SAMbuCa: Sensors Acquisition and Motion Control framework at CERN

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Paper TH2BCO04

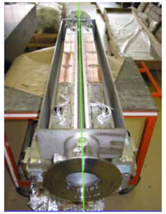
The background: Beam Intercepting Devices (BIDs) Mechatronics

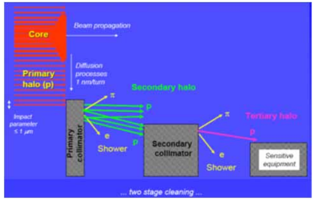
The key challenges:

- High linear or angular positioning precision (1 ppm)
- Highly radioactive environment (TID 30 MGy)
- Long cables (up to 1 Km) vs Industrial solutions working up to 30 m cable length
- Distributed axes to be synchronized within few hundred us

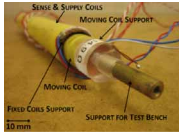
The main achievements over the last 15 years:

LHC Collimators mechatronics: crucial to protect the LHC !



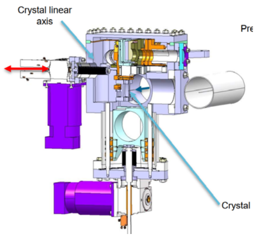


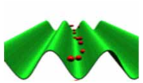
- *More than 200 Collimators jaws (i.e. 400 stepping motor axes) positioned at 20 µm precision over 40 mm range and synchronized at us level !*



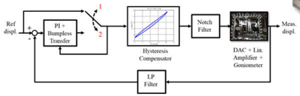
- *New rad-hard stepping motors, innovative position sensors, novel reading and driving solutions*
- *Control system uptime > 99.9% !*

LHC Piezo goniometers: crucial for ion beams cleaning !



