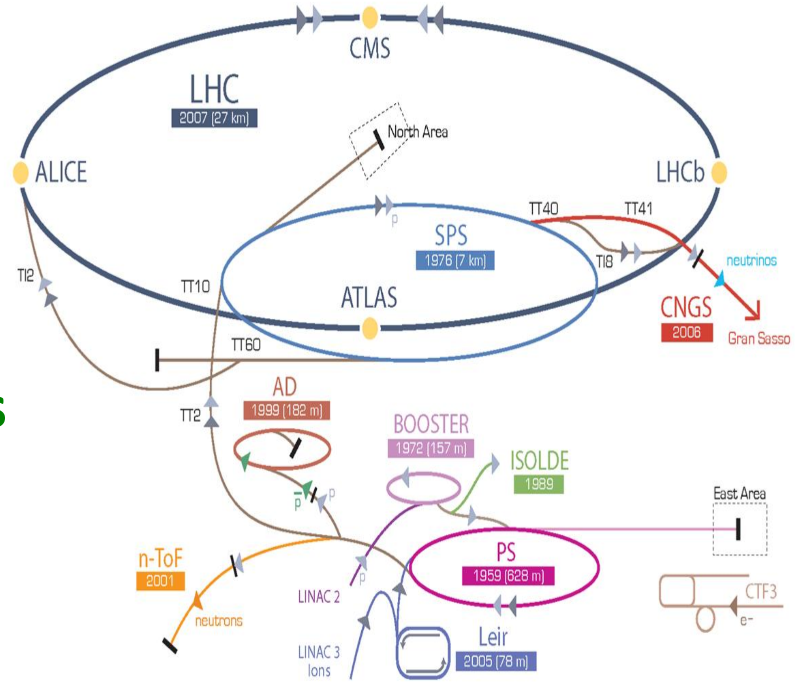
Upcoming Topics

- Levelling / Anti-levelling
  - With the performance increase and also in view of the HL-LHC luminosity levelling becomes important
  - Depending on the type of levelling the control process can be complex
    - Beam separation → "easy", routinely used
    - Crossing angle → "demanding", being exploited today
    - β^* → "challenging", under development to be used in the coming years

- New developments of more complex controls system components required/ongoing to link seamlessly existing systems in the machine together (e.g. orbit, collimators, optics, machine protection, ….)

- All these upcoming work can be achieved with efficient collaborations of experts, operators and developers across the accelerator sector

Additional challenge

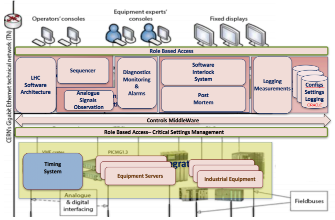


The **same controls infrastructure**
is deployed on **all CERN accelerators**

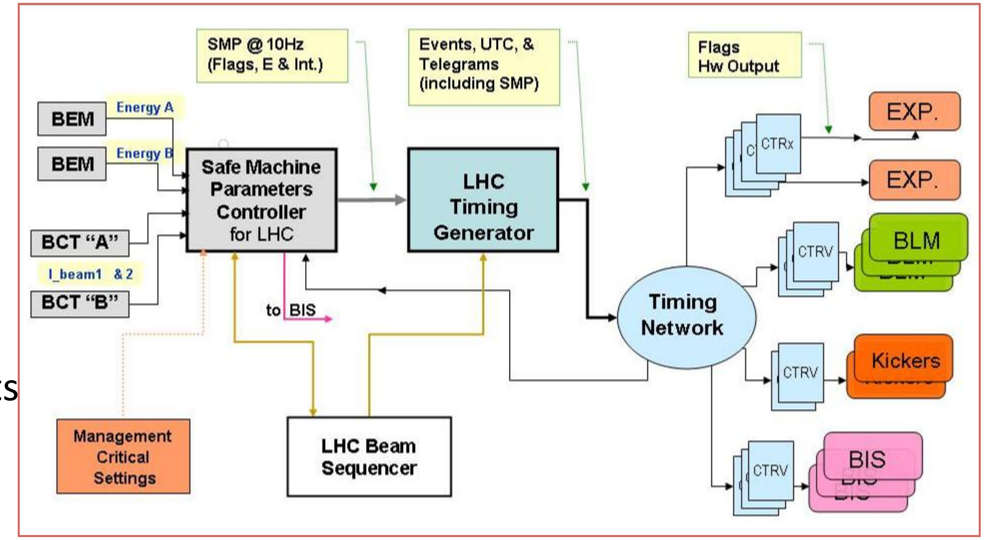
Important Technical Challenges

- Highly exposed, critical operational services
- Serves dissimilar set of users, commonality vs. customisation
- Complex dependencies
- Challenging integration, difficult maintenance
- Technical errors ⇔ high impact
- Stability vs. fast turn around
- High reliability and availability

LHC Timing System



- Event-based timing system
- Dedicated network
- Active and hot spare nodes
- Manually calibrated
- Have many systems acting in **sync**
  - synchronously ramp up LHC magnets
  - ~1000 receivers serving ~8000 clients
- Provides **common notion of time** in distributed systems - to make sense of acquired data
  - LHC: data timestamps have 1 μs precision



