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An object-oriented approach to cryogenic control systems for the CERN test facilities: a case study based on the UNICOS framework

Master thesis written under
supervision of Dr. Grzegorz Wróbel

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To my family…

Acknowledgements

Spending five months at the European Organization for Nuclear Research gave me a great opportunity of expanding my skills and my knowledge, as well as the chance to develop my thesis in the best possible conditions. I worked with many persons to whom I would like to thank.

I would like to express my sincere gratitude to my university supervisor Dr. Grzegorz Wróbel for his kindness, understanding and full-time guide I have received whilst writing this thesis.

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Introduction

The work presented in this thesis took place at the European Organization for Nuclear Research (CERN) in the context of the Large Hadron Collider (LHC) project. The LHC is the world's largest and highest-energy particle accelerator, which will be capable of colliding opposing particle beams, giving a total collision energy of 14TeV. To bend and focus the particle beams along their circular trajectories a large variety of magnets are used in the LHC, including dipoles, quadrupoles, sextupoles, octupoles, decapoles etc. which gives about 9600 magnets. The dipoles represent the most important technological challenge. In particle accelerator the maximum energy that can be achieved depends on the strength of the dipole field. Scientists calculated, that to bend the particles traveling at 0.999999991 times the speed of light around the ring, the field of 8.3T is required. To achieve that, LHC uses superconducting niobium-titanium (NbTi) cables, which are capable of conducting the electricity without resistance below a temperature of 10K.

Another important part of the LHC are superconducting Radio Frequency (RF) Cavities. Their main role is to keep 2808 proton bunches tight, to assure high luminosity at collision points. They are also responsible for delivering power to the beam during acceleration to the top energy. The RF specific feature is that, it can store high amounts of energy with small losses. The cavities operate at temperature of 4.5K.

I spent five months at CERN, working and learning at Technology Department in the Cryogenics Group. I was assigned to Controls and Electrical Support section, which was responsible for the support and maintenance of the controls for cryogenic systems and test areas. To its tasks belonged the electrical support for cryogenic equipment and infrastructure, interface and database management of controls, as well as the upgrades of cryogenic control systems. Goal of the team I was part of was to modify and extend the capabilities of the largest test facility at CERN. The improvement included the migration from the old control system to a new one, based on the UNified Industrial COntrol System (UNICOS) framework developed at CERN. What is more, in our responsibility was also to prepare controls for the Block4 experiments (four cryostats for testing cables/magnets — in cryogenic temperatures — used in the LHC) previously hosted in another test facility.

Before installing parts of the LHC which are described above, they are tested in the SM18 test facility which was specially built for this purpose. This thesis deals with the modifications of that test hall, as an example of prepared cryogenic control system it focuses on the Radio Frequency Cavities test station.

This paper consists of two parts, the first of which is more general and presents the reason of particle collision research, the LHC accelerator and its main detectors (Chapter 1). It also provides information about the test stations in SM18, the cryogenic architecture of the hall and the significant properties of the liquid helium, which make him perfect coolant for the superconducting devices (Chapter 2). The second part of this thesis presents the revamping of the SM18 test facility. It describes the previous functional view and changes that were done. The new layout of the Radio Frequency Cavities rack and communication is also presented (Chapter 3). Chapter 4 gives the information about the software frameworks, code generation for the PLC and the synoptic production.

Chapter 1

The Large Hadron Collider

This chapter presents genesis of CERN, its main mission and achievements. It also provides information about last particle accelerator, its structure and main goal of its existence.

1.1 Origin of the CERN

History of CERN starts in 1949 at the European Cultural Conference in Lausanne, when the French physicist and Nobel Prize winner Louis de Broglie proposed creation of a European Science Laboratory. After three years and two UNESCO conferences held in that matter, eleven European governments signed agreement which set up a provisional Conseil Européen pour la Recherche Nucléaire. A site near Geneva was selected as a location of a new laboratory. Eventually on 29th of September 1954, due to ratifications of the arrangement establishing CERN, a European Organization for Nuclear Research was formally created. Convention laid down the main missions for the Organization:

> *"The Organization shall provide for collaboration among European States in nuclear research of a pure scientific and fundamental character (...). The Organization shall have no concern with work for military requirements and the results of its experimental and theoretical work shall be published or otherwise made generally available."*

Thanks to experiments held at CERN, many significant achievements in particle physics have been made. The Nobel Prize in Physics in 1976 went to the Large Electron–Positron Collider experiment L3 spokesman Sam Ting and Burt Richter for *"their pioneering work in the discovery of a heavy elementary particle of a new kind"*. In 1984 Carlo Rubbia and Simon Van der Meer received the Nobel Prize in Physics for *"their decisive contributions to the large project which led to the discovery of the field particles W and Z, communicators of the weak interaction"*. The main purpose of the project was to collide protons and antiprotons in existing Super Proton Synchrotron. Results of the experiment confirmed the unification of weak and electromagnetic forces, the electroweak theory of the Standard Model. A CERN physicist Jack Steinberger together with Leon Lederman and Mel Schwartz won in 1988 the Nobel Prize in Physics for *"the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino"*. The discovery showed, that there was more than one type of neutrino. In 1992 Georges Charpak was awarded the Nobel Prize in Physics for *"his invention and development of particle detectors, in particular the multiwire proportional chamber, a breakthrough in the technique for exploring the innermost parts of matter"*. Results of his work started new era of electronic particle detection [1].

Nowadays the European Organization for Nuclear Research consists of twenty European Member States and it is one of the world's most prestigious research center. Work at the laboratory went much deeper than the nucleus, into high-energy physics (study of interactions between particles), that is why CERN sometimes is referred to as the European Laboratory for Particle Physics.

1.2 Purpose of building particle accelerator

Everything began 13.7 billion years ago when the huge explosion, referred as "The Big Bang" occurred. The Universe was remarkably hot and dense, but it needed only a few moments to rapidly expand and cool down. These conditions were adequate to give rise to the quarks and electrons, which a millionths second later produced protons and neutrons. After three minutes the first nuclei was formed, but it took 380 000 years to put it together with electrons and create the first atom.

At present, our knowledge about the Universe is incomplete. Over the years, the theories and discoveries of physicists have resulted in defining a Standard Model of particle physics, which summarizes understanding of relation between twelve basic building blocks and three fundamental forces. It has been tested in a host of experiments and it has predicted the existence of previously undiscovered particles. Unfortunately, the Standard Model is not a complete theory of fundamental interactions. It contains information about three out of four fundamental forces, it does not provide unified description of gravity. It also does not explain the origin of mass and why some of the particles are heavier than others. The answer to the last question may be the Higgs mechanism. The theory says, that the whole of space is filled with Higgs field and particles obtain their masses by interacting with it. The more they interact, the heavier they are. It also predicts new particle associated with the field, the Higgs boson [2, 3].

Between 1970s and 1980s cosmological and astrophysical observations have shown, that only 4% of Universe is made of visible matter. The rest consist of invisible substances called dark matter (26%) and dark energy (70%). Because they do not emit electromagnetic radiation, the only way to detect them, is through their gravitational effects. Today, we still don not know what dark matter is made of and what role together with dark energy it played in the evolution of the Universe.

Every kind of particle has a corresponding antiparticle, which magnitude of electric charge is the same, but it has opposite sign. It is believed, that matter and antimatter have been created in the same amounts at the time of the Big Bang, however the results of our observations show, that the Universe is made only of matter. Why there is such disproportion is still a mystery. Proton-proton and heavy ion collisions at LHC will also give information about the state of matter called quark-gluon plasma, which would have existed in the early state of Universe [4].

If we want to answer all these questions and inquire why the Universe is expanding, we need to go to the beginning of its existence. To recreate the conditions after the Big Bang, physicists use particle accelerators to collide two beams at very high energy. Nowadays, the world's largest and highest-energy particle accelerator is Large Hadron Collider. Scientists hope, that thanks to experiments in LHC we will be able to form missing theorems.

1.3 The LHC overview

The Large Hadron Collider is the largest and highest-energy particle accelerator in the world. It straddles the Swiss and French borders and it is located in the tunnel buried around 50 to 175m underground. It consists of 27km ring of superconducting magnets, together with a structures increasing the energy of the particles along the way.

The LHC is not a perfect circle, it consists of eight arcs and the same number of long straight sections (LSS). In each arc, there are 154 dipole magnets which are the most complex parts of the accelerator. Thanks to their superconductivity, they are able to carry very high currents and produce extremely strong magnetic fields in order to bend the trajectory of the particles, without any loss of energy. To reach that state, magnets have to be cooled to 1.9K. Each LSS is approximately 528m long and it is used as an experimental or utility insertion. At point 1 and point 5 are located high luminosity experimental insertions, ATLAS and CMS. Another two are at point 2 (ALICE) and point 8 (LHCb), which are at the same time the injection systems for beam 1 and beam 2. Only in these four locations beams crosses. The straight section at point 3 and at point 7 contain two collimation systems. Two identical 400MHz accelerating systems (one for each LHC beam) are located in insertion number 4. Long straight section 6 contains independent abort system for each beam. It uses combination of horizontally deflecting magnets and vertically deflecting double steel septum magnets [5].

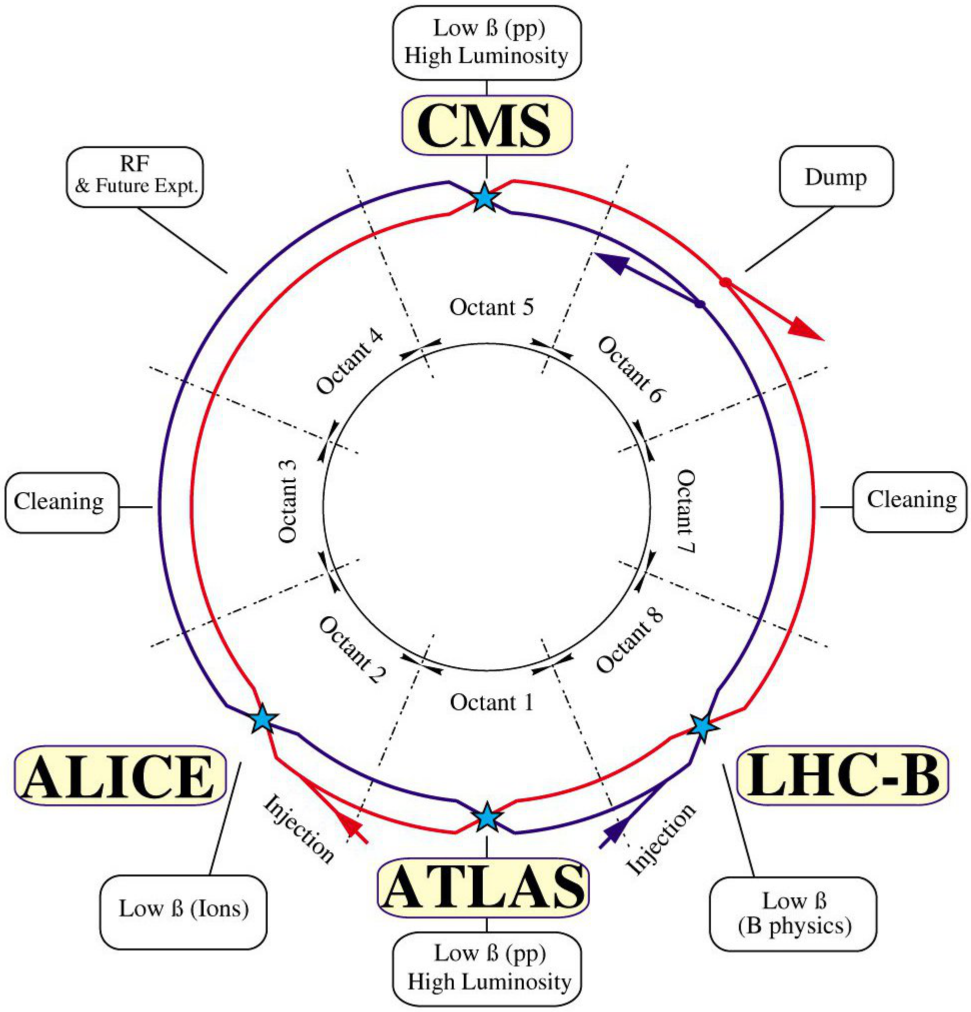


Figure 1.1: Basic layout of Large Hadron Collider.