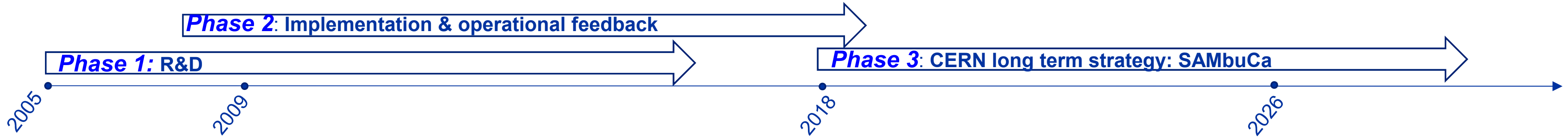


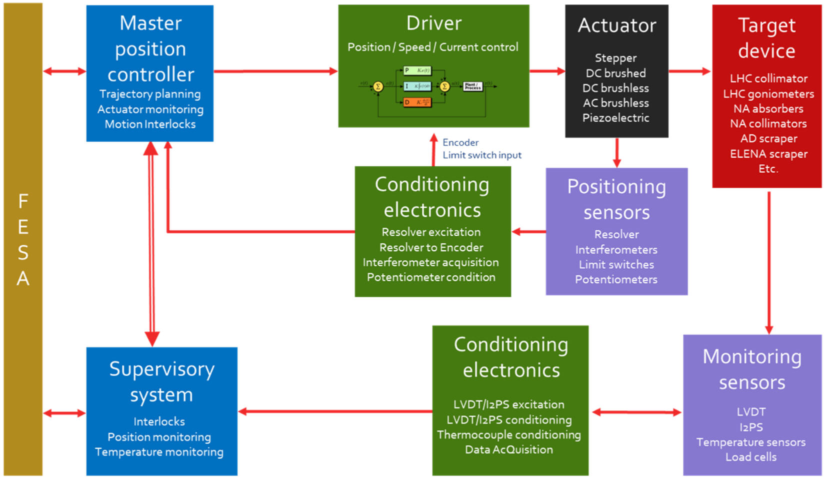
- *1 µrad precision over 20 mrad*



- *Piezo technology in the LHC vacuum !*

The novel CERN Motion Control Framework

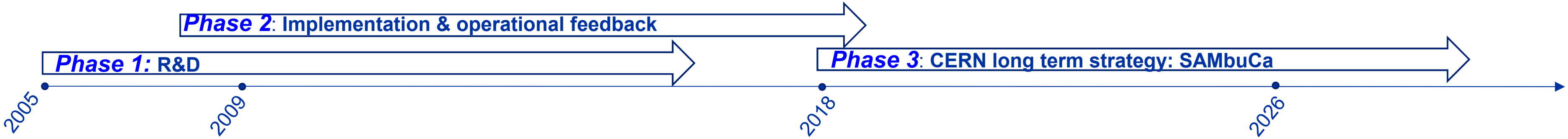


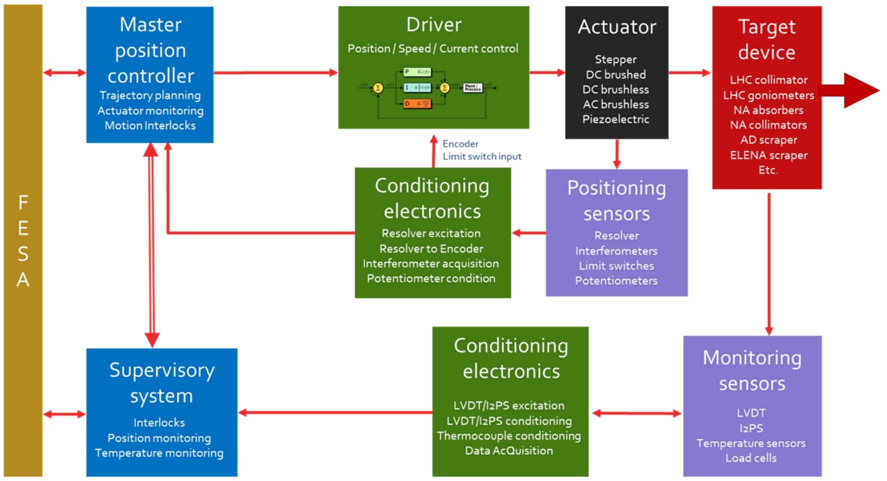


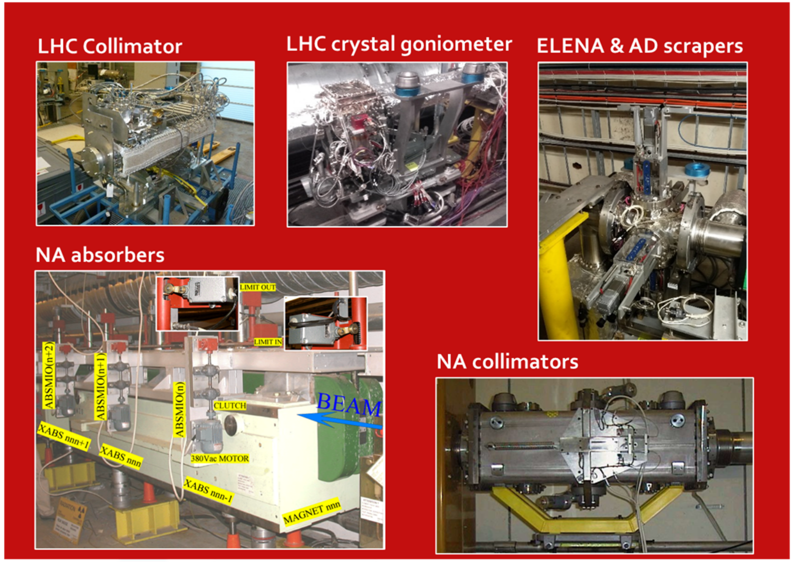
SAMbuCa: Sensors Acquisition & Motion Control

- **Flexible** and **modular hw** and **sw framework** to cope with any BIDs mechatronics application at CERN:
  - **Simplifying the design**
  - **Optimizing development & maintenance cost**
- Standardises R&D achievements and 15 years return of experience
- In 2028 SAMbuCa will control more than 1200 axes:
  - LHC Collimation Low Level Controls consolidation
  - HL-LHC Full Remote Alignment System (FRAS) Controls

The novel CERN Motion Control Framework







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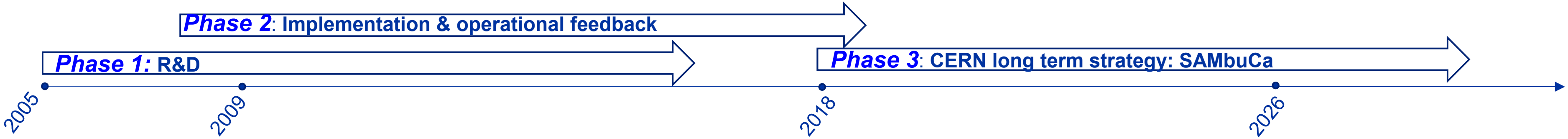