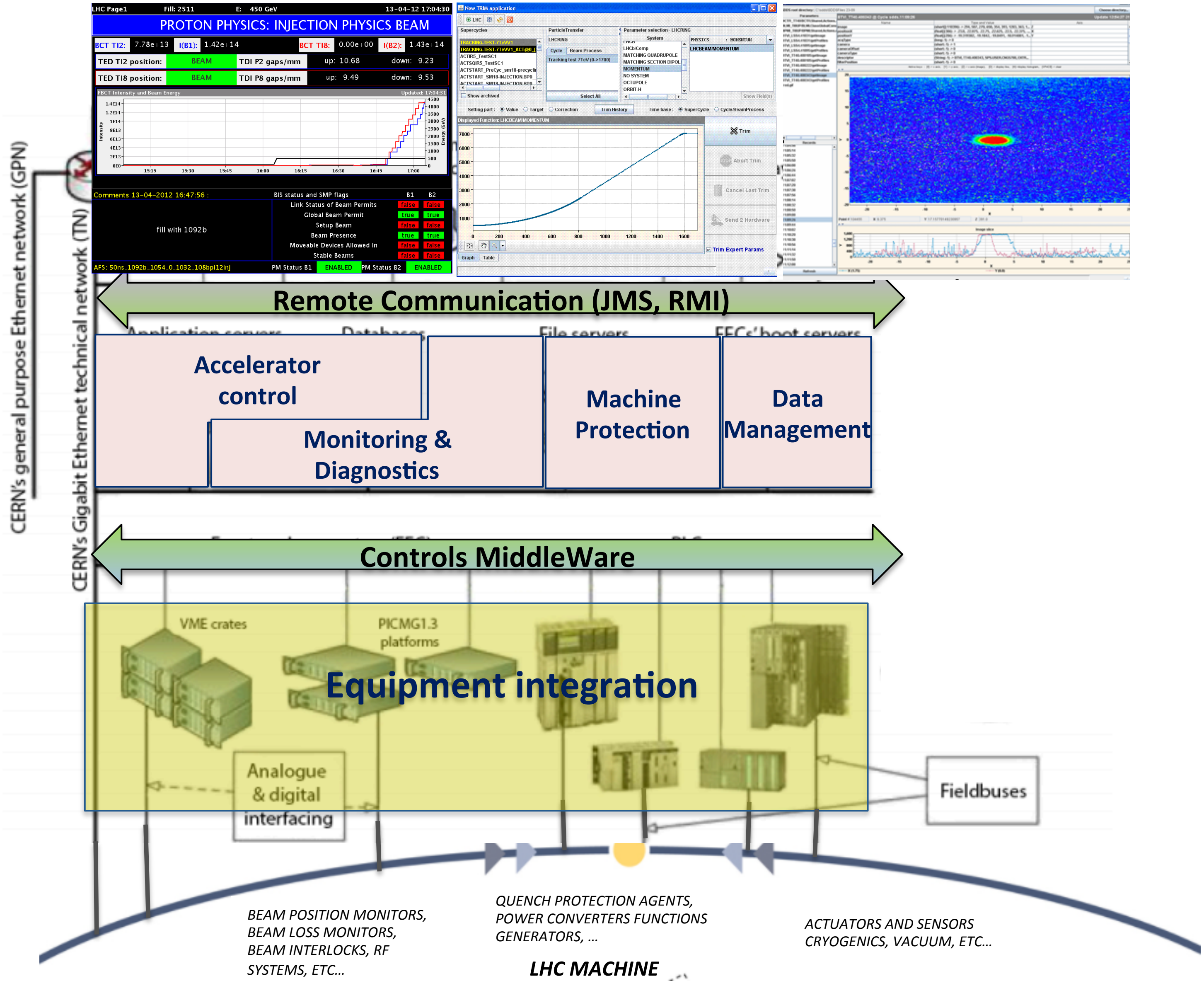
Distribution of critical parameters over the Timing network
- Beam Energy,
- Safe Beam Flags,
- …

Interfaces with
- Kicker systems (BEM)
- BCT system
- BLM system
- Experiments
- Beam Interlock Syst.