Inside the LHC, two beams of subatomic particles — protons or lead ions — travel in opposite directions in two tubes at 0.999999991 times the speed of light before colliding with one another. CERN possesses complex of machines, each with greater energy. LHC is the last one, particles are provided to it using six other accelerators:

- the 90keV duoplasmatron source,
- the 750keV RFQ,
- the 50MeV Linac 2,
- the 1.4GeV synchrotron injector (PS Booster),
- the 25GeV Proton Synchrotron (PS),
- the 450GeV Super-Proton-Synchrotron (SPS).

Every machine increases the energy of particle beam and injects it into the next higher energy accelerator. At first, hydrogen atoms are stripped of their electrons and then, after accelerating them to 50MeV by Linac 2 the particles are injected into the PS Booster. When the beam obtain the energy of 1.4GeV it is transferred to Proton Synchrotron (PS), where the energy goes up to 25GeV. Last accelerator before LHC is Super Proton Synchrotron (SPS), the particle beam stays there as long as it hits the threshold of 450GeV [4].

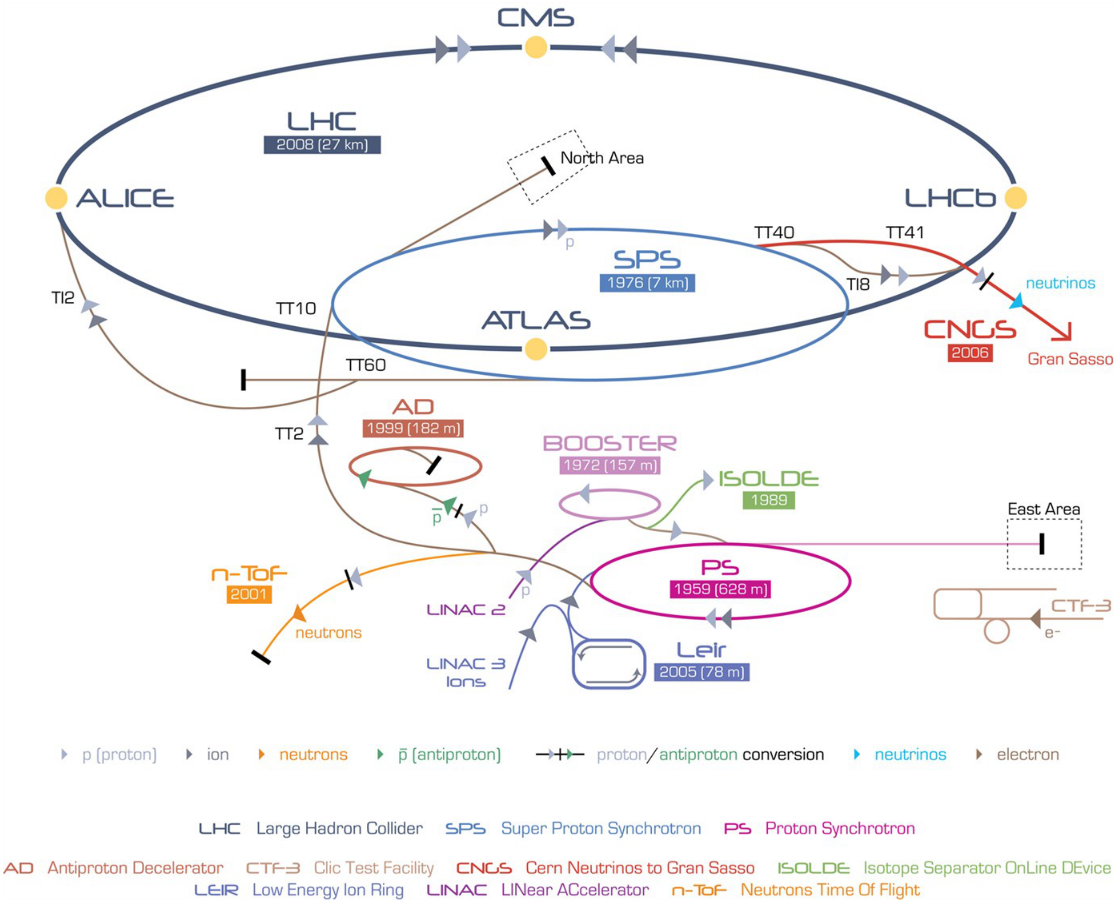


Figure 1.2: The CERN accelerator complex.

Eventually, the LHC will be capable of rotating each beam (clockwise and anticlockwise) with energy of 7TeV, which gives a collisions at highest achievable energy of 14TeV.

1.4 Accelerator superconducting Radio Frequency Cavities

The injected particle beam is captured and accelerated by 400MHz superconducting cavity system. The cavities contain electric field, that pushes the proton beams to higher speeds. Each cavity is capable of delivering 2MV, which gives an accelerating field of 5MV/m. To do so, the accelerating system has to provide at least 16MV, while at injection about 8MV is needed. Every cavity is controlled by individual RF system with klystron, circulator and load. Complex feedback loops around each cavity assure accurate control of the field, important for the proton beam. Usage of one klystron per cavity avoids problems of coupling between cavities and instability in the system, when one klystron supplies more than one cavity. Maximum of RF power is generated by sixteen 300kW 400MHz klystrons, which gives the full energy of 4800kW. Every klystron feeds a single-cell superconducting cavity through a Y-junction circulator and a waveguide line. The average waveguide length is about 22m [6].

The LHC uses eight cavities (length of each is $\lambda/2$), which are arranged in fours in cryomodules, with two cryomodules per beam. A cell to cell distance is 1122mm which is $3\lambda/2$ at 400MHz. Every module operates at temperature of 4.5K and is installed in the LSS of the machine, where the distance between the beams is increased from 195mm to 420mm. All the cavities are identical and if any problem occurs to one of them, it can be easily replaced.The cavities inside the cryomodule are connected with each other by large diameter beam tubes. The technology used for manufacturing the cavities is similar to that one used for LEP accelerator — niobium film on copper. They are produced by spinning and electron-beam welding. The cavities are covered with a thin — from $1\mu m$ to $2\mu m$ — film of niobium by magnetron sputtering. Such solution reduces very much the susceptibility to quenching. Local overheating caused for instance by defects or impurities is quickly conducted away by the copper. The tests displayed, that produced cavities are capable of reaching twice nominal accelerating field without quenching. The niobium sputtered cavities are not sensitive to the Earth's magnetic field and there is no need for installing special magnetic shielding as it is necessary for solid niobium cavities. The thickness of the cavities wall is a result of compromise between tuning force and mechanical stability. With thickness of 2.8mm to 3mm, the cavity axial spring constant is about 20kN/mm [7].

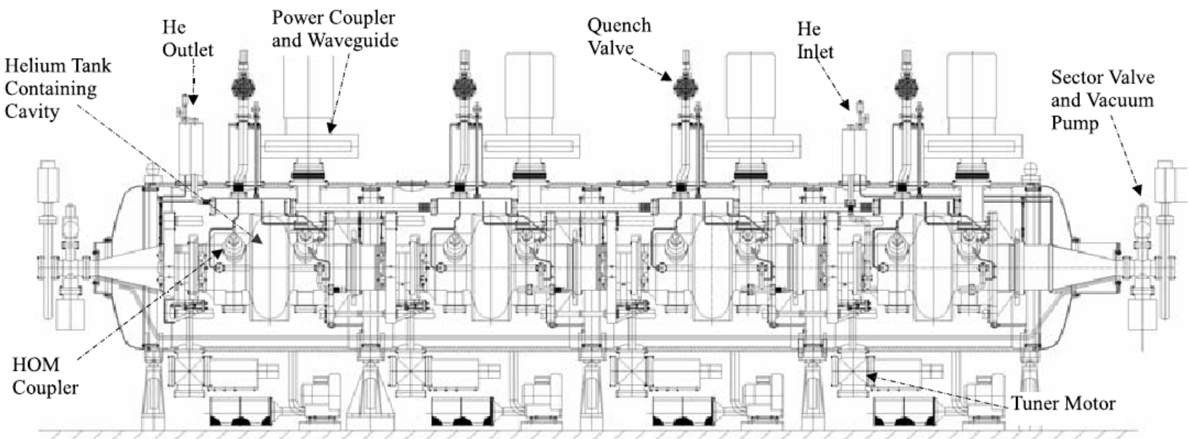


Figure 1.3: Model of cryomodule with four cavities inside.

Every cryomodule has a liquid helium inlet and outlet for the evaporated helium caused by static and dynamic losses. The level of the coolant in regulated by the input valve

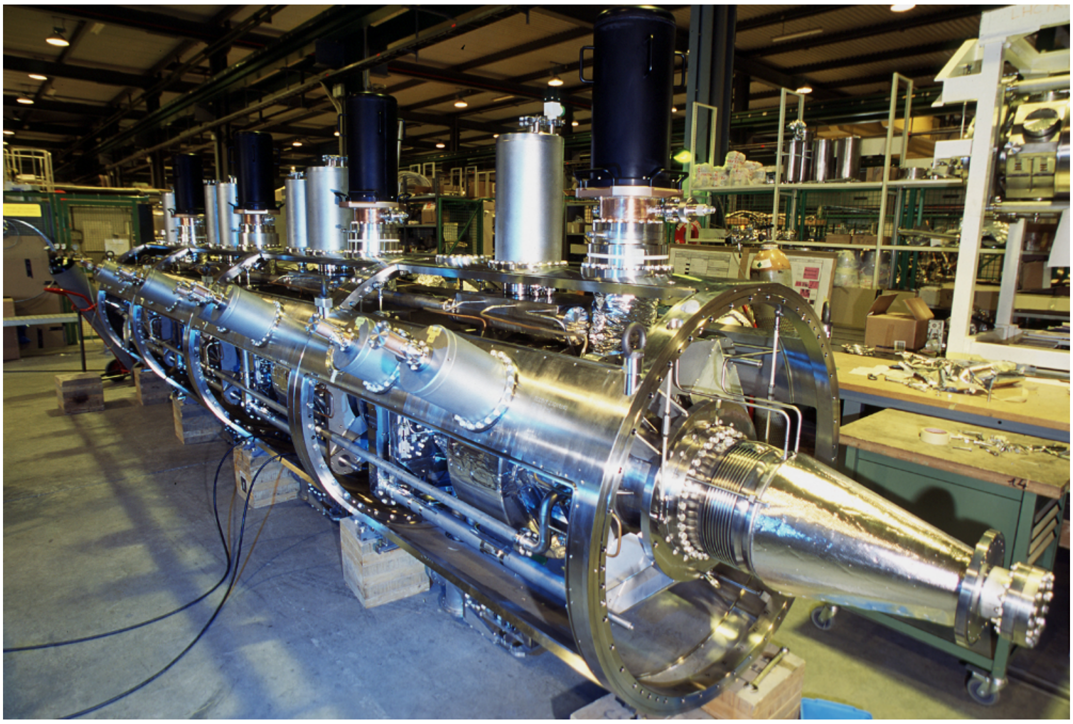


Figure 1.4: Cryomodule with four cavities inside.

using feedback from the superconducting wire level sensor. The losses at the nominal field of the RF are 100W and when the field is twice the nominal, the losses rise up to 800W per module. When we add 150W of static losses we get 250W and 950W respectively. The control of the pressure inside the helium tank has to be precise to avoid frequency variations of the cavity. The cavity sensitivity is significant and equals 150Hz/mbar. The maximum allowed variation around the nominal value of 1350mbar is $\pm 15 mbar$.

The superconducting RF cavities possess three different and independent types of vacuum systems: for the cavity, for the beam and the cryostat. Two 60l/s ion pumps mounted at the ends of the RF modules pump cavities at room temperature. At 4.5K, an additional pumping speed of more than 300000l/s comes from the cryogenic pumping of the cavity walls. The background pressure is less then $10^{-12} mbar$. Control signals for vacuum come from Pirani and Penning gauges mounted on the pumping ports. It is possible to isolate the vacuum inside the cavity by two metal valves at the ends of each module. The chamber are made of the stainless steel, which is coated by electro-deposition with a copper film of 1mm of thickness. The vacuum for insulation is not so demanding and the modules are pumped to $10^{-3} mbar$ before being cooled down. It also benefits from the cryogenic pumping and the operating pressure decreases to $10^{-7} mbar$ [6].

1.5 Experiments associated with the LHC

In order to record the results of millions of proton collisions, gigantic detectors were built. They not only register the results, but also are capable of visualizing the explosions of particles. Their intricate trigger system measures the passage time of a particle to billionths of a second and it is capable of locating them to millionths of a meter. This unbelievably quick and precise response is relevant for ensuring, that the particle recorded in another layers of a detector is one and the same. Gained information of particle speed, mass and electric charge are relevant to physicists to identify the particle. Advanced particle physics apparatus consists of layers of sub-detectors, which specialize in one type of particle or property. There are three types of sub-detectors:

- tracking device — detects path of particle,
- calorimeter — measures the energy of particle,
- particle identification detector — identifies type of particle.