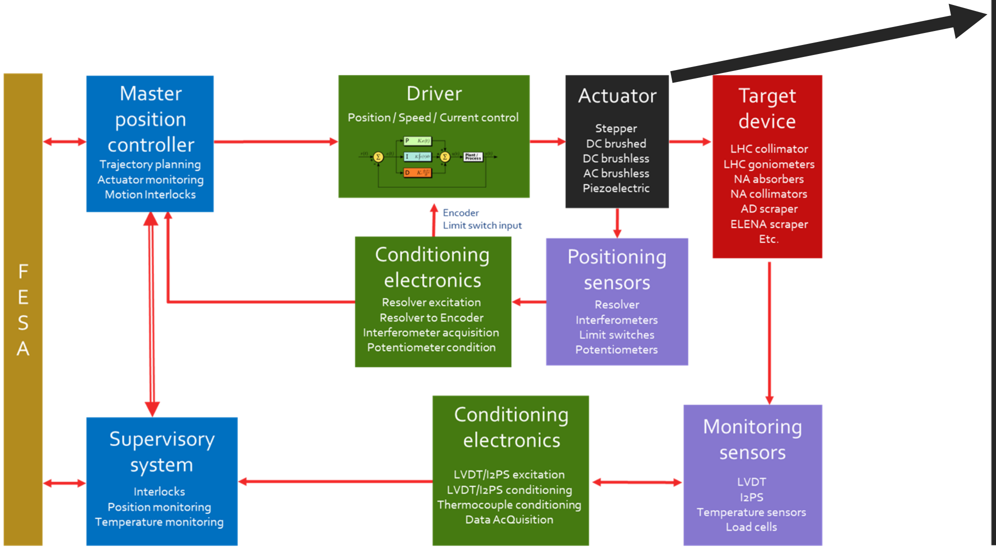

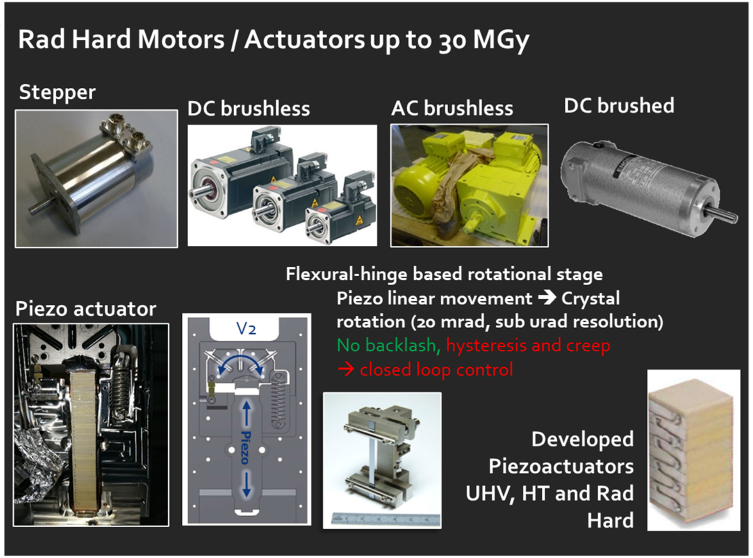

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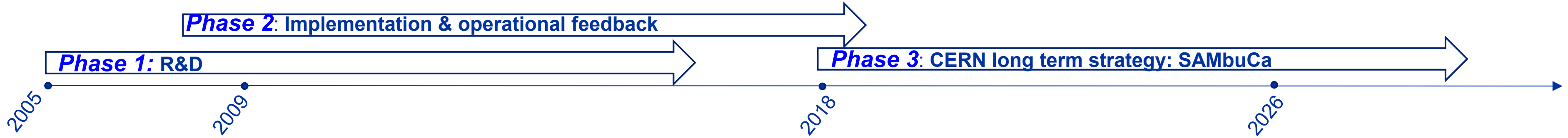