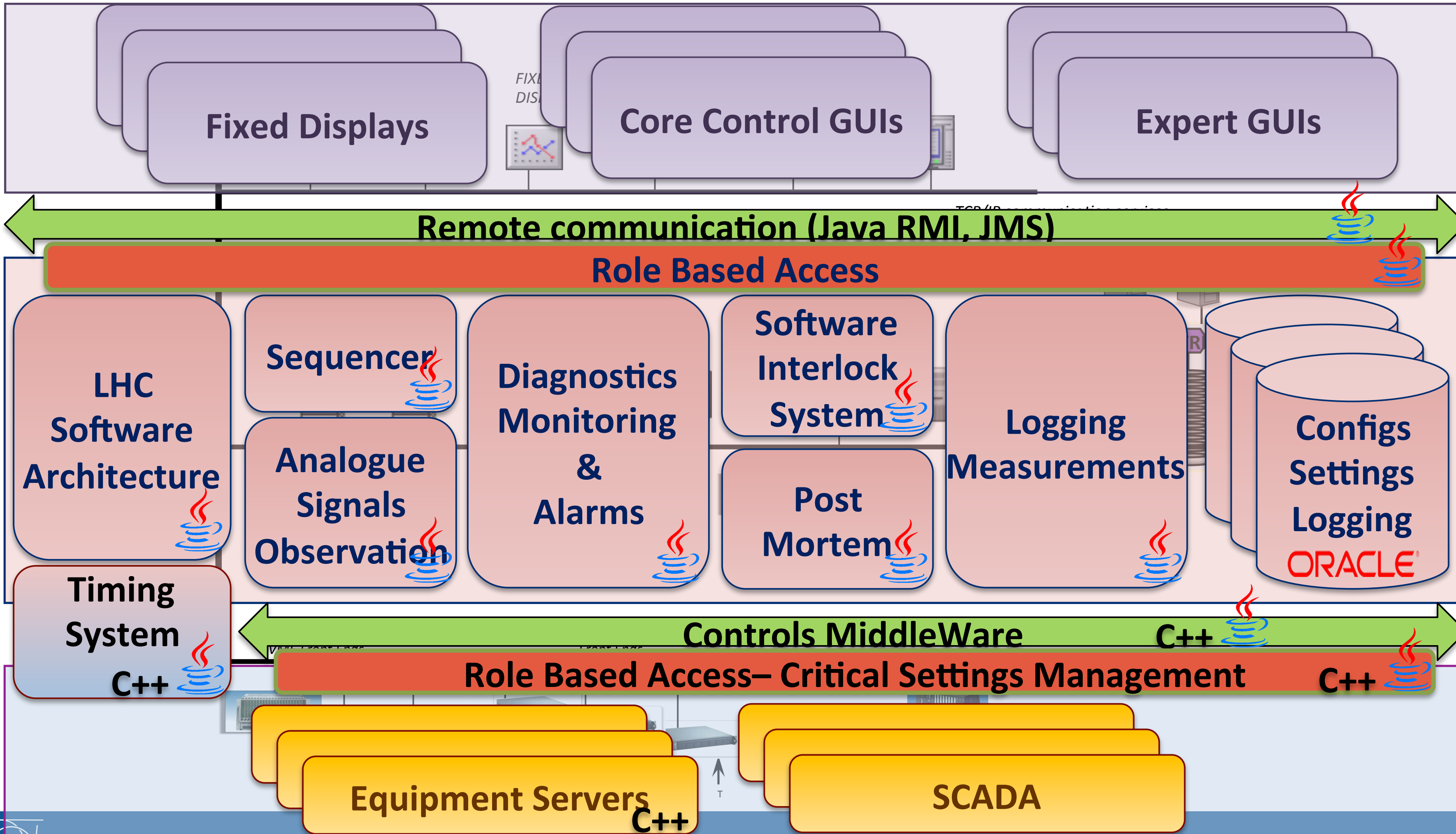
Philosophy of development

- Provide **extensible Frameworks** and **Tools**
- **Domain experts** fill in the domain-specific knowledge
- Develop and deploy **Generic** services
- **Applicability** to **all accelerators**
- Thorough **Quality Assurance**
- Successful and efficient **collaboration**
  - with equipment groups and operators
  - with other laboratories (FermiLab, GSI, ESRF, ITER, MedAustron, Dubna)

Control Software Architecture

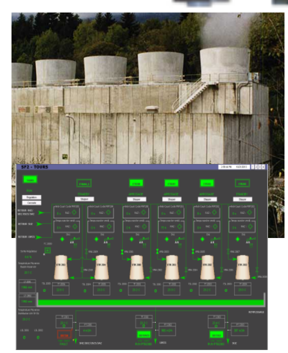


Controls SW Infrastructure



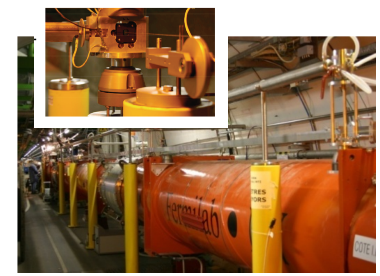
Industrial Process Control System

- Process Control application framework UNICOS
  - PLC or PAC-based applications
  - UNICOS proposes a method to design and develop the control application which will run in commercial off-the-shelf products
- JCOP FRAMEWORK
  - Common Framework of tools and core components
  - Device modelling, configuration, monitoring, alarms, etc
  - Main users are software developers and LHC experiments
  - Large software system
  - Users >750 History: 14 years
  - Many external contributions: e.g. experiments

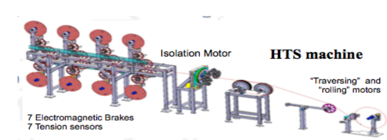


Cooling & Ventilation

LHC Cryogenics

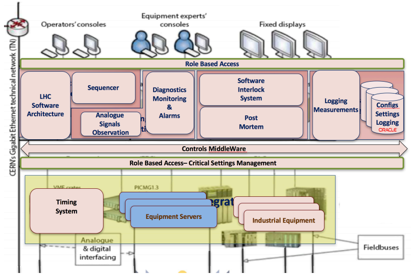


LHC Magnet alignment



HTS Winding machine

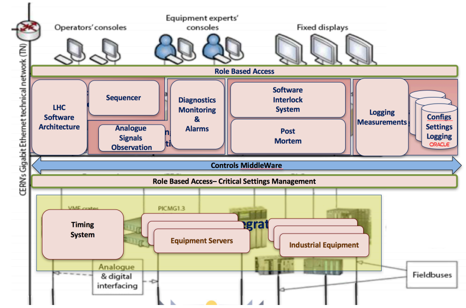
Front End Software Framework



- **Standard** software framework to develop **real-time** Front-End Software to control **all accelerators** equipment
- Hides the complexity of the controls infrastructure, **simplifies** the development, allows equipment experts to **focus on their HW-specific logic**

- **~100 developers** from 16 equipment groups
- **~700 hardware device types** (~200 in LHC)
- **~70000 devices** (~25000 in LHC)
- **~1000 Front-Ends machines** (~500 in LHC)
- **Exportable**: used in GSI (Darmstadt)