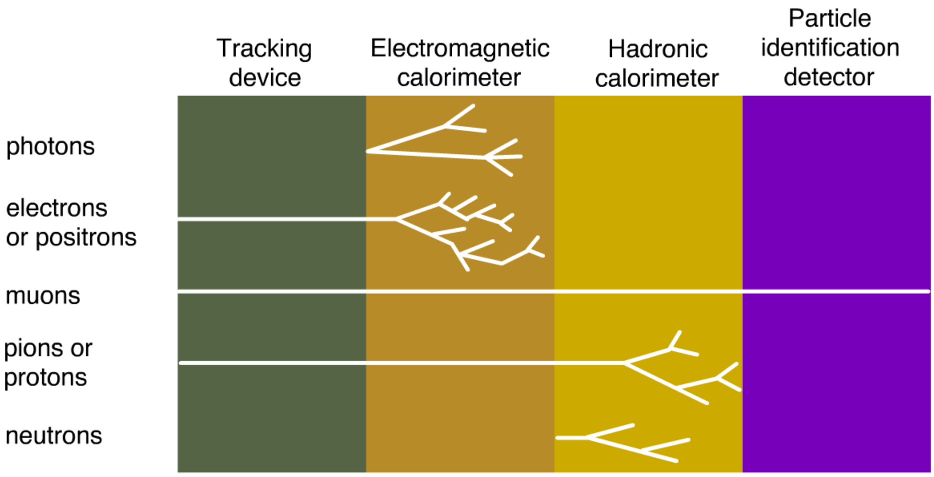


Figure 1.5: Layers of sub-detectors.

Detectors often use magnetic field to bent particle's path. From the curvature, physicists are able to calculate momentum of the particle, which helps in identifying its type. There are four main experiments with huge detectors installed at the LHC:

- A Large Ion Collider Experiment (ALICE),
- A Toroidal LHC ApparatuS (ATLAS),
- the Compact Muon Solenoid (CMS),
- the Large Hadron Collider beauty (LHCb).

All of them are located in four huge underground caverns, built around the four collision points of the LHC beams.

1.5.1 The ALICE

The main goal of this experiment is to detect and study properties of quark-gluon plasma, by analyzing lead ion collisions. Such state of matter occurs under very high temperature and density, where quarks and gluons are no longer confined inside hadrons. It is believed, that such state existed just after "the Big Bang" before protons and neutrons were created. Collisions in the LHC will generate temperatures 100 000 times higher than the heart of the Sun. It will allow physicists to study quark-gluon plasma as it expands and cools, it will also give an opportunity to observe the rise of particles that build matter that we know today. This inquiry is considered fundamental to understanding the evolution of the early Universe.

The ALICE detector consists of a central barrel part, which is responsible for measuring hadrons, electrons, and photons, and a forward muon spectrometer. Central part is embedded in a large solenoid magnet, which was previously used in L3 experiment. Going in the outward direction, the barrel contains an Inner Tracking System (ITS) of six planes of high-resolution silicon pixel (SPD), drift (SDD) and strip (SSD) detectors, a cylindrical Time-Projection Chamber (TPC), three particle identification arrays of Time-of-Flight (TOF), Ring Imaging Cherenkov (HMPID) and Transition Radiation (TRD) detectors, and two electromagnetic calorimeters (PHOS and EMCal). The forward muon arm consists of a complex arrangement of absorbers, a large dipole magnet, and fourteen planes of tracking and triggering chambers [8, 9].

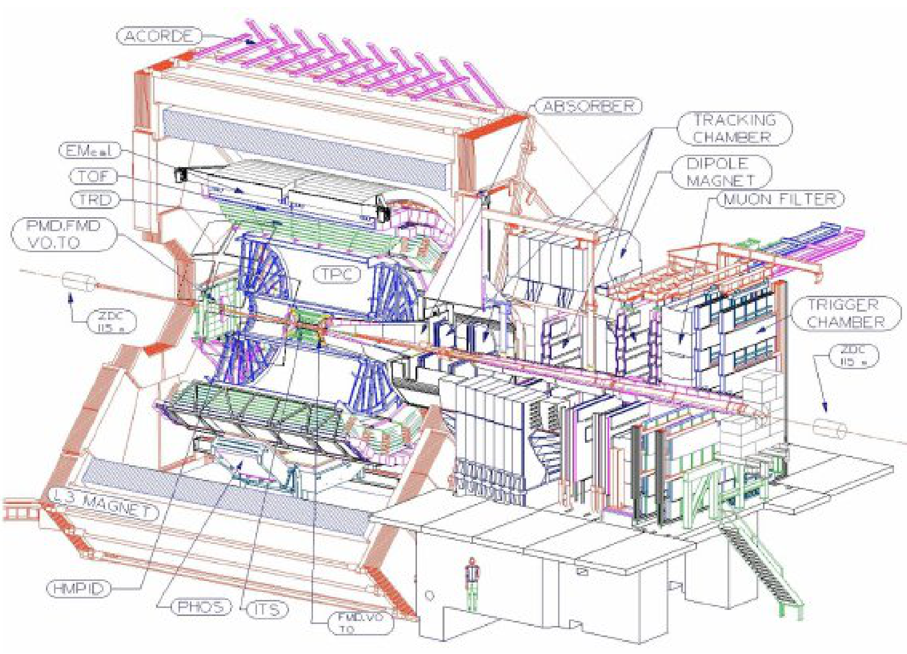


Figure 1.6: General layout of the ALICE detector.

1.5.2 The ATLAS

ATLAS is a general purpose detectors installed at the LHC. It is designed to cover the widest possible range of physics, including the search for the Higgs boson, extra dimensions, and particles that could make up dark matter. When two opposite beams collide in the center of the detector, a variety of different particles may be produced. ATLAS function is to measure range of signals, to ensure, that whatever come into existence it will be possible to detect it and measure its properties.

The detector consists of concentric cylinders around the point where the particles beams from LHC collide. It can be divided into four major parts: the Inner Detector, the calorimeters, the muon spectrometer and the magnet systems. Each of these is build out of layers with sub-detectors on in. Charged particle tacking is provided by the Inner Detector (ID) in magnetic field of 2T. Looking from inside out, the ID consists of three subsystems: the silicon Pixel Detector, the silicon strip detector (SCT) and the straw drift tube tracking device (TRT). The calorimeters are located outside solenoidal magnet and their purpose is to measure the energy of absorbed particle. The muon spectrometer function is to detects muons and measures their momentum. These particles are important for a number of interesting physical processes and it will not be possible to calculate the total energy of particles in an event if they were omitted. To allow momentum measurements two superconducting magnet systems were built to bend charged particles. A 2.5m long, 2.5m diameter superconducting solenoid provides magnetic field of 2T for the Inner Detector. The barrel and two end-cap toroids each have eight coils. Each coil is 25m long, 5m wide, weighs 100t and its typical field is 0.5T [10].

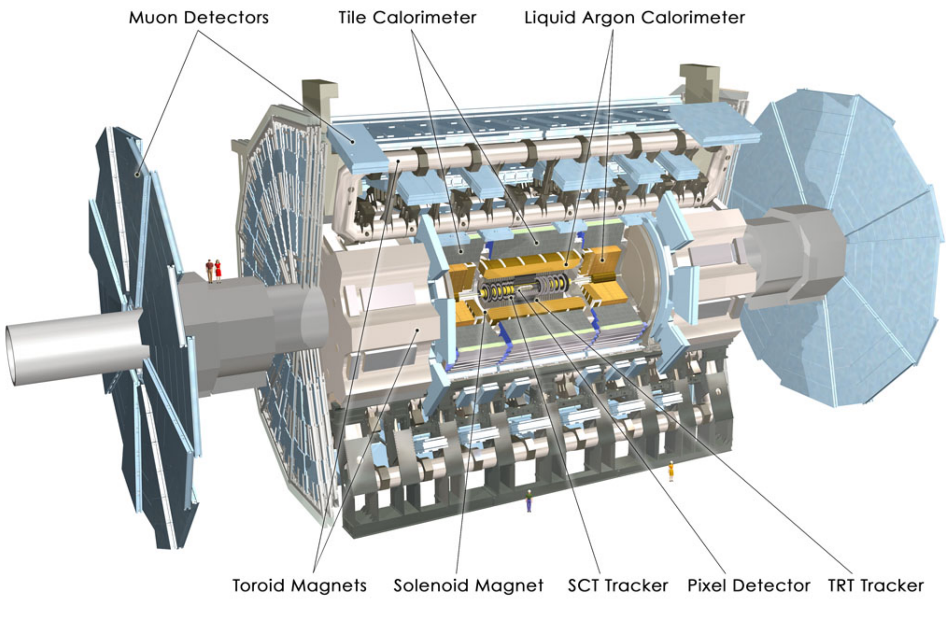


Figure 1.7: General layout of the ATLAS detector.

1.5.3 The CMS

The CMS is a second general purpose detector allowing to study wide range of physics, including the search for the Higgs boson, extra dimensions and particles, that could form dark matter. Despite it covers the same aspects of physics as ATLAS experiment, the technical solutions and design of its magnet system are different. The detector measures the energy and momentum of photons, electrons, muons, and other products of the collisions.

The detector consists of 13m long with inner diameter of 5.9m superconducting solenoidal magnet, which generates field of 4T. It is surrounded by five cylindrical structures and two end caps of muon absorber and muon tracking chambers. Complex of three charged particle tracking devices and two section calorimeter to measure particle energies are located inside the magnet cryostat. The end cap calorimeters are installed on the inside of the two muon end caps and are inserted into the ends of the cryostat. The CMS tracker is build of a silicon pixel barrel and forward disks, followed by silicon microstrip devices again placed in a barrel and forward disk configuration. This silicon tracker system is surrounded by microstrip gas chamber (MSGC) planes with the same barrel and disk geometry. The tracker is located inside the calorimeter system and is supported by it. The CMS electromagnetic calorimeter barrel consists of about 100000 rectangular crystals of $PbWO_4$, each has 23cm in length and approximately 2cm $\times$ 2cm in cross-section. Outside the crystal calorimeter there is hadron calorimeter. Response of the electromagnetic and hadron calorimeters provides data for the reconstruction of particle jets and missing transverse energy [11, 12].

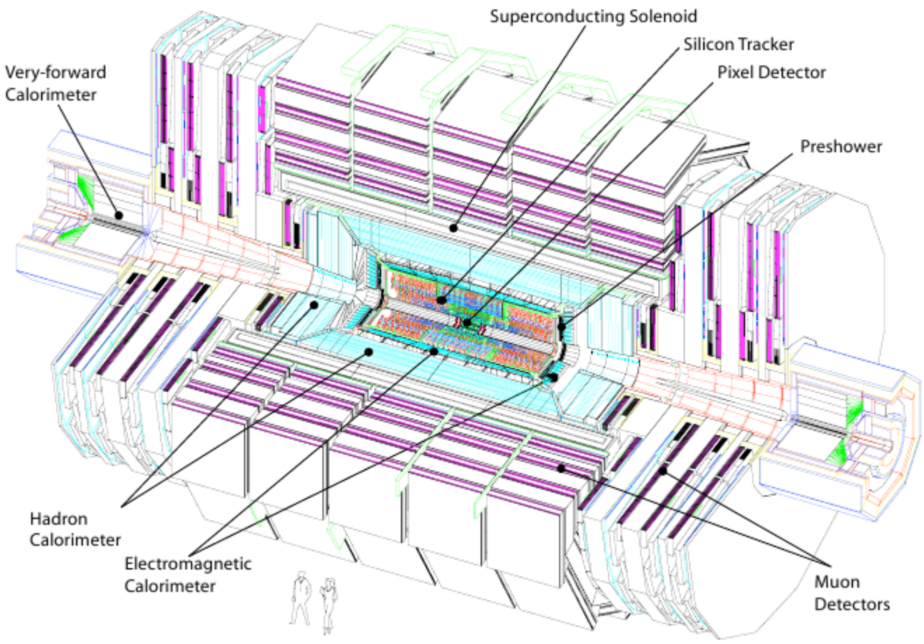


Figure 1.8: General layout of the CMS detector.

1.5.4 The LHCb

This experiment will help us to understand why there is such imparity between matter and antimatter in the Universe, that we live in. To do so, LHCb was specially designed to filter out the decay of particles containing b and anti-b quarks, also known as b-mesons.