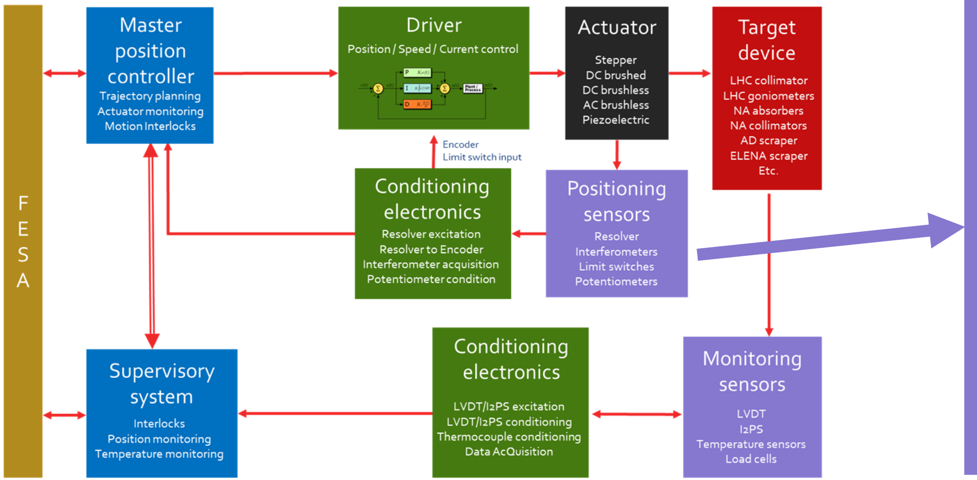

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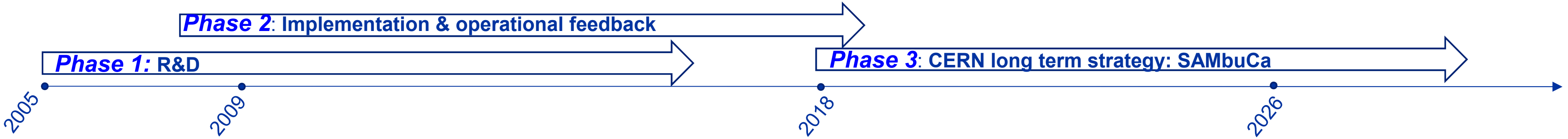
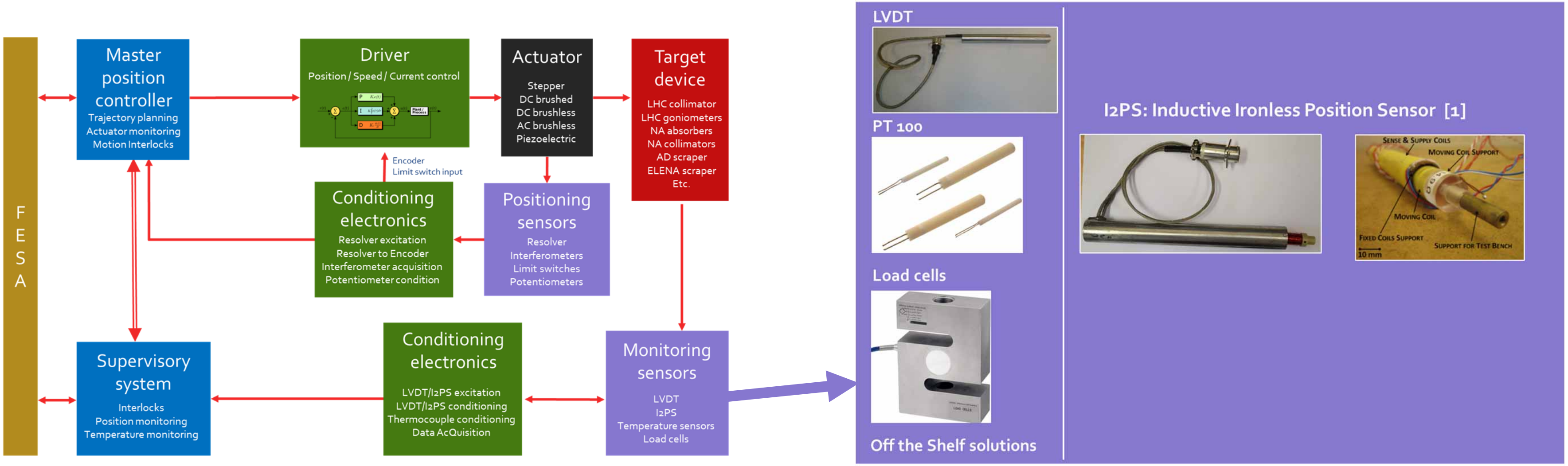
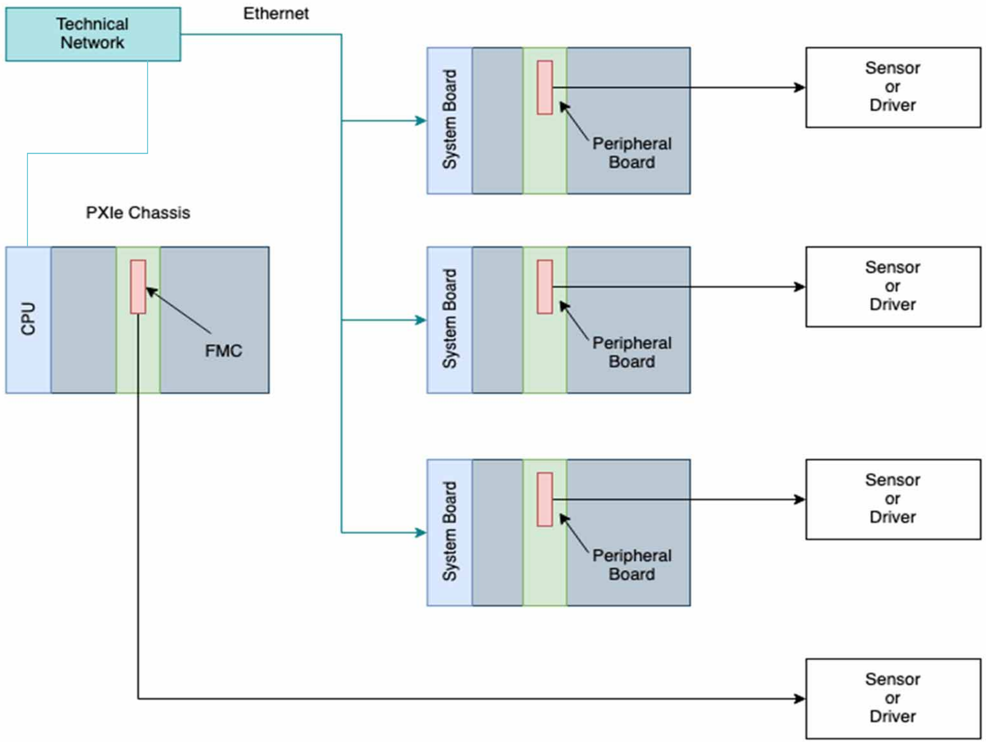