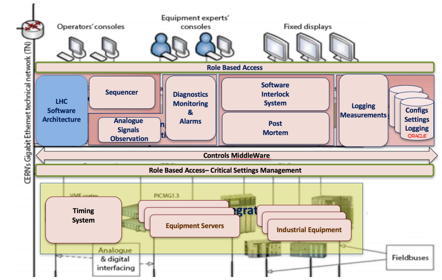
Controls MiddleWare



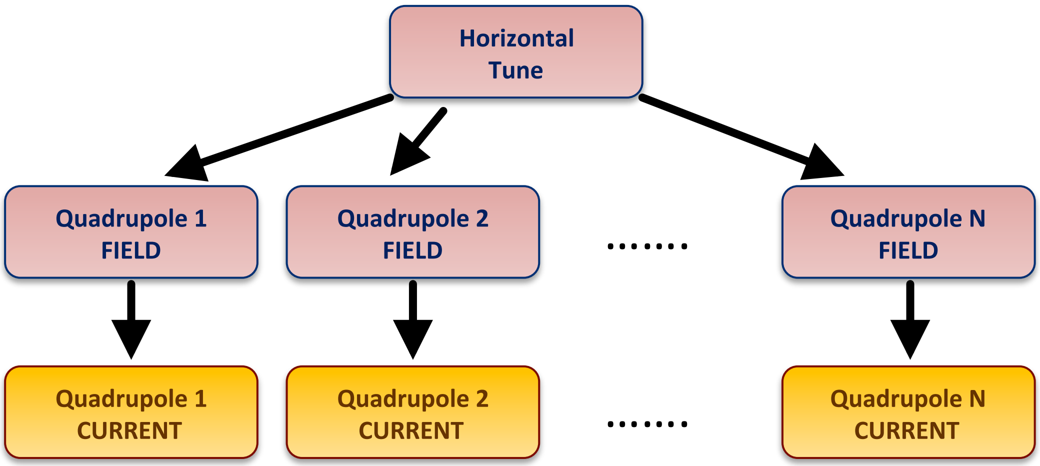
- Reliable decentralised core **communication** layer based on ZeroMQ
- Collection of software **components** & **services**
- Operations: **GET**, **SET**, **SUBSCRIPTION**
- Widely deployed for **all CERN accelerators**
- Provides **comprehensive diagnostics**

- **4'200 Front-End servers** processes
- **85'000** (incl. SCADA) **devices**
  - **85'000 devices**
  - **2'000'000 equipment controllable properties**
- 2 Directory Servers for device information how to connect
- **Exportable**: used in GSI (Darmstadt)

LHC Setting Management

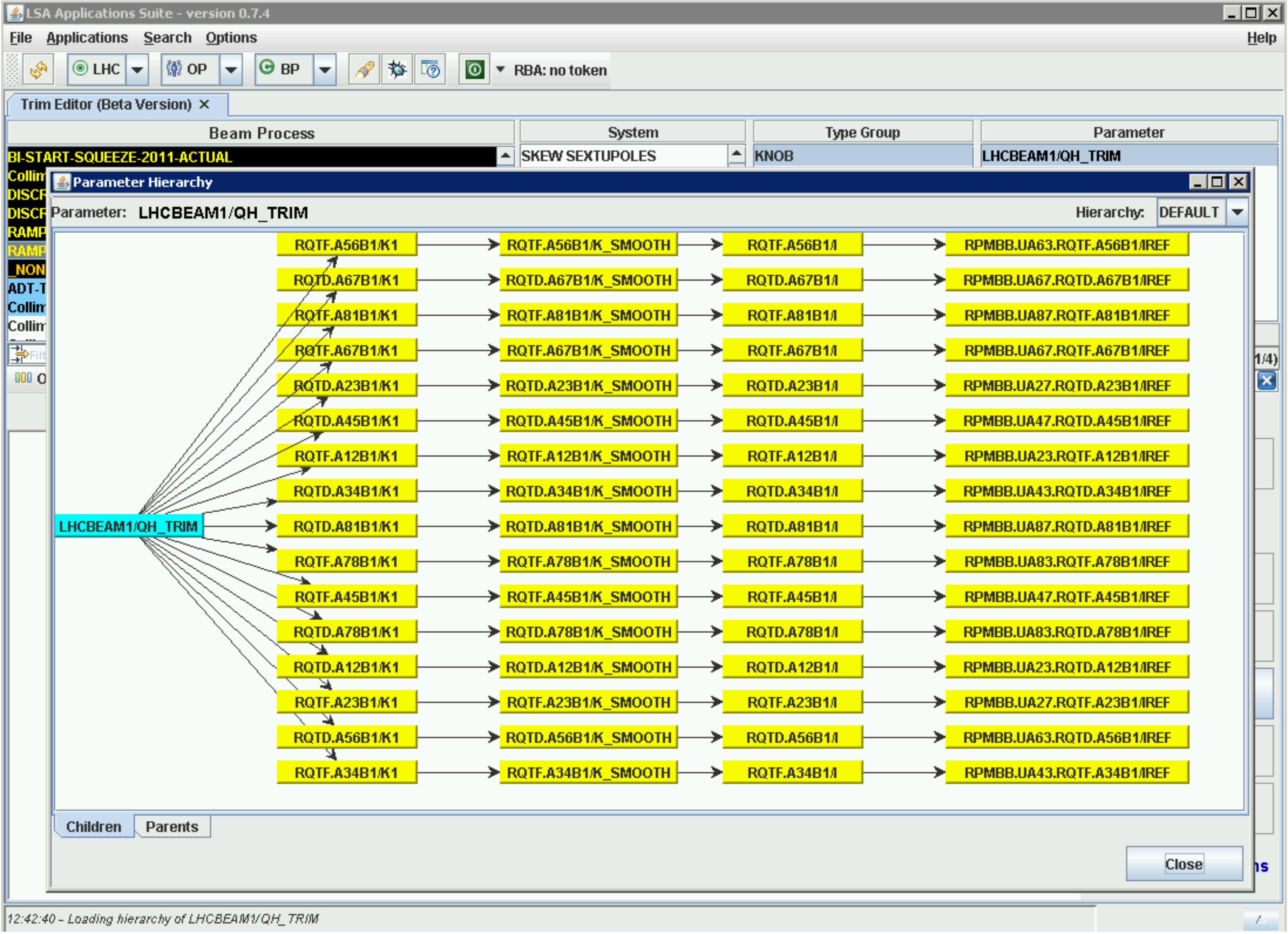


- Generation of initial settings based on optics
- Storage/modification of settings for all devices
- Coherent modifications of settings
- Settings versioning
- History of changes and rollback
- Communication with the hardware
- **Translation** of high-level accelerator parameters to low-level device properties