The detector is a single arm forward spectrometer with a polar angular coverage approximately from 10 to 300mrad. It consists of vertex detector system, aerogel and gas RICH counters, tracking system, an electromagnetic calorimeter with preshower detector, hadron calorimeter and muon sensor. The vertex detector is built around proton interaction point. It is measuring particle trajectories close to the collision point. The RICH1 detector is used for particle identification of low momentum track and it is located after the vertex detector. The second RICH detector is installed 10m from the interaction point and it is used for identification of high momentum particles. The main tracking system is placed before and after the dipole magnet and its purpose is to reconstruct the trajectories of charged particles and to measure their properties. The electromagnetic and hadronic calorimeters provide information about energy of electrons, photons, and hadrons. The muon system identifies muons in collision [13, 14].

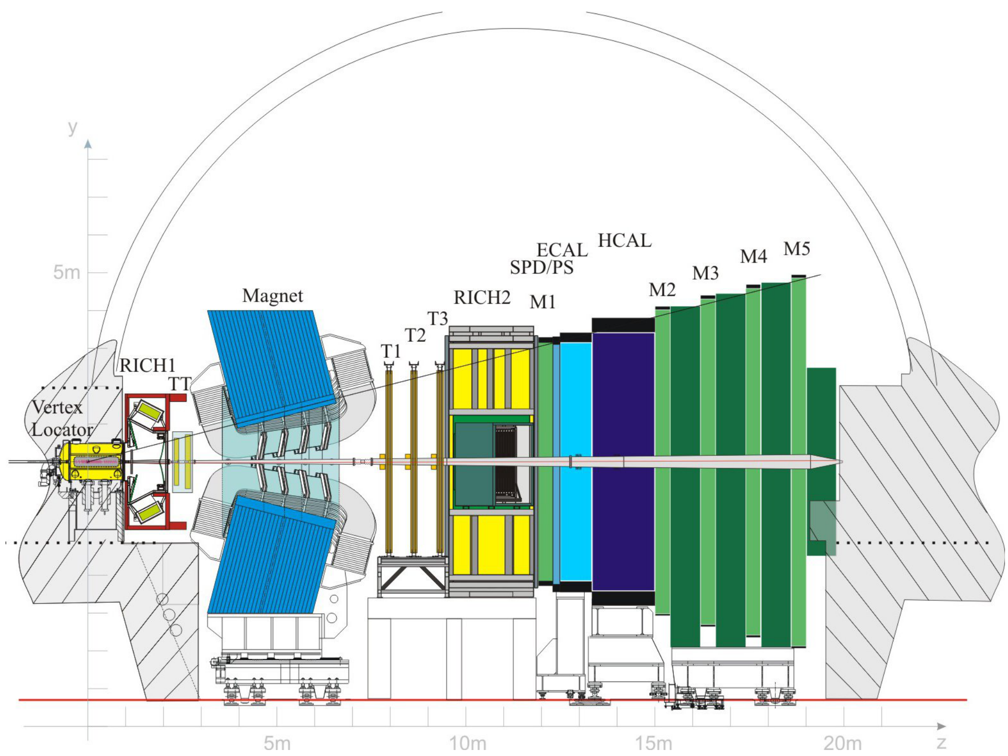


Figure 1.9: General layout of the LHCb detector.

Chapter 2

Cryogenic test facilities for the LHC components

This chapter introduces the experimental installations in SM18 at CERN. It presents the main test benches and distribution of liquid helium for them. It also provides characteristics of LHe as a technical coolant, which derive from its specific transport properties.

2.1 The SM18 test hall

The LHC ring consists of 1706 superconducting magnets — the 1232 15m long arc dipoles and the 474 short straight sections quadrupoles. Before installation, they must pass the strict performance requirements throughout extensive tests in cold conditions. These test are being made in a big hall of CERN called SM18. It was created in the former magnet assembly hall in 1992 for testing and final processing of the 196 cavities for previous particle accelerator (Large Electron–Positron Collider) [15].

In the meantime, other test facilities like cavity test station have been installed and soon, the SM18 has become the largest cryogenic test facility where all main components of the LHC are being tested before final installation in the accelerator tunnel. The facility carry out the cryogenic tests of 1232 dipole magnets, 392 Arc SSS (Short Straight Section magnets) and 82 IR-SSS (Insertion Region-SSS magnets). The number of cold masses tested in SM18 is 11% more than the above figures because of repeat magnets, so the real amount came to approximately 1900 magnets. In ZONE18 there are also examination stations for RF-cavities, superconducting cables, current leads and a high-Reynolds turbulence experiment. All these tests are possible, because of co-operative effort of three different teams. Operation group is responsible for conducting the electrical tests, training, and magnetic measurements on the magnet. ICS team connects and disconnect the cold masses to the test bench and the purpose of cryogenics crew is to cool down the magnets from room temperature to superconducting temperatures [16].

2.1.1 The superconducting magnets test benches

The test facility in SM18 possess six clusters of two test benches each. Each cluster has one power converter, one set of data acquisition system and one set of quench heater power supplies, shared by both benches. Cryogenic infrastructure has limited resources and cannot fulfill the demand of all twelve benches independently. To achieve the optimum throughput, operation team generates bench cryo priorities and conveys them for implementation. Water resources are also limited, that is why operation crew has to keep switching the water for various benches to obtain correct water flow.

Once a magnet has passed the preliminary tests at room temperature it is prepared for cold tests which consist of mounting an anti-cryostat — a pipe fitted with electrical heaters inserted into each of the two apertures. The anti-cryostat allows the magnetic field measuring equipment to be inserted and maintained at room temperature and atmospheric pressure along the magnetic field to be measured, while the magnet itself and its beam pipes are at cryogenic temperatures and under vacuum. Normal operation temperature of superconducting magnets is 1.9K. To achieve that, special cryogenic system was developed. The magnets are ramped down from room temperature to 80K using helium gas and then liquid helium cools down magnets to 4.2K. After that, low pressure pump are used until the magnets temperature hits 1.9K [17].

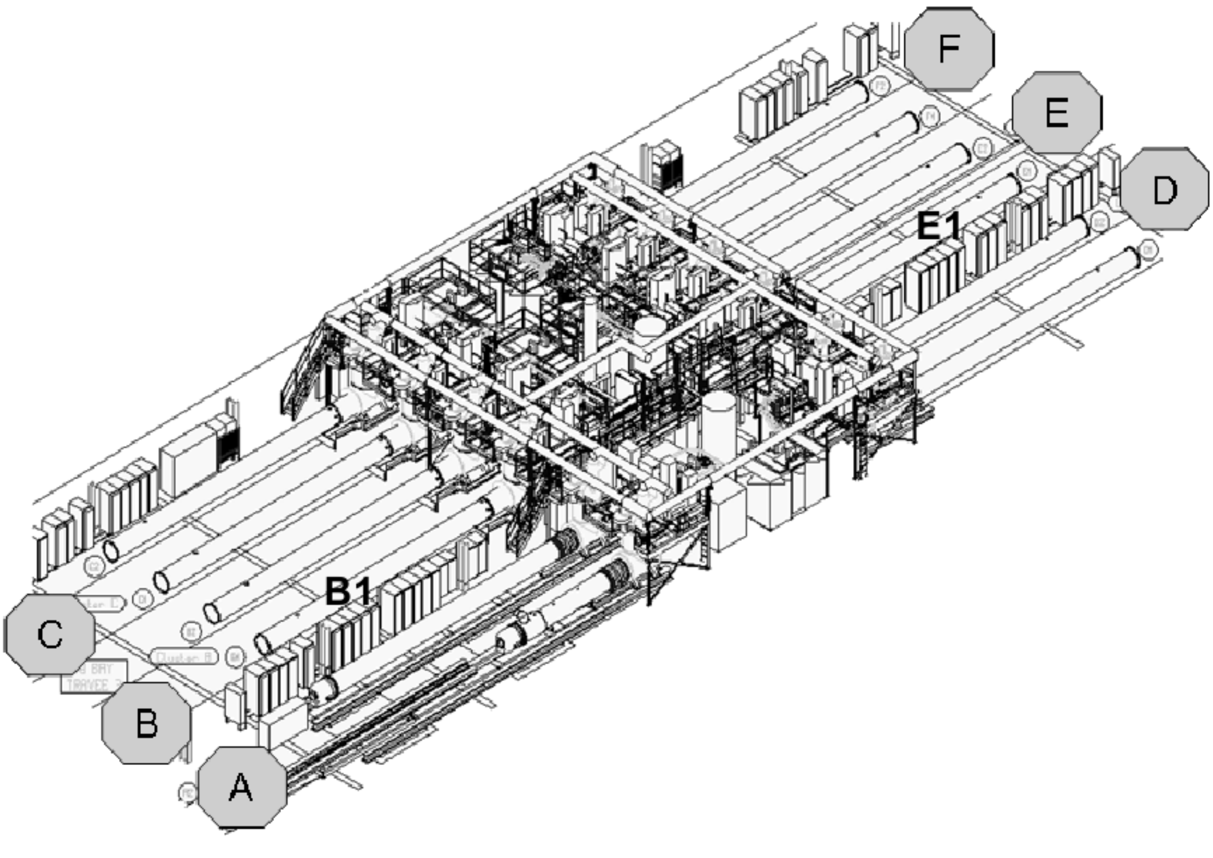


Figure 2.1: Layout of superconducting magnet test plant consisting of 12 test benches grouped in 6 clusters (A to F) in the SM18 hall

2.1.2 The facility for testing superconducting cables

One of a new Block4 experiment now installed at SM18 is FRESCA. The abbreviation of the name of this test station stands for the Facility for the REception of Superconducting CAbles. It measures the electrical properties of the LHC superconducting cables, which later on are used to manufacture the magnets for the CERN's largest accelerator.

Thousand of kilometres of superconducting NbTi cables have been produced for the coils for the main magnets of the Large Hadron Collider. Part of the quality acceptance test of these cables is the measurement of their critical current (I_c) — the current when the cable quenches.

The tests take place in a cryostat, which is approximately 3.6m high and 1.6m diameter. It consists of an outer cryostat, which contains a superconducting NbTi dipole magnet, capable of delivering field up to 9.5T. The current supplying the magnet is delivered through an external 16kA power supply and fed into the cryostat through a pair of 18kA current leads. The cryostat is divided in two parts — lower and upper bath. They are separated from each other by a so called lambda-plates. The lower bath of the cryostat, can be cooled down to temperature of 1.9K because of a subcooled superfluid refrigeration system.

Inside the outer cryostat, an inner cryostat can be found. It contains the superconducting cable samples. Both of them are vertical double-bath cryostats operating with He II in the lower part (at 1.9K) and He I in the upper bath (at 4.3K). Likewise the outer cryostat, the inner cryostat is separated by the lambda-plates. The concept of double cryostats allows to change the samples while the background magnet stays cold. This solution decrease the helium consumption and cool-down time of the samples. Furthermore, the magnet will not undergo many thermal cycles, which may have a negative impact in its stability.

The cable samples are connected to an external 32kA power supply. FRESCA gives the ability to rotate the samples while remaining at liquid helium temperature, this enables measurements with the background field perpendicular or parallel to the broad face of the cable. In order to estimate the current imbalances between the strands of the cables, two arrays of 26 hall probes are installed on one edge of each cable. The measurement operation consists of cooling the two cable samples connected in series and mounted on the Sample Holder down to the temperature between 1.9K and 4.5K. Following this, the current flowing through the samples are increased until the Sample Protection System detects a rapidly increasing voltage across the samples. If the quench occurs, the sample power supply reduce the current to zero to avoid overheating the samples [18, 19].