SAMbuCa: The Hardware Architecture



- **Based on PXIe standard**
- **Modularity:**
  - **PXIe carrier** equipped with a large SoC for data processing and RT control
  - **FMC cards** to interface with the instrumentation (LVDT, resolvers, IOs, strain gauges, interferometer reading, motor drivers, etc.)
- **Expandability** ensured by expansion chassis
- **Improved field connectivity:** robust external connectors such as Lemo or military grade micro SUBD used on the FMC cards
- **White Rabbit (WR) synchronization**
  - PXIe timing card synchronises at ns level each PXIe chassis (i.e. clock and start trigger)
  - WR input available also on each PXIe carrier for deterministic data exchange

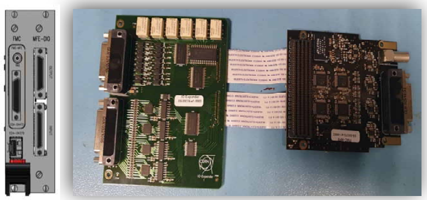
- **Hw building blocks available in Open HardWaRe Repository (OHWR)**

The Hardware Building Blocks

- **PXIe High Availability Chassis**
  - Based on the NI 1082 backplane
  - Redundant power supplies and fan trays
  - Monitoring card for diagnostics (Ethernet)
  - Redundant DC/DC power converter
  - Remote reset power cycle BNC input

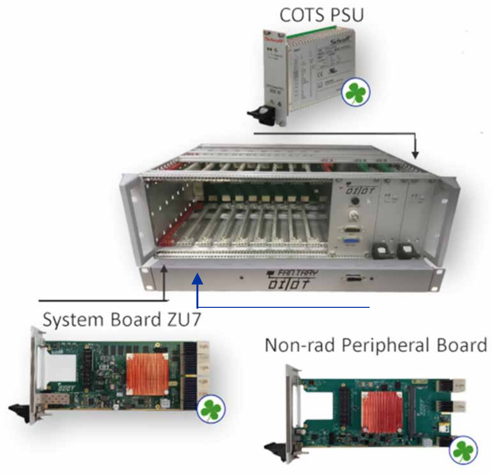
- **COMe/PXIe adapter** developed to host COMe CPU – it will run Debian 12 Linux distribution

- **SPEXI7U PXIe FMC carrier** based on the Xilinx SoC Zynq UltraScale+ MPSoC family
  - 64-bit dual-core Arm® Cortex®-A53 Application Processing Units (APU)
  - Dual-core Arm Cortex-R5F Real Time Processing Units (RTU)
  - Xilinx programmable logic (PL) UltraScale architecture

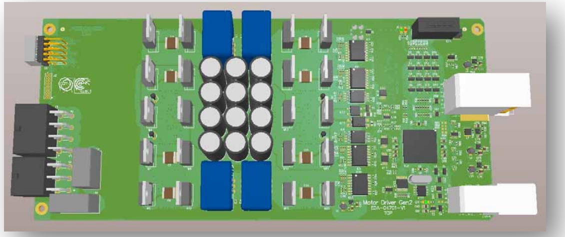


- **FMC Motion Front End (MFE)** provides both analogue and digital interfaces for:
  - Position sensors (i.e. LVDT, resolvers, potentiometers)
  - High speed incremental encoder interface
  - Limit and home switches
  - Analogue and digital I/O fields
  - Motor drivers (STEP/DIR, analogue output)