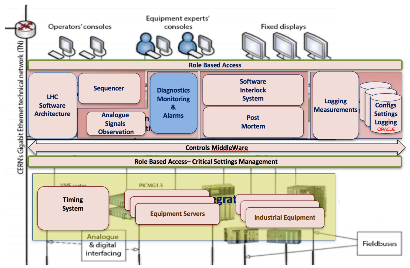


- 6 accelerators:
  - LHC, SPS, LEIR, PS, PSB, ISOLDE
  - **Exportable**: used in GSI
- > 200 HW types
- > 150 M of settings
- ~ 200 client applications
- ~ 1M lines of code

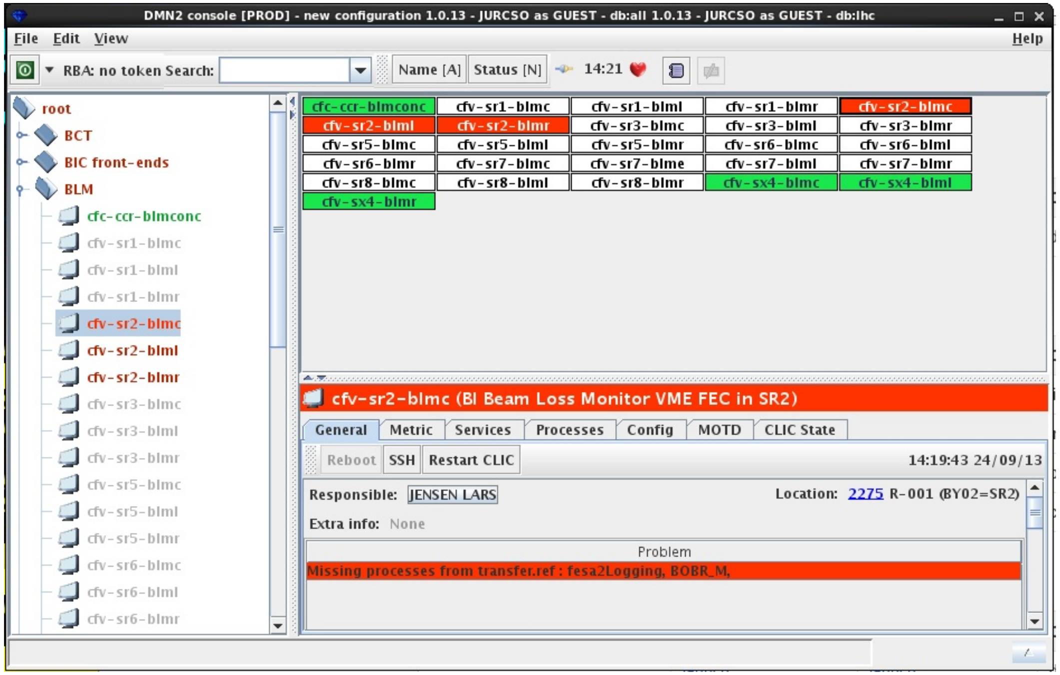
LSA Parameter Hierarchy



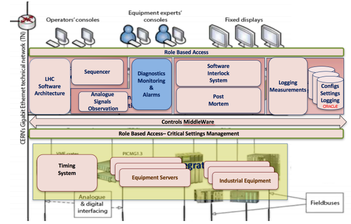
Diagnostic Monitoring



- **Monitors** controls infrastructure
  - Computers (front-ends, servers, consoles)
  - Network
  - Software applications
- Provides **overview** of infrastructure state
- Helps finding the **root cause** of the problem
- Provides **evolution history**
- Allows certain **actions**
  - restart system
  - restart process
- Metrics from >2000 computers
- ~10 M updates / day