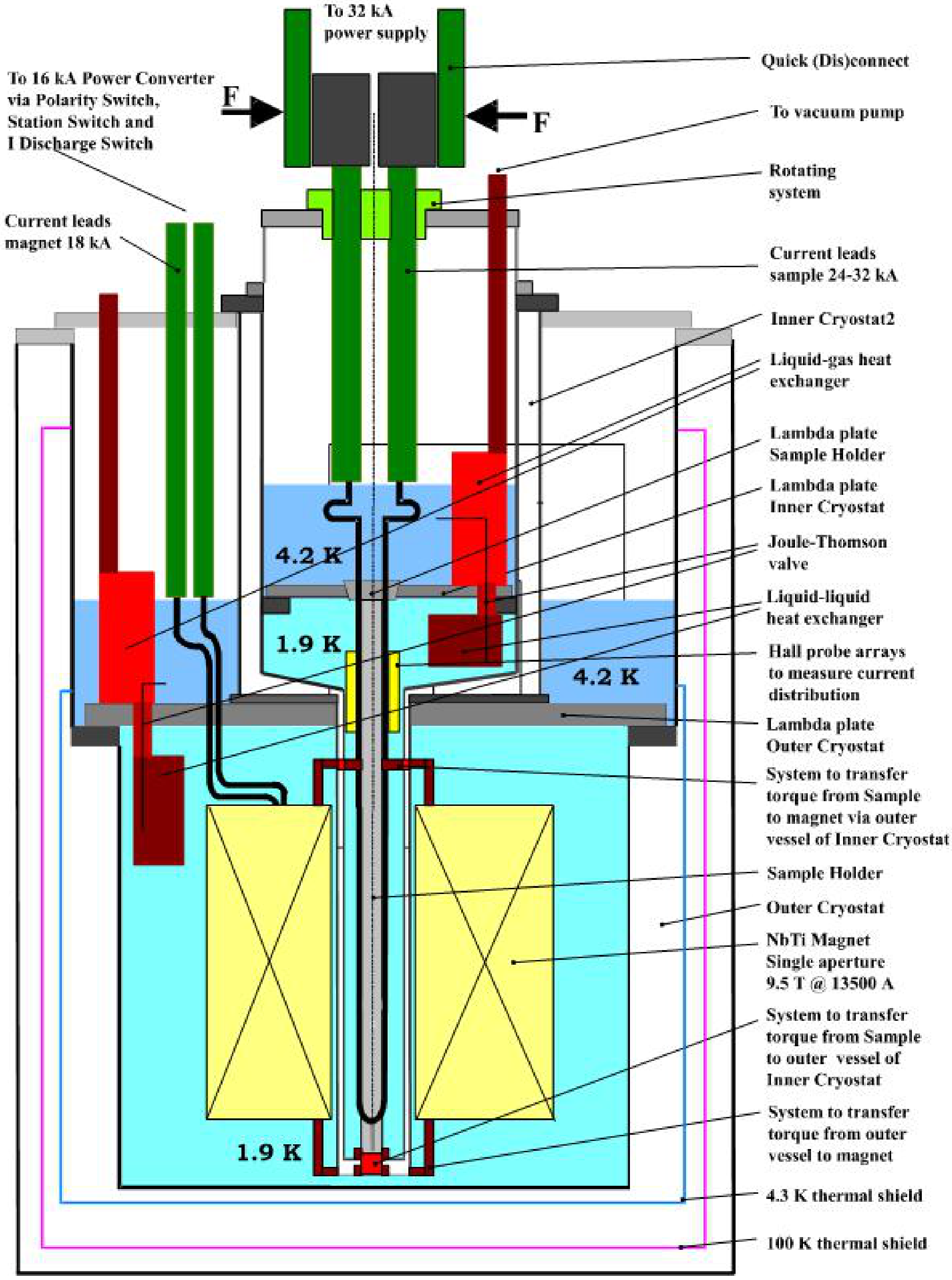


Figure 2.2: FRESCA test bench.

2.2 Cryogenic architecture of the SM18

To meet all requirements related to cooling, the test facility has been improved and upgraded over the last few years. The 18kW refrigerator for the LHC has been added to increase the cryogenic capacity for the area by 25000 liter liquid helium dewar. Also the 6kW refrigerator is used to commission LHC cryogenic components. The operational diagram of the cryogenic infrastructure of ZONE18 is presented in Fig. 2.3.

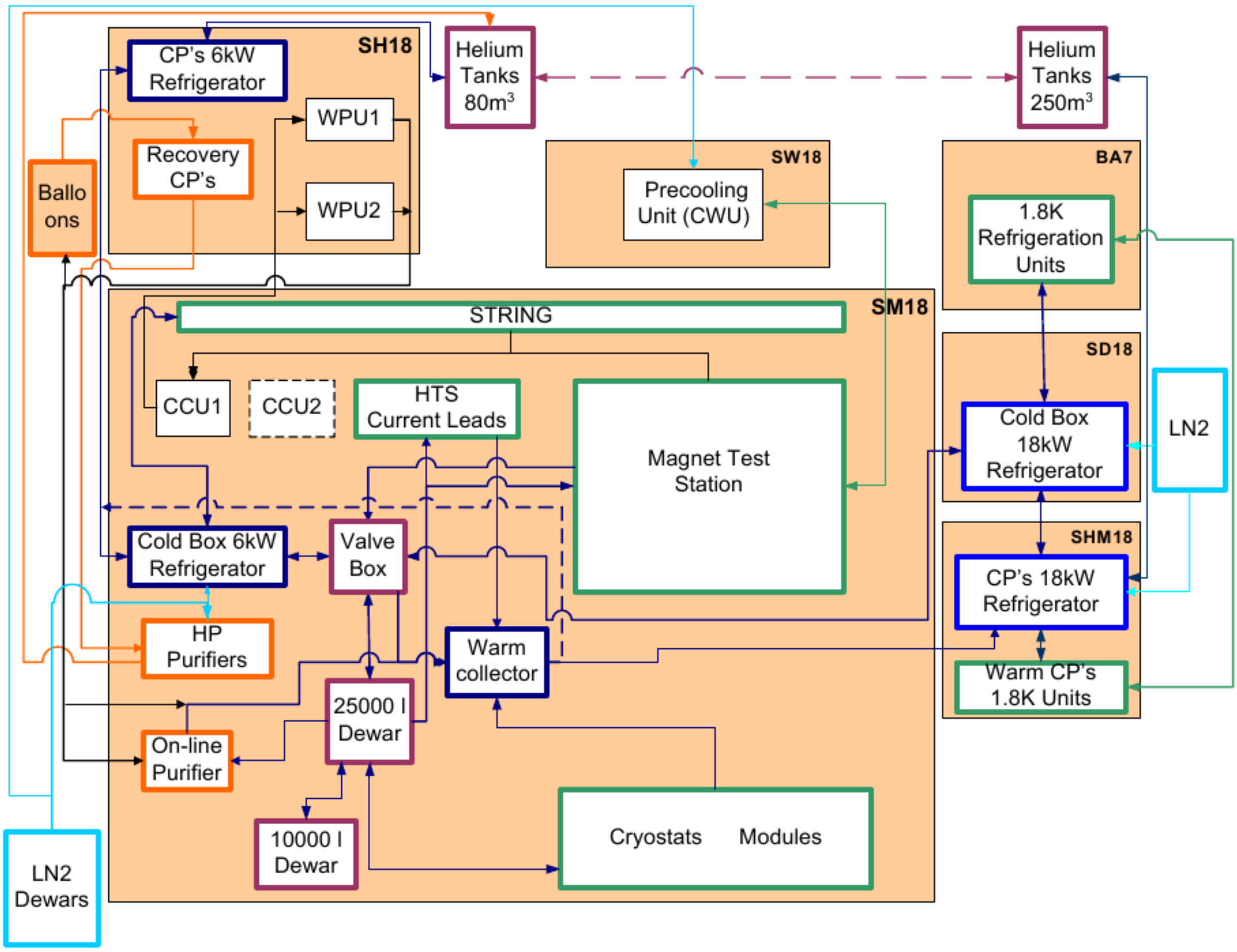


Figure 2.3: Diagram of the cryogenic infrastructure of SM18.

Two refrigerators of 6kW and 18kW at temperature of 4.5K provide liquid helium to the main users through the 25000 liter dewar which is located in the main building SM18. Cryogenic Valve Boxes and distributed warm collectors ensure the complete redundancy of liquid helium distribution as well as cold and warm gas recovery from any of the two refrigerators. Both refrigerators can also directly supply liquid helium to another users. Supercritical helium at pressure 0.3MPa and temperature of 4.5K is delivered by 18kW refrigerator installed in an abutting building (SD18) to the 25000 liter dewar using 250m long cryogenic transfer line and by another cryogenic transfer line to the test station of the 1.8K refrigeration units in building BA7. Its maximum liquefaction capacity is

150g/s with nitrogen precooling and maximum low pressure process flow of 770g/s. This refrigerator is one of the four 18kW at temperature of 4.5K refrigerators which will be fully dedicated for the LHC machine in the future.

The 6kW refrigerator is also installed in SM18. A cryogenic Valve Box and two transfer lines are responsible for supplying the dewar and a second user. Its maximum liquefaction capacity is 32g/s with nitrogen precooling and maximum low pressure process flow is 410g/s. It has been used for the string experiments until July of 2003. In future it will be reused for other LHC cryogenic components testing as well as the redundancy for liquid helium supply and gas recovery for magnet testing.

To decrease helium temperature to 1.8K, the magnet test station and String (full size model of a regular cell in an LHC arc) is connected via pumping line to a very low pressure pumping system. It consists of a cold compressor unit (CCU1 — one centrifugal compressor), a 30 kW heater and a warm pumping unit (WPU1 — three roots in series followed by three rough pumps in parallel) which give a pumping capacity of 18g/s at pressure of 1kPa. Second warm pumping unit (WPU2) and a 30kW heater have been installed and used during 2003 for the String. Second pumping system with cold compressor (CCU2) was installed to have redundant pumping system for the magnet test bench.

To clear the flow coming form the WPUs the online low pressure helium purification system (POL) is used. It is capable of purifying 18g/s of impure gas and can be directly connected to the low pressure of any of the refrigerators. In SM18 there is also a high pressure purification system, which is made out of five low pressure balloons of $80m^3$ capacity each, three recovery compressors connected in parallel of capacity of $100m^3/h$ each and two high pressure purifiers also connected in parallel and capacity of $200m^3/h$ each at pressure of 20MPa.

The gaseous helium storage system has nine tanks of $80m^3$ at pressure of 2MPa for the 6kW refrigerator. It is also composed of twelve tanks of $250m^3$ at 2MPa for the 18kW refrigerator and eighteen bottles of $0.9m^3$ at 20MPa. The 25000 liter container is used as a liquid helium buffer and can be supplemented by two mobile 10000 liter dewars. Two 50000 liter dewars supply liquid nitrogen for the magnet station precooling unit, the high pressure purifiers and the 6kW precooler. Two other 50000 liter dewars are used for the precooler and dryer of the 18kW refrigerator [20].

Most of the time, helium is supplied to CERN in a liquid form and majority of all deliveries are held at SM18. Normally the helium is transferred to the dewars, but it can also be done directly to the 18 kW refrigerator by mixing the liquid helium to the low pressure warm gas at the outlet of the Cold Box. The helium is directly transferred into the 25000 liters dewar or to a mobile 10000 liters dewar [21].

In normal operation the 18kW refrigerator is connected to the 25000 liter dewar which supplies the magnet test station and the RF cavities station. Each client is able to decrease the temperature of helium to 1.8K by pumping on the helium bath. A 1.8K units test benches requires liquid helium flow between 50g/s and 150g/s. The return flow from the magnets is directly sent to the low pressure of the refrigerator unless a contamination of helium is detected. In that case, the LHe is sent to the balloons or to the purification system. Return cold gas can be directly sent to the inlet of compressor by control valve and 100kW electrical heater during intense flow return. In situation when major problem occurs and 18kW refrigerator production stops, the refrigerator takes over and can be cooled down and connected to the dewar in less than 12 hours (1 hour if it is already cold). Large number of connection/disconnection, cool down/warm up of clients and purification of recovered helium needs constant monitoring of inventory and losses. Average weekly losses are 250kg with purification rates of 800-1000kg per week. A huge helium storage capacity of approximately 4800kg is kept in SM18 to ensure coolant supply for all clients, even if an major losses occurs. The mobile dewars are capable of supplying and receiving liquid helium from other CERN zones via high pressure line which provides safe gas transfers.

Nitrogen is mainly used for 6 kW and 18 kW refrigerators precoolers, high pressure purifiers and precooling unit for the magnet tests station. The average consumption of LN over the years has been less than 6000 liter per day. Intensified activity of the magnet test station will increase the consumption up to 20000 liter per day. All remote control of cryoplants take place in control room located in SM18.

2.3 Properties of liquid helium

Cryogenics is often defined as a branch of physics, which deals with the production of very low temperatures — which do not naturally occur on Earth — and their effect on the properties of matter. It is also described as the science and technology of temperatures below 120K. The explanation of the last definition is fact, that the temperature of 120K is a normal boiling point of the main atmospheric gases, as well as of methane which constitutes the principal component of natural gas.