The Hardware Building Blocks

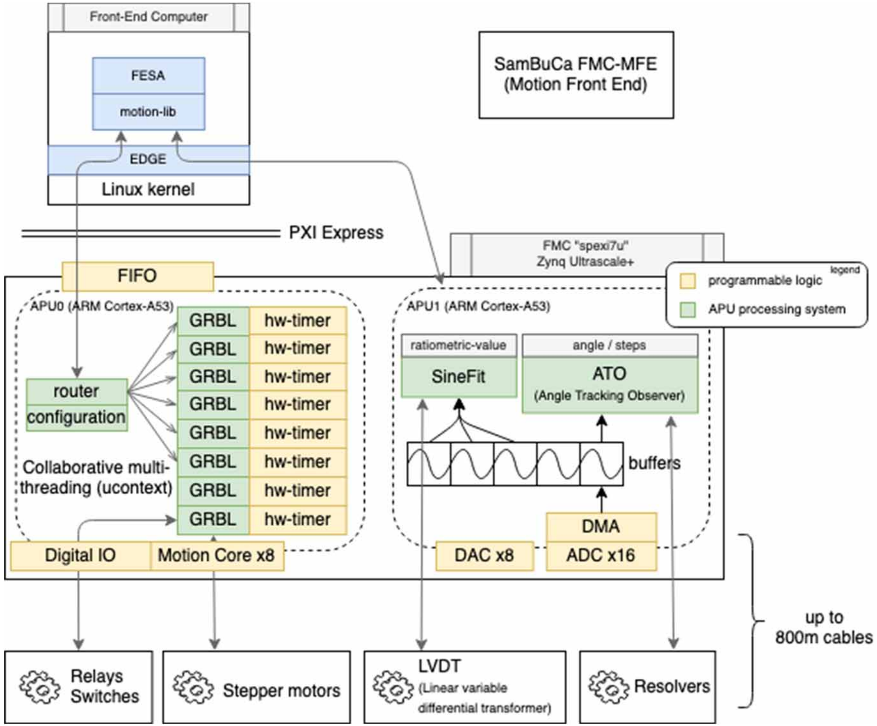


- **CERN DI/OT non rad tol version as expansion Chassis**
  - 8 slot CPCI-S crates
  - Off-the-shelf CPCI-S 300W power supply
  - System Board equipped with a SoC Xilinx Zynq Ultrascale + ZU7, featured with:
    - ✓ White Rabbit node
    - ✓ Ethernet high speed communication mezzanine



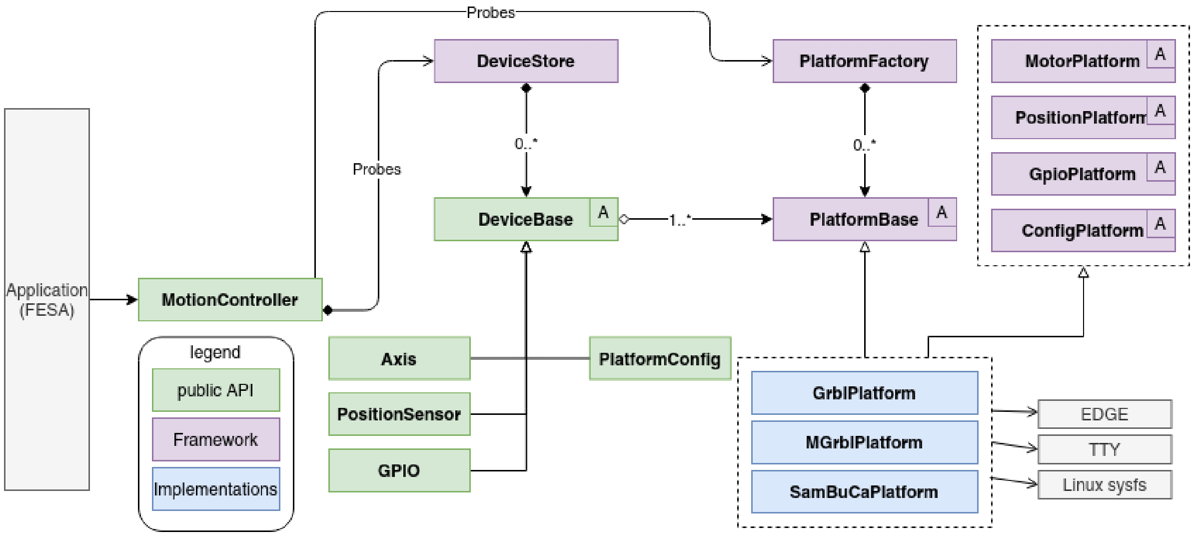
- **Motor Driver:**
  - Accommodates all motor types (brushed and brushless DC, stepper)
  - 8 independent phases up to 130 V and 5 A (continuous)
  - DI/OT format (16 stepping motors driven per chassis)
  - Based on DSC C2000 family from TI
  - Main features:
    - ✓ Ability to compensate cable lengths up to 1 km
    - ✓ Detection of steps lost and torque estimation based on Kalman filters.
    - ✓ Closed loop control for encoder/resolver.
    - ✓ Switching between closed and open loop control running in case of position feedback failure.
    - ✓ Field Oriented Control (FOC)