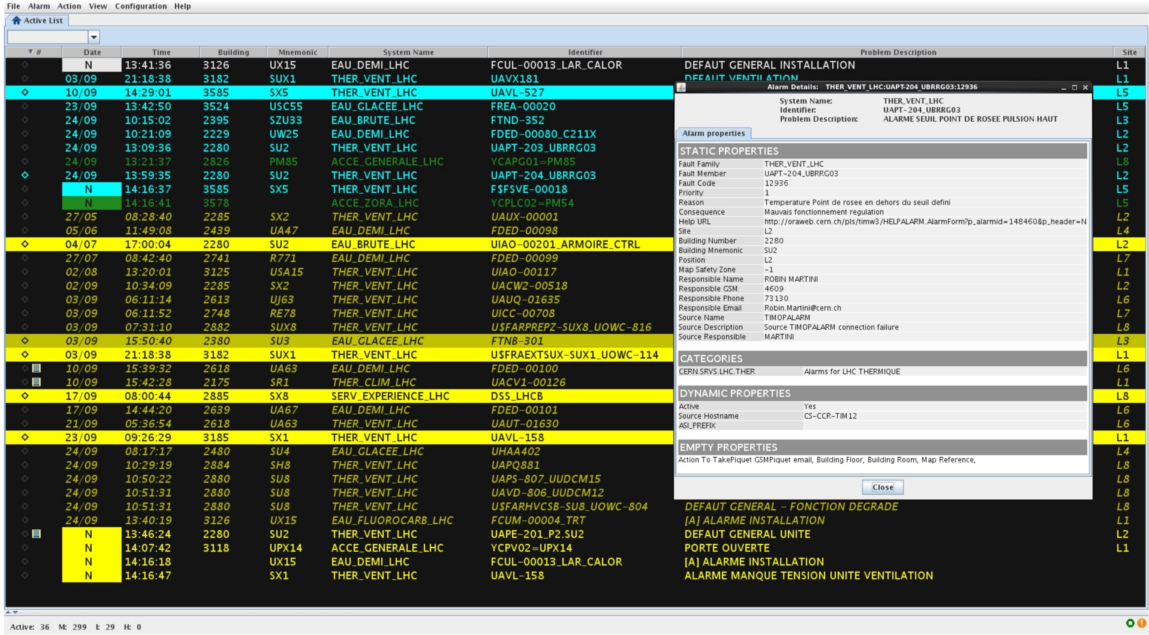


Alarms

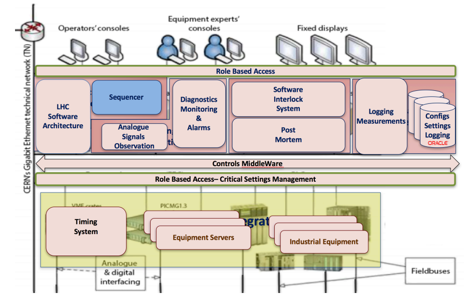


- **Software alarms system**
  - Problem => notification
- Does not deal with human/equipment safety
- Notifies about problems requiring **human intervention**
- **Maps** alarms **to people** and **possible actions**
- **Relevant** alarms only
  - Depends on accelerators
- Alarms **history**
- Alarms **priority**

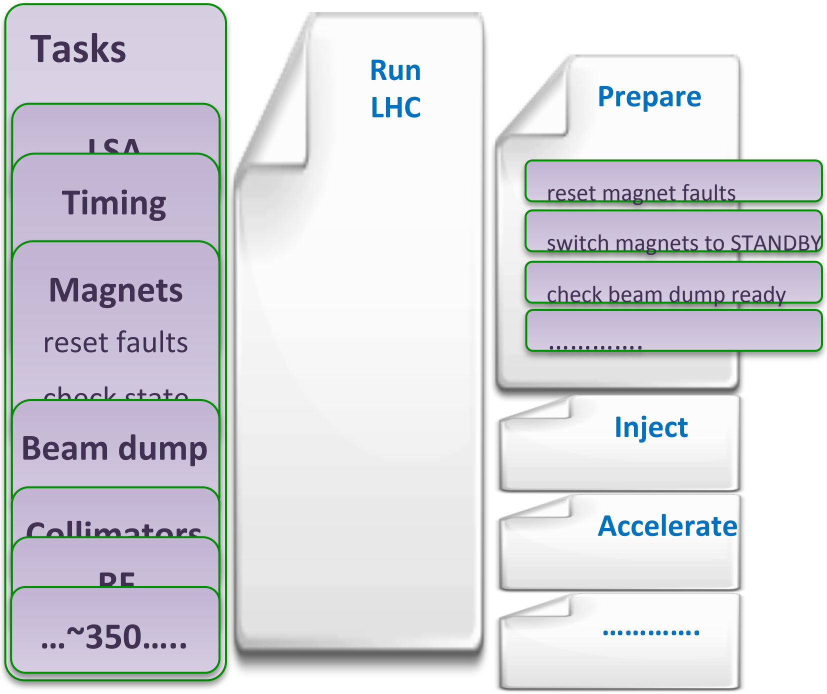
- **~200 K alarm definitions**
  - **80'000 for LHC**
- **~150 alarm events/min**