The search for cryogenic temperatures finds its origin in early thermodynamics. In 1703 Amontons's gas pressure thermometer opened the concept of absolute zero surmise a century later by Charles and Gay-Lussac, and eventually formulated by Lord Kelvin (William Thomson) in 1848. The Boltzmann's statistical thermodynamics which turned out in the late nineteenth century stated, that the temperature could be explained in terms of microscopic structure and dynamics.

The easiest way of cooling something with a cryogenic fluid is to make use of its latent heat of vaporization, for example by immersion in a bath of boiling liquid. As a consequence, the useful temperature range of cryogenic fluids is that in which there exists latent heat of vaporization. This section concentrates on LHe which is the only liquid at very low temperature [22].

Over the last two decades, in laboratory experiments and in large industrial projects the superfluid helium has become cooling medium for superconducting devices. The LHC uses pressurized superfluid helium for cooling to 1.9K the long strings of superconducting magnets and RF cavities. In total 31000t of material will have to be cooled down with 12 million liters of liquid nitrogen and 700000 liters of liquid helium. The SM18 consumption of LHe is about 50000 litres per year. Phase diagram of helium (Fig. 2.4) shows, that the working range of saturated helium II is reached by lowering the pressure down below 5kPa along the saturation line. The same conditions are also possible to obtain by subcooling liquid helium at any pressure above saturation. If helium is not exposed to very high pressures it does not exist in solid state at low temperature. LHe has two liquid phases, helium I and helium II. There is no latent heat associated with this phase transition, but a peak in the specific heat, the shape of which gave the name λ-line to the phase boundary. Helium I is a regular liquid and helium II is superfluid, which means, that is can flow without friction through a very narrow channel. This frictionless flow suggests disappearance of velocity. However, it has been observed, that disk which has been dumped in helium oscillates at a small amplitude.

Saturated He I provides fixed temperature and high boiling heat transfer at moderate heat flow, which may develop instabilities in two-phase flow and it can lead to boiling crisis. This can be avoid when using mono-phase supercritical helium in forced-flow cooling system. In addition, supercritical helium exhibits no latent heat, which means that applied heat loads result in temperature increases. This forces the cooling system to have high flow-rate or periodic re-cooling.

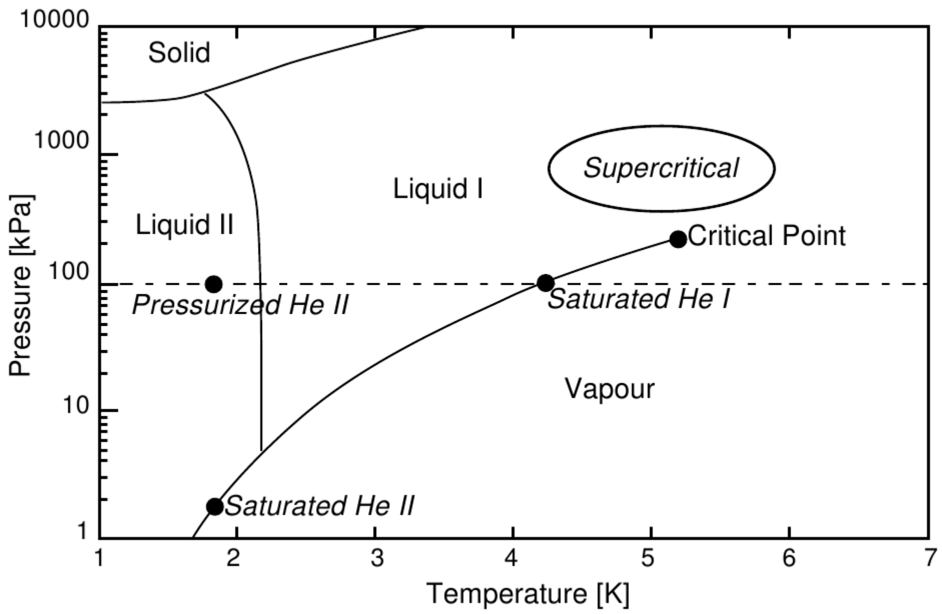


Figure 2.4: Helium phase diagram. The λ-line separates liquid helium I from liquid helium II.

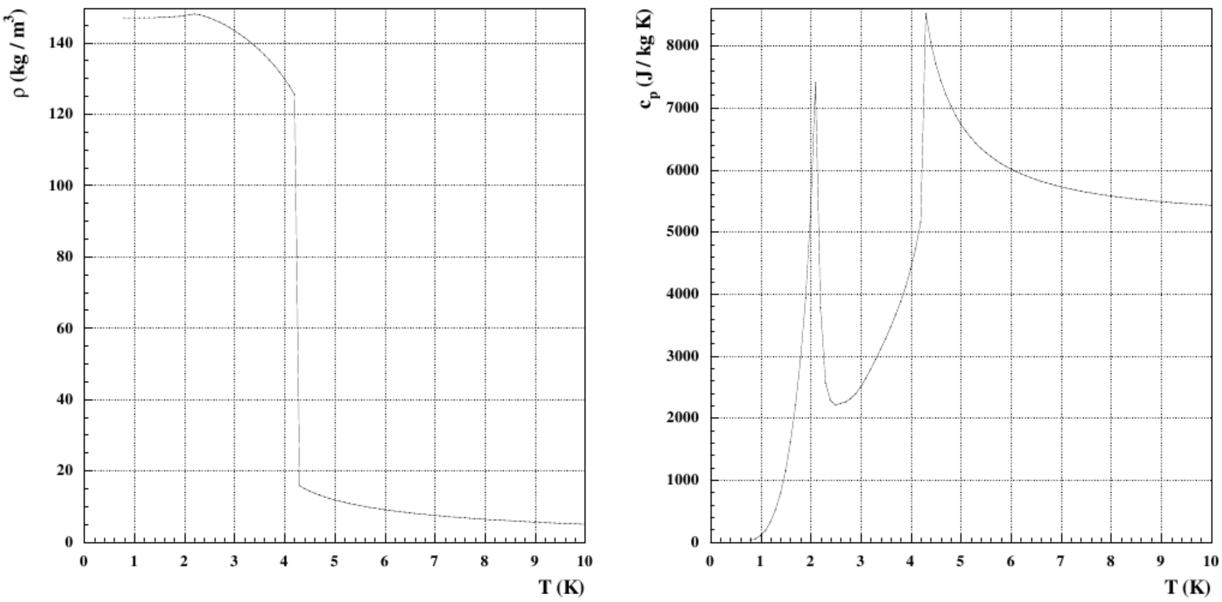


Figure 2.5: Density (left) and heat capacity (right) of helium as a function of temperature.

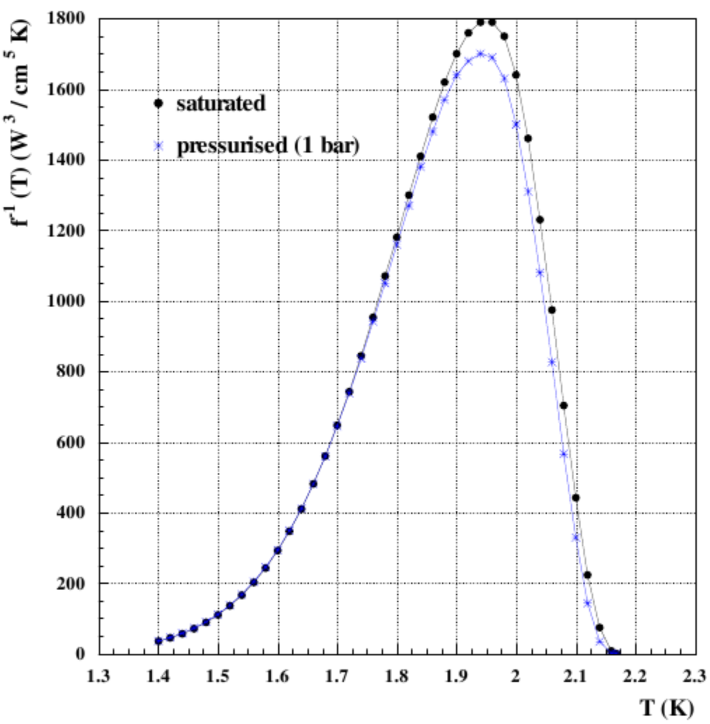


Figure 2.6: Conductivity of helium as a function of temperature.

Helium low temperature of operation and unusually efficient heat transport properties, such as high heat capacity, low viscosity, good effective thermal conductivity are excellent for transporting kilowatts of refrigeration over more than a kilometer with a temperature drop not higher than 0.1K.

The thermodynamic properties of LHe at cryogenic temperature are presented in Fig. 2.5, 2.6. Superfluid helium has very high conductivity with an unconventional behavior, the temperature fluctuations do not diffuse, instead they propagate as a wave. All these properties make He II an excellent coolant for advanced superconducting devices.

Avoiding operations at low pressure in huge cryogenic system, limits the risk of air inleaks and contamination of the helium. In addition, in case of electrical devices, low pressure helium vapour brings the risk of electrical breakdown at low voltage. Operating in pressurized helium II avoids this kind of problem. The most interesting thing of pressurized helium II in the operation of superconducting devices, derive from capability of cryogenic stabilization. As a subcooled liquid with high thermal conductivity, pressurized helium II is capable of absorbing heat up to the temperature at which the local boiling starts due to low thermal conductivity. Saturated helium II can only absorb heat deposition up to the point, when the saturation line is crossed and change of the phase occurs [23].

Chapter 3

Update project of the SM18

This chapter provides information about the old functional status of the test hall, as well as communication connections between systems at Point18. It also gives a detailed description of update requirements and solutions adopted for the cryogenic control system at P18. In this chapter can also be found information about the process management of the RF Cavities test station, Programmable Logic Controllers, Supervisory Control and Data Acquisition system used in this project.

3.1 Modification of the cryogenic control system in SM18 test facility

As an intern at the CERN's Control and Electrical Support for the Cryogenics Group, I took part in the project, which main idea was to revamp the largest testing hall at CERN. The changes of the SM18 concerned cryogenic infrastructure, new test benches and the control systems for both, as well as new communication model for the cryogenic devices in the hall. The strong argument for the changes was the availability of the CERN UNICOS (Section 4.3) standard — capable of integrating the architecture of the whole control system — and lack of experts for old automation systems, as well as the need for extending the test hall in a new functionalities. All these arguments persuaded to the migration of a Distributed Control System (DCS) of the SM18 to a new, more efficient one, based on modern PLCs and Supervisory Control and Data Acquisition (SCADA) system. The team I was part of, was responsible for preparing the cryogenic control racks, software for the PLCs and synoptic panels for the operators. In this thesis, I present results of our work, based on example of the Radio Frequency Cavities test station control system.

Years of operation of the cryogenic equipment, with many undocumented modifications made by several external operation teams, have left their effect with the result of a technical documentation of SM18 no longer up to date. An intensive electrical and control process study was mandatory as a first step of a renovation control project. The migration from the old DCS, which was mainly based on ABB and Siemens-PcVue32, was essential to maintain efficient operability also in view of the future projects that will be held in the SM18 test facility. For better organizing the update project, it was divided into three main sections: critical, consolidation and new projects.

The first one aimed to reestablish normal reliability of the control system itself — years have passed and no hardware and software control support had been given, with the consequence of rendering the system fragile. The cryogenic control system strongly depends on the network equipment. If a failure occurs, the SM18 cryogenic test facility will not be able to operate with all the functionalities. The interventions included:

- Valve Box and 25000l liquid dewar,
- Warm Pumping Unit,
- Cold Compressor Unit.

While the WPU is a single dedicated unit in terms of operation, the main distribution Valve Box including 25000l liquid helium dewar was the most critical part of operation, because when it fails all the cryogenic operation must be stopped since the gas infrastructure is not able to treat any gas return from the clients. What is more, if we wanted to proceed with consolidation while new projects (migration of Block 4 cryostats) come in, the infrastructure part was essentially needed. Another important aspect we needed to take into account was the multi-clients priorities management.

The WPU and Cold Compressor Station (CCS) were controlled by a PLC Siemens S5 using Sinec H1 communication protocol which is not supported anymore at CERN. In order to use a standard communication protocol based on ethernet and IP addressing, the PLCs we used in the project support the Profinet standard (Siemens S7 and Schneider Premium/Quantum):

- the cryogenic infrastructure (PLC Schneider),
- the cryogenic test benches (PLC Schneider/PLC Siemens).