The Software Architecture



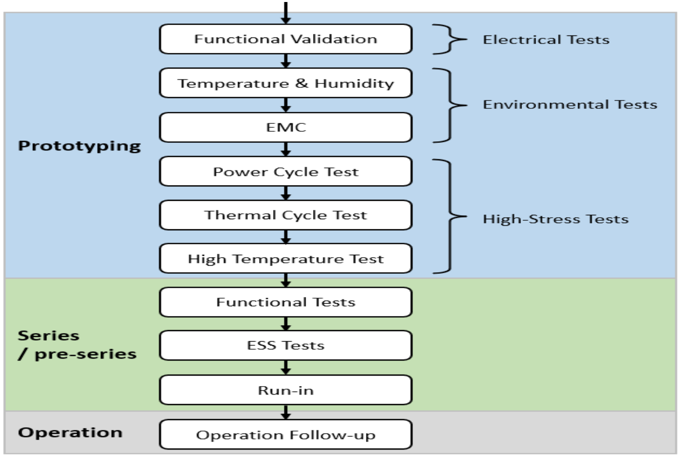
- **CERN FESA based control application**
- **motion-lib** high-level motion library that provides a user-friendly abstraction of all the functionalities of motion control and field sensor acquisition
- **EDGE driver** automatically generated by the SPEXI7U FPGA registers
- **Stepping motion controller:** generate the motion profiles for stepping motor axes, providing advanced features such as a motion-queue, backlash compensation, and homing sequences
  - **On the APU** motion-core based on the GRBL-Hal open-source project with a custom implementation for independent axes control
  - **On the PL** dedicated HW timers
- **Position Sensors readings achieved through** proper algorithms for high precision over long cables:
  - **On the APU** sinefit based algorithm for LVDTs reading, Angle Tracking Observer algorithm for resolvers reading
  - **On the PL** DMA data transfer for ADC and DAC

The Software Architecture: motion-lib



- **Public API:** abstracts devices as Axis for motion control configuration, PositionSensor for the settings and acquisition of the supported position sensors, GPIO for general purpose I/O management
- **Internal set of abstract platforms** define the framework and interface for back-end implementors
- **Platform implementors** depending on the targeted hardware (e.g. SamBuCaPlatform, GrblPlatform)

SAMbuCa testing methodology



➢ Prototypes testing:

- **Functional Validation tests** performed on all the SAMbuCa building blocks as soon as a mature prototype version is ready - RobotFramework an open-source test automation framework is used
- **Reliability tests** temperature and humidity min/max cycles while the system is powered and operating under heavy load
- **High Stress Tests** uncover failure mechanisms and vulnerabilities, ultimately leading to iterative design improvements to enhance system reliability:
  - Power Cycling Tests
  - Temperature Cycling test
  - High-Temperature Test

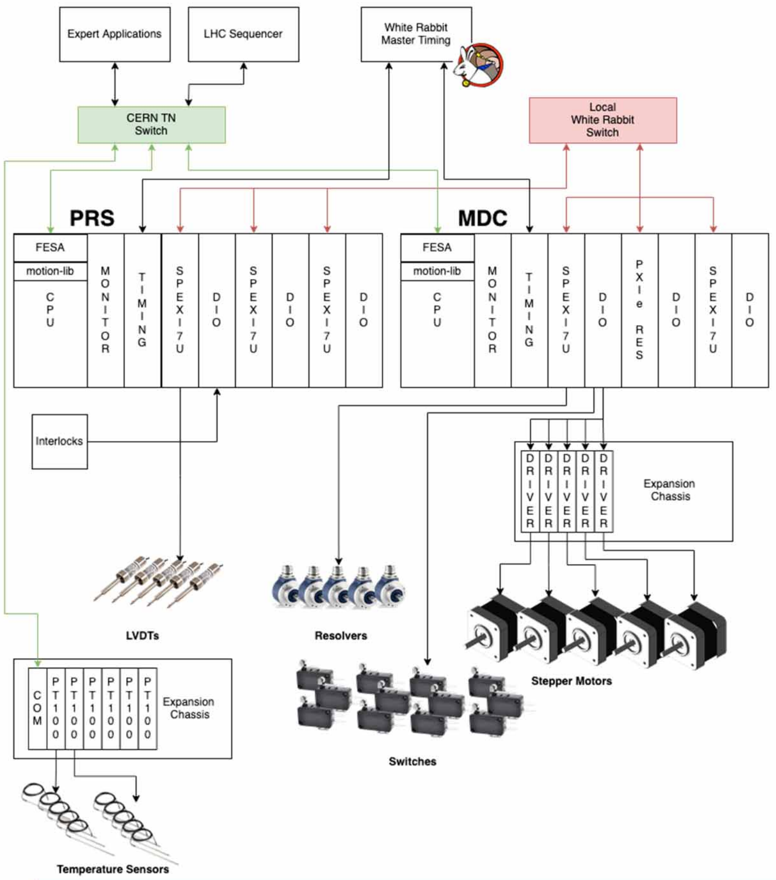
➢ Pre-series and series testing:

- **Functional tests** based on the Production Test Suite (PTS)
- **Environmental Screening Tests:** thermal tests triggering, and discovering premature failures, often related to assembly defects
- **Run-In** to assess the expected MTBF. It is performed after the systems installation