Sequencer

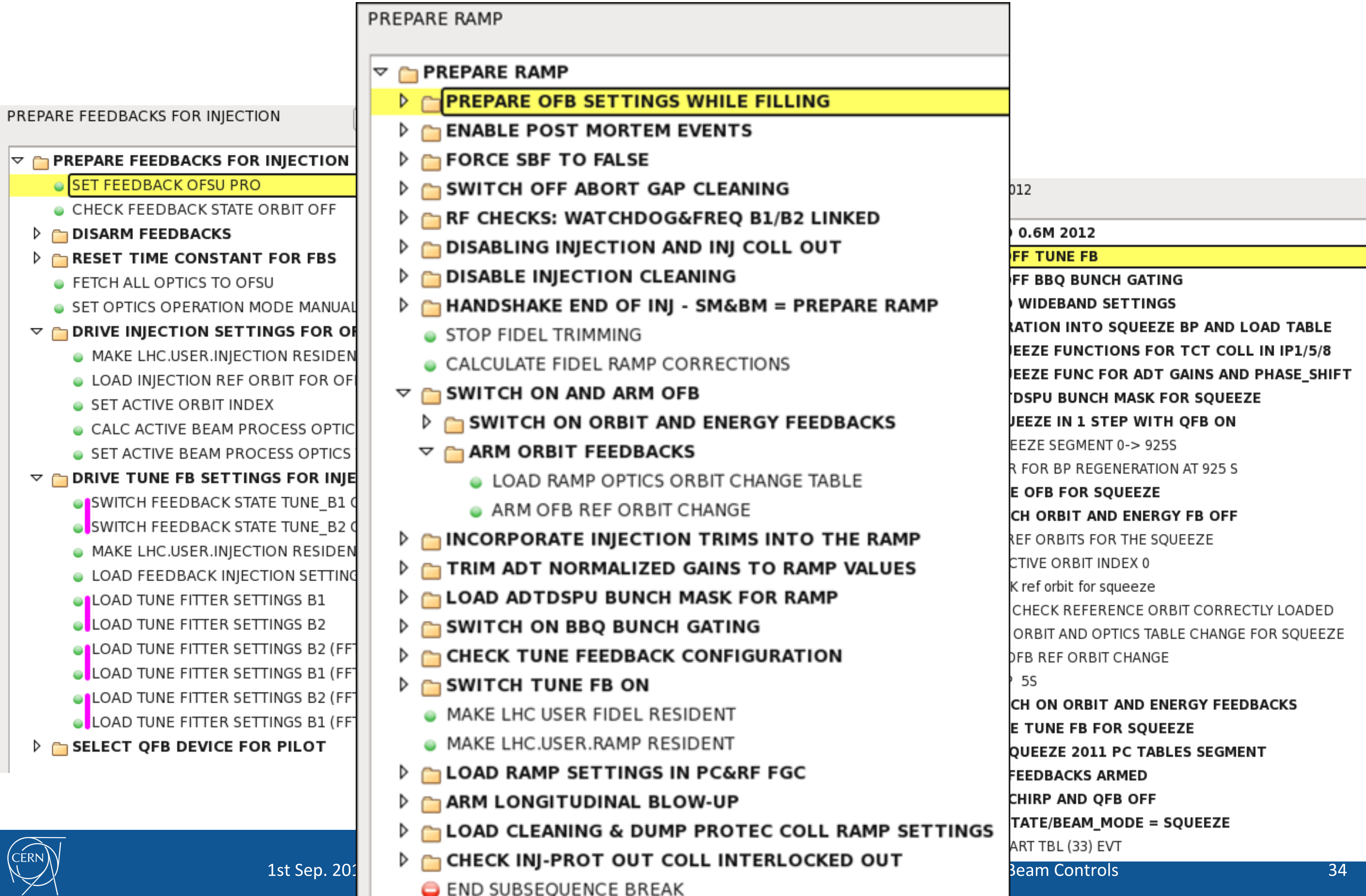


- **Automates** execution of **sequences of tasks**
  - Check the values of devices
  - Ask the control system to load the settings
  - Wait for the equipment to be ready
- **Operators** memory
- **Reliable** execution and error reporting
- **Safe** mode
  - run-through automatically
  - run until task
  - step task-by-task
- **Expert** mode
  - skip task
  - jump to task
- Parallel task execution
- Sequence editing

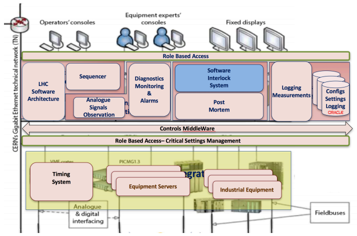


- ~ 1250 sequences for LHC Beam Operation
- ~ 350 tasks types
- LHC main sequence: ~1100 tasks in total

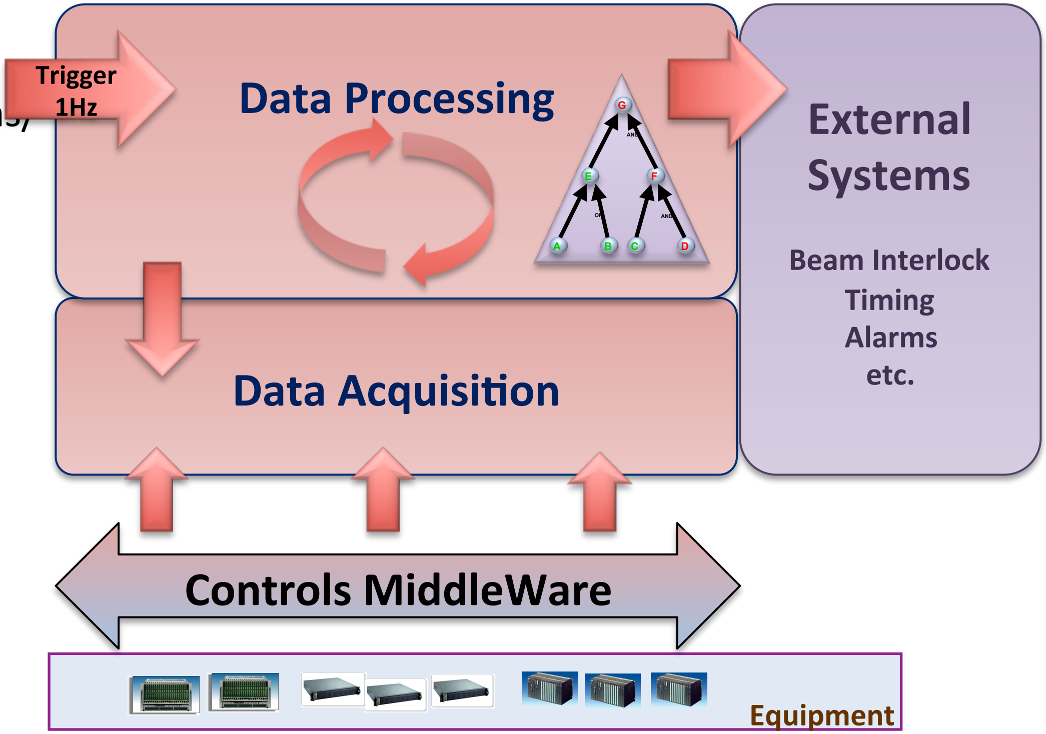
Sequencer Implementation



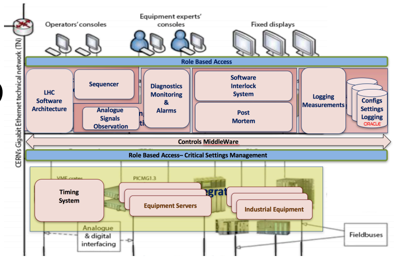
Software Interlock System



- Part of overall **Machine Protection**
- **Surveys** the state of key LHC components using **complex** condition **logic**
- Provides the operations with condition calculation **diagnostics**
- Extendable - add/modify/remove conditions/reactions
- **Deterministic** and highly **reliable** system
- **Acts** if necessary
  - abnormal situation ⇒ beam dump
- Deployed practically for all accelerators
- LHC has
  - ~2700 subscriptions
  - ~5200 elementary values
  - ~800 logical channels
  - 8 permits