Such approach allows communication via TCP/IP as well as the real time communication if needed. The first one assures the reaction times in the system in the range of 100ms, while the second one depending on the protocol, RT (Real Time) or IRT (Isochronous Real Time), is capable of driving systems with cycles times up to 10ms and less than 1ms respectively. What is more, the large amount of address space in the network allows almost unlimited scalability, which means that the system can be extended easily at any time. In addition, such solution allowed us to apply PVSS SCADA together with the UNICOS framework — both simplify the management of the process. The SM18 PVSS SCADA is executed on two Linux machines in CERN Control Center (CCC).

As it is shown in Fig. 3.1, the control system of the main Valve Box and Radio Frequency Cavities was managed from a unique ABB PLC. Because both systems used only one PLC, we needed to perform the migration of the two system in parallel. In order to improve availability and modularity, we decided to use two different PLCs for controlling those system. This solution will allow interventions on Radio Frequency Cavities, while others clients remain operational. The results of first step of migration is presented in Fig. 3.2.

To migrate from the old DCS we needed to define a strategy to maintain the communications between systems in the test hall. Figure 3.3 shows the previous situation of the communications in SM18:

- the data exchange between the ABB controllers used the ABB MB300 bus,
- the Valve Box and the Purifier online PLCs were used like a central ABB machine for operator beep call and helium inventory calculation,
- the communications to others PLCs (not ABB) were hardwired.

Because of the change from old ABB PLCs to Schneider Premium controllers of the main Valve Box, Cavities and Purifier online, we were allowed to use ethernet to directly connect the 18kW Air Liquid cryoplant Schneider PLC with the Valve Box PLC. Despite possibility of usage of the Profinet, some hardwired communications was still required to keep the data exchange with remaining ABB PLCs. After this steps of the first migration part, only communication between the Compressors and the Cold Box of the 6kW Linde cryoplant remained on ABB [24]. The structure of the new communication is illustrated in the Figure 3.4.

The consolidation part of the project concerned the extension of the UNICOS standard to the external cryogenic facilities with their infrastructure, including:

- Compressor Station and Cold Box Linde 6kW,
- LHC magnets test bench,
- Helium Storage.

The control migration was divided into smaller projects, which were grouped in two main categories:

- the external cryogenics with its infrastructure and distribution piping,
- the different clients — the LHC magnet and Radio Frequency Cavities test benches are involved in the system update,

The functional schematics of the SM18 area is shown in the Figure 3.2. The activities related to the consolidation part of the project are presented on the next pages of this thesis.

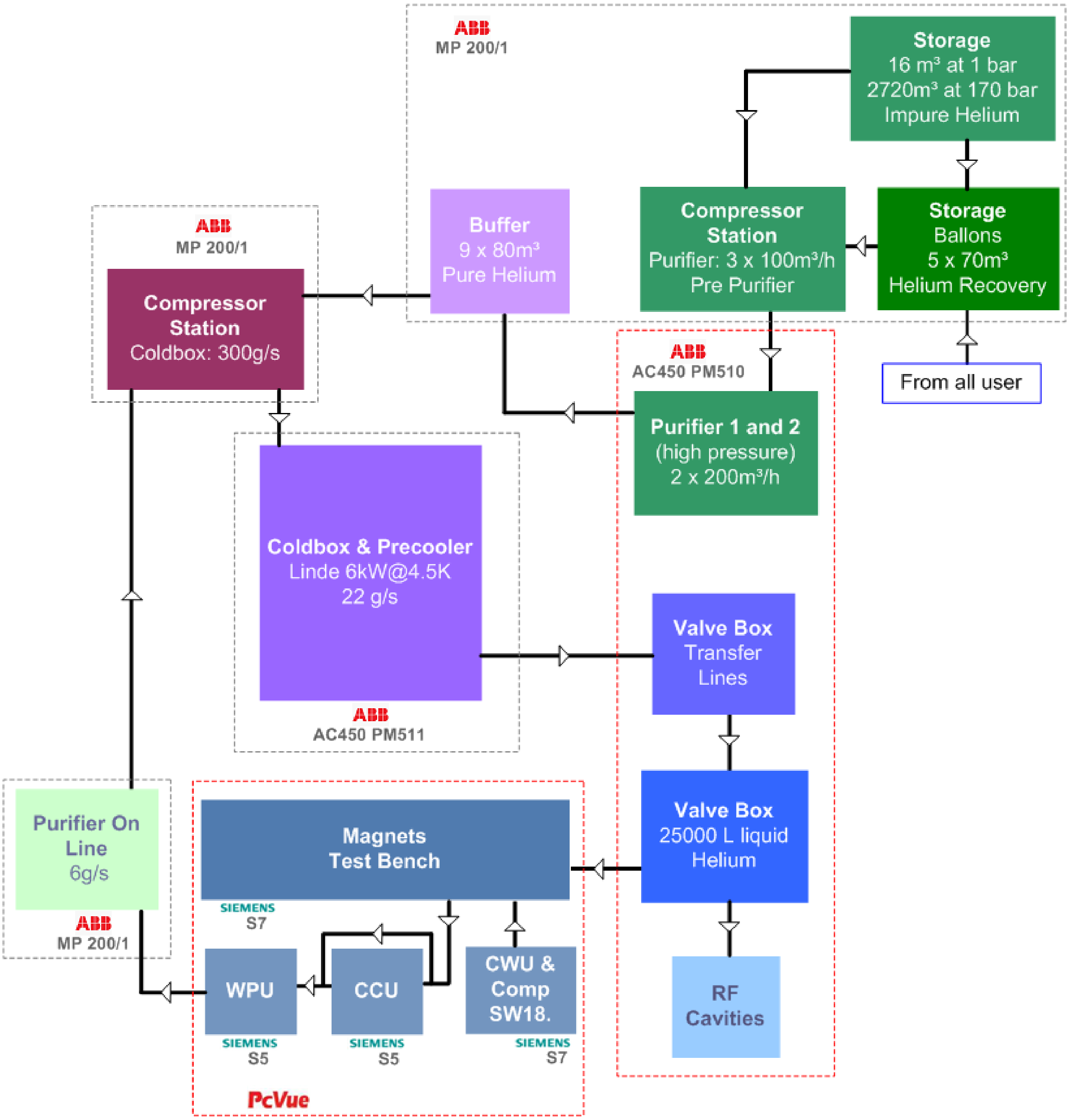


Figure 3.1: SM18 ABB functional view.

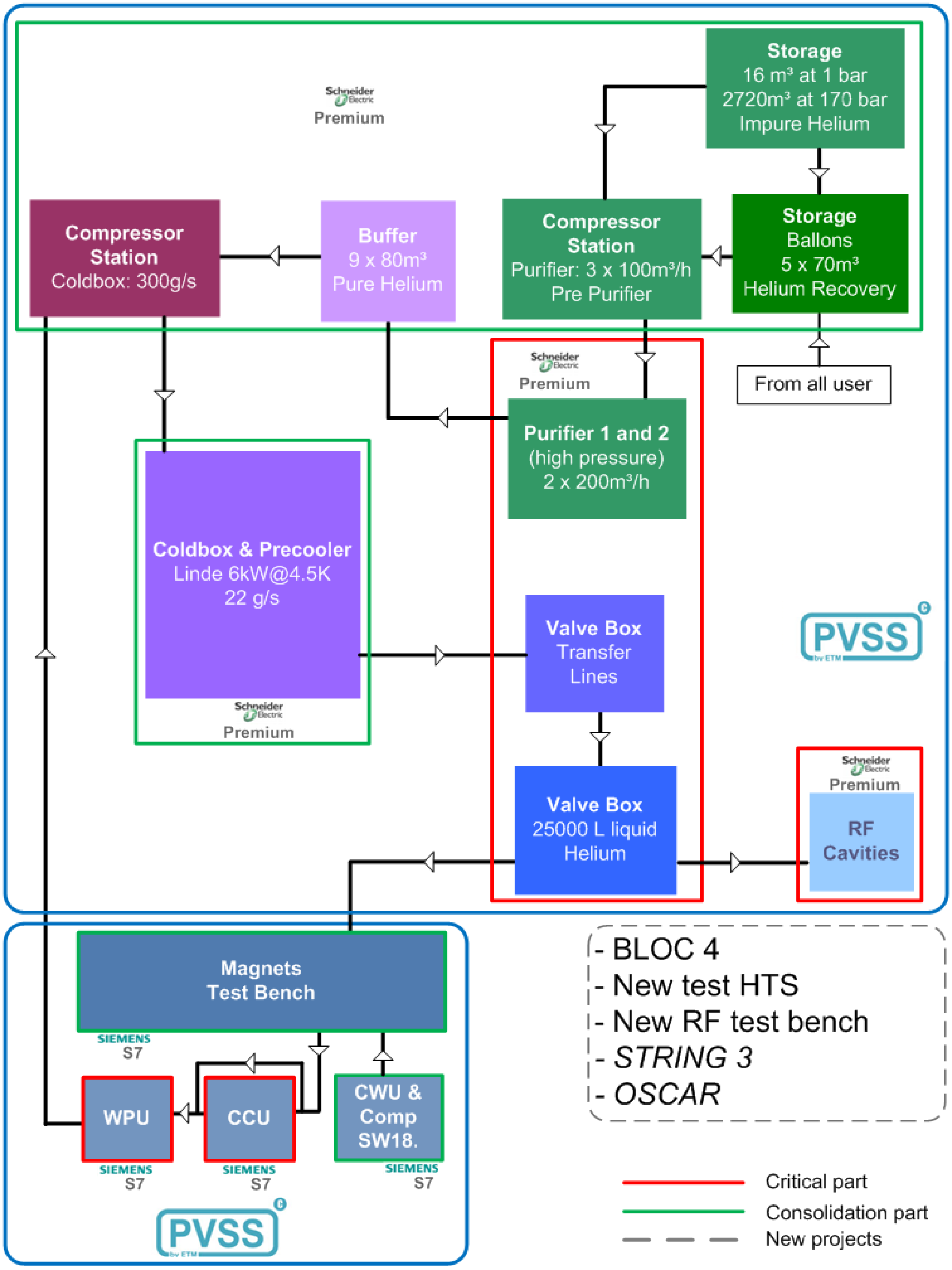


Figure 3.2: New functional view of SM18.

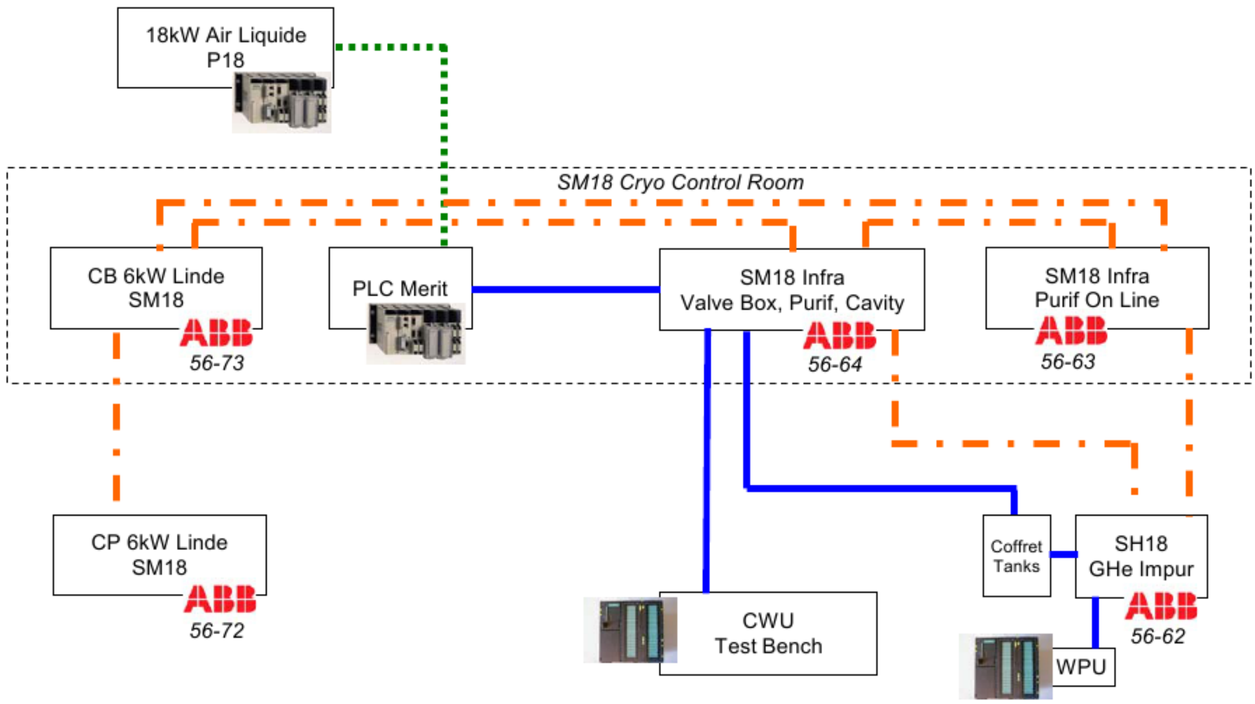


Figure 3.3: Previous communication model in SM18.