➢ Continuous operational monitoring:

hardware commissioning, preventive and corrective maintenance tools

The use case: LHC Collimators controls consolidation

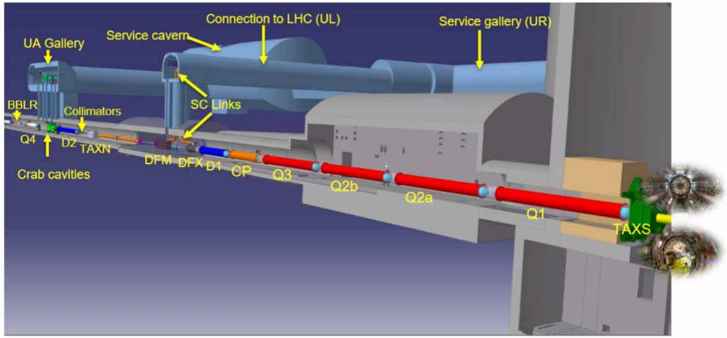


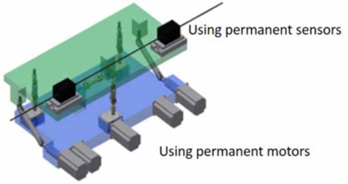
Control system requirements	
Axes positioning accuracy	few µm
Axes motion synchronization	below 1 ms
Cable length	Up to 800 m
Response delay to a digital start trigger	100 µs
Position sensors RT survey frequency	100 Hz
Reliability	Very high
Availability	>98 %

Control system parameters	
Axes to control	555
Positioning sensors to monitor in RT	750
Resolvers to read synchronously with the motors` steps	400
Limit switches to acquire	1200

- **1 system controls up to 3 collimators: 15 axes, 21 LVDTs, 12 Resolvers**
  - **MDC** stepping Motors Drive Control acquiring resolvers for steps lost detection and limit switches
  - **PRS** Position Readout and Survey through LVDT
- **White Rabbit for**
  - axes synchronization
  - precise motion triggering
  - Command exchanges between PRS/MDC
- **Installation size:**
  - 150 MDC/PRS
  - 300 SPEXI7U and FMC MFE
  - 270 motor driver cards and 92 DI/OT Chassis

The use case: FRAS low level control

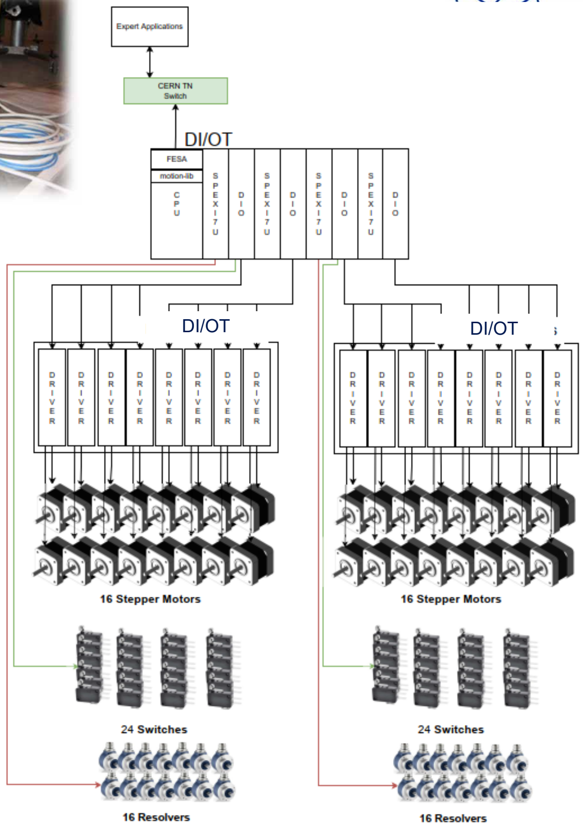




- **The Full Remote Alignment System (FRAS) aims at the remote alignment of the new HL-LHC components in the Interaction Points reducing the number of correctors and saving dose to surveyors**

Control system parameters/requirements	
Axes to control	384 (96 per rack)
Limit switches to acquire	1152
Resolver reading precision	10^-5 degree
Axes` range	2.5 mm
Positioning precision	+/- 1 um
Cable length	300 m

- **The actuators: Special jacks and the Universal Alignment Platform based on stepping motors axes and resolvers**



Conclusions & outlooks

- The new hardware and software Sensors Acquisition and Motion Control (SAMbuCa) framework has been conceived to cover all the critical motion control applications at CERN ensuring:
  - ✓ High reliability
  - ✓ High availability
  - ✓ Precise positioning
  - ✓ Easy development
  - ✓ Optimized long term maintenance
- Most of the hardware building blocks are currently in the functional validation phase
- Series production will start end of 2024
- During the Long Shutdown 3 (2026-2028) two critical LHC mechatronic systems, and not only, will be controlled with SAMbuCa counting more than 1200 axes