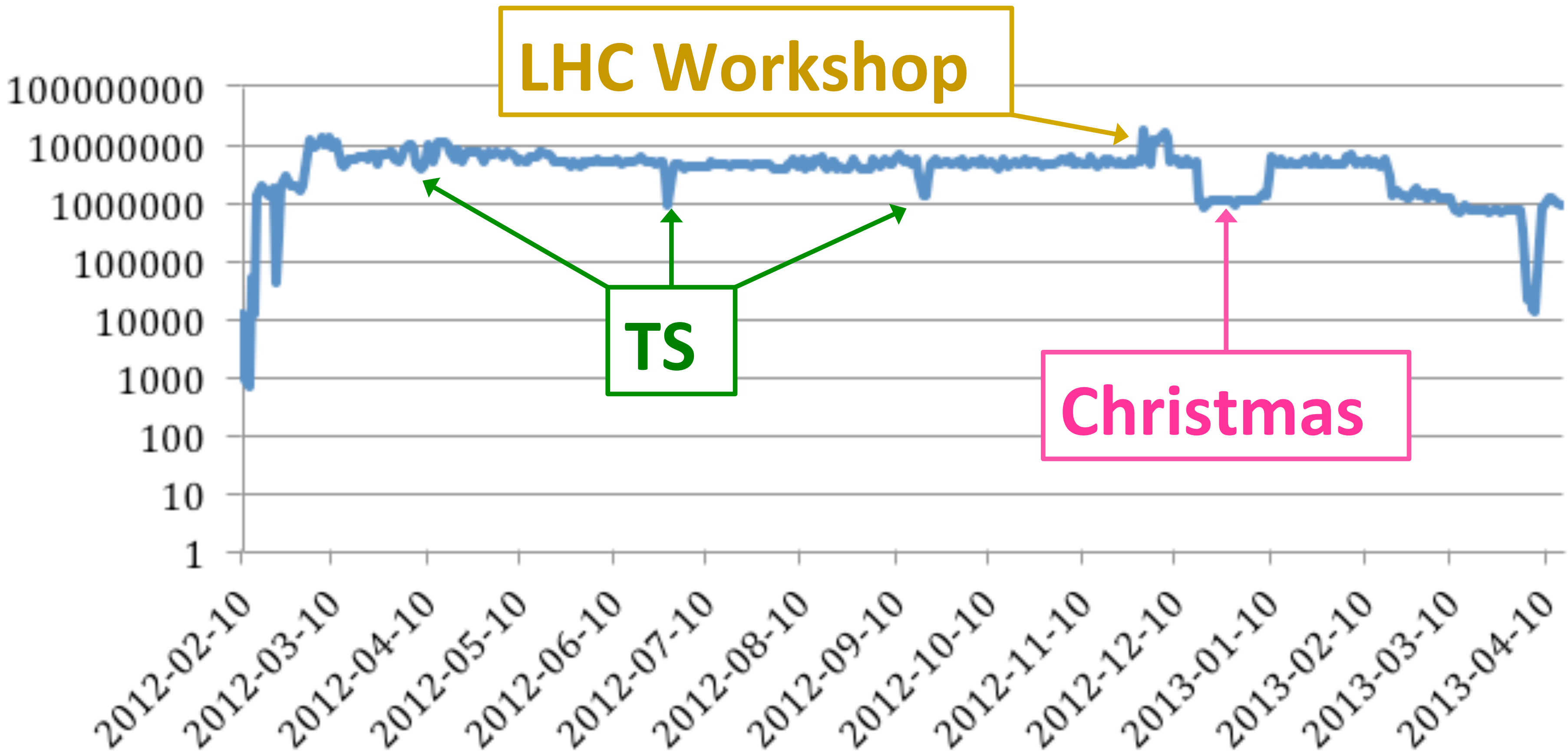


Management of Critical Settings



- **Protects the value**, not the action, ex.
  - BLM, BPM thresholds
  - Collimator thresholds
  - …
- Only experts can modify the value
- All the operators can use this value
- Digitally signed values
- 100 critical value types => 1500 properties

Logging: daily extraction requests



LHC's Figure of MERIT

- Peak luminosity is important

$$LUMINOSITY = \frac{N_{event/\sec}}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi\sigma_x\sigma_y} F$$

- Integrated Luminosity, hence machine/beam availability is key

$$L = \int L dt$$

LHC Future Timing System

- Move to WhiteRabbit technology
  - Time-based timing system
  - Automatically synchronized “common time”
  - Ethernet-based deterministic solution for ~0.5 ns accuracy and < 10 ps precision reliable data delivery among a few thousand nodes over large distances (tens of kilometers)
  - Reliable: redundant both for topology and data
  - Initiated and developed in the Controls group
  - Open Source Hardware and Software

White Rabbit CERN Users

- ATLAS
  - Synchronisation of seismic measurements (M.Guinchard, Nov-Dec. 2015)
- General Machine Timing system upgrade in the Antiproton Decelerator and the ELENA ring
- Beam Instrumentation
  - Time-stamp events based on a reference clock that will be received by WR
- Btrain over White Rabbit on CERN CO wikis (CERN access only)
  - Magnetic field measurement and distribution of the data in real-time
- LHC Instabilities Trigger Distribution
  - Instability diagnostics
- ProtoDUNE - CERN Prototype of DUNE
  - SM-18: Magnetic field measurement and distribution of the data in real-time
- SPS RF distribution over White Rabbit
- **CNGS** Timing for neutrino measurements (2012-2014)

White Rabbit Non CERN Committed Users

- **Arkus, Japan**
- **Cherenkov Telescope Array**
- **China Spallation Neutron Source Institute of High Energy Physics Chinese Academy of Sciences - CSNS**, Beijing, China
- **CHIRON-IT**, The Netherlands
- **Culham Centre for Fusion Energy**
- **DESY**, Germany
- **DLR** (German Aerospace Center, Institute for Technical Physics)
- **EISCAT**, Sweden
- **EPFL, ESPLAB** Switzerland
- **GSI,** FAIR facility
- **ESS Bilbao**, Spain
- **JINR** (Russia)
- **Fermilab**, USA
- **Paris Observatory**
- **MIKES** (Centre for metrology and accreditation, Finland)
- **LHAASO** (**Tsinghua University, China**)
- ....