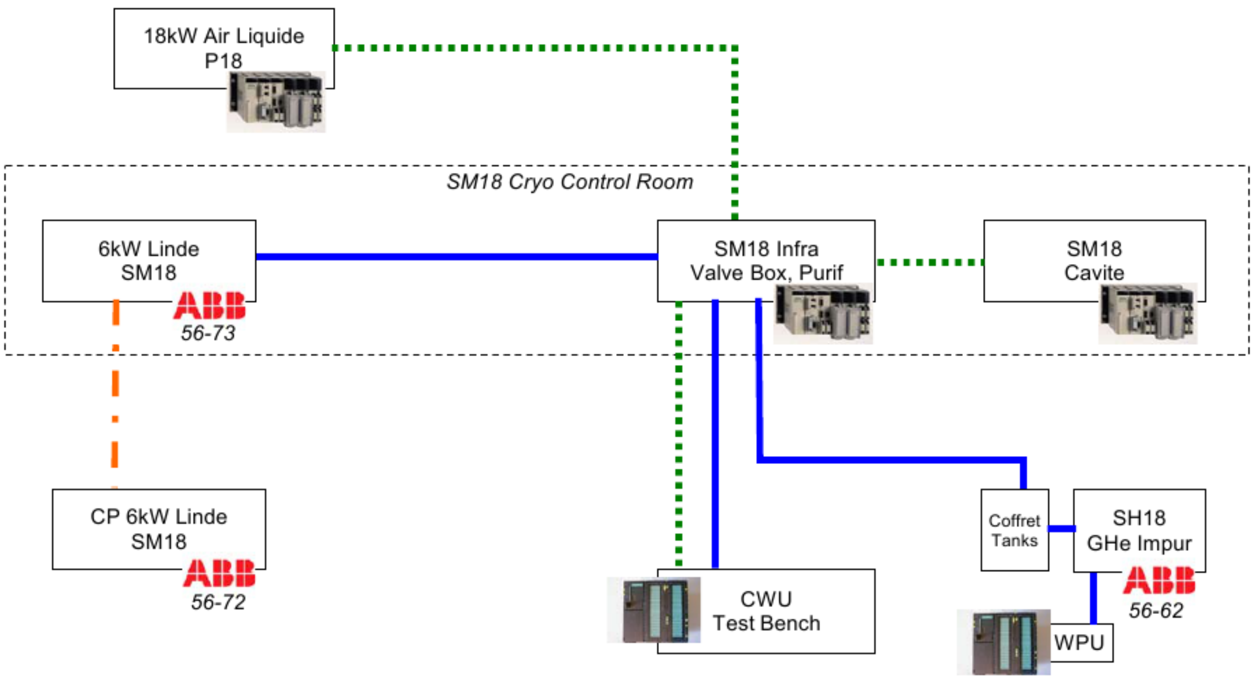
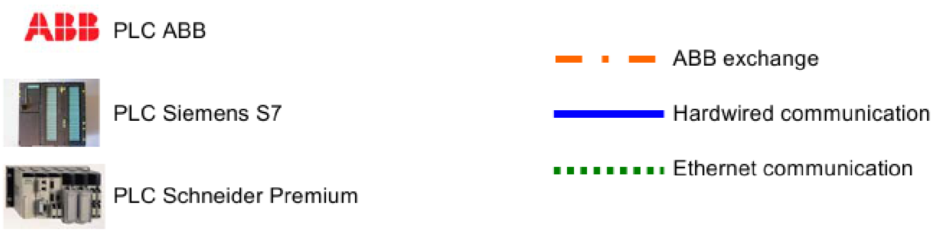


Figure 3.4: New communication model in SM18.



The consolidation part of modification was introduced in the following steps. At first, the Compression Station and the Helium Storage plant were migrated from two obsolete ABB PLCs to a single Schneider PLC, which resulted in unifying the handling of both subsystems. Moreover, the transfer of the Cold Box Linde 6kW control system to a Schneider PLC was also performed. This step was carried out at a later stage with respect to the previous one. In this case, it was necessary to temporarily employ a hardwired connection to allow the communication between the Schneider and the ABB control system.

All the above mentioned updates had paved the way for applying the extension of the UNICOS standard to the external cryogenic facilities with their infrastructure, as well as to the cryogenic clients (various test benches), which resulted in better management of the whole plant under the CERN standard platform. Furthermore, the structure of the PLC which were handling the LHC magnet test benches was revised.

The migration strategy assumed a short shutdown time during commissioning. This was achieved because of a preliminary no-errors preparation of the electrical cabinet and application according to the old (but still up to date) technical documentation of the installations. Usually all the works related to wiring were kept at minimum during commissioning period. What is more, in order to minimize the commissioning time, we had done an offline precommissioning using the CERN PROCOS environment simulator [24].

The last part of the modifications consisted of the activities, which main purpose was to implement the new projects in the SM18 test hall. The first task related to this part of the project was to move the installations of the Block4 (four cryostats to test magnets in vertical position) station to the SM18. The team I was part of was responsible for all the control and electricity support for the multiple projects that now are installed in the SM18 test facility, such as:

- Block 4 cryostats,
- new High Temperature Superconducting (HTS) test bench,
- new Radio Frequency Cavities test bench,
- String 3,
- OSCAR.

Such solution to unify the superconducting magnet test stations will optimize the use of resources and man power. It was carried out by exploiting the solution already developed for the Block 4 FRESCA installation. In addition, the new test benches for the test of the LHC Radio Frequency Cavities were added as a clients of the cryogenic system. Also the test station for the HTS current leads was set up — it investigates if they can be used to link groups of superconducting magnets to remote power converters. The realization of the new projects required an extension of the cryogenic capabilities [24].

3.2 The Radio Frequency Cavities test station

As a member of the Control and Electrical Support Group I participated in the all modifications of the SM18 test hall which are described in the section above. To give an idea of the structure of the one control systems we have designed and programmed afterwards, in the section below I present a detailed description of the electrical connections and data exchange in the Radio Frequency Cavities test station.

Besides preserving the previous functionalities of the test bench, the system was updated to include some modules with new features for the examination of the Radio Frequency Cavities. The solutions we have chosen to employ for this test station were based on the standards defined for the Large Hadron Collider's applications.

Furthermore, the cabling for the data transfer was simplified. Instead of the cabled links previously used for the transmission of the information to the SM18 Control Room and from there to the Cryo Control Room, links were realized for a direct exchange on a shorter cable length. Finally, except for the critical signals requiring a cabled link to assure the safety of the system, we have chosen the solution, in which most of the information is transmitted though exchange crate on a field bus [25]. The Radio Frequency Cavities test station includes six cryostats:

- two horizontal
  - M7 (LHC Cavities at 400MHz),
  - M9 (LINAC4 warm tests),
- four vertical
  - V3 (Tests SPS),
  - V4 (RF study),
  - V5 (ISOLDE),
  - V6 (LHC tests).

Figure 3.5 presents the layout of the SM18 test benches for the test of Radio Frequency modules.

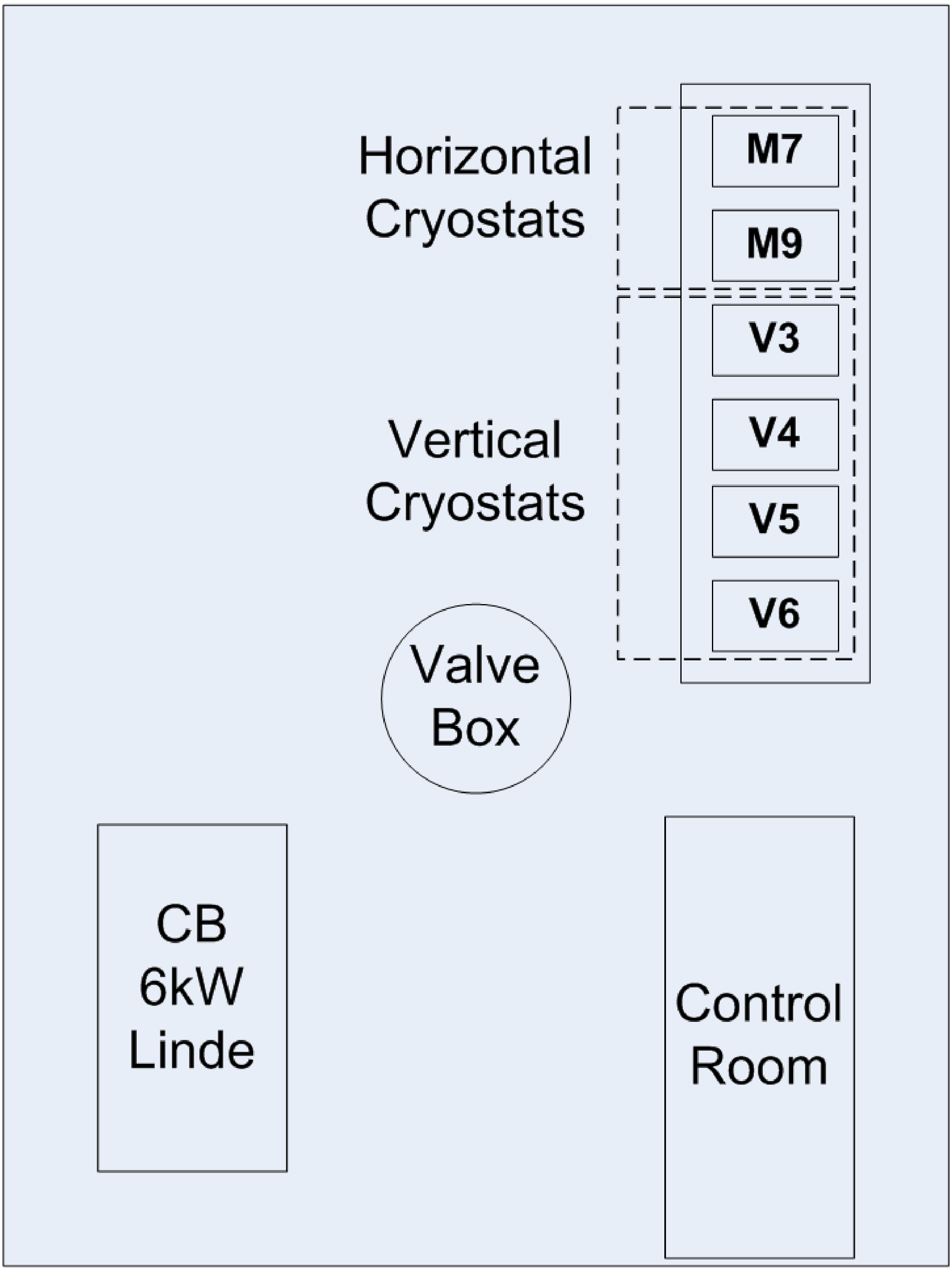


Figure 3.5: New layout of SM18 RF cavities test benches.

3.3 Control system configuration for the Radio Frequency Cavities test bench

3.3.1 Layout of the rack

Programmable Logic Controllers (PLCs) are widely used for controlling industrial equipment. They provide ease of programming process logic through high level languages, cost efficiency, high reliability and adaptation to industrial environment. They are used in CERN not only for typical industrial controls fields such as electricity, water, gas, cooling, ventilation, but also to control cryogenics, interlocks, vacuum, radio frequency and beam extraction. PLCs are part of a bigger system and in some cases, they are accessed through Front End Computers (FECs) [5].

New Radio Frequency test station which we have prepared has many sensors, cryogenic valves, end switches and heaters. To manage all these I/O, special electrical infrastructure was built, in the center of which, the process control rack can be found. It consists of three twelve slot backplanes — with one power supply on each — one Schneider Electric Premium CPU (with RJ45 connector for connection to the ethernet network, slot for PCMCIA memory extension card and slot for a PCMCIA communication card), nine Analog Input (AI) modules with sixteen channels, seven Analog Output (AO) cards with eight channels, six Digital Input (DI) modules and three Digital Output (DO) cards with thirty two channels on each. Figure 3.6 presents the arrangement of described modules.

All the equipment is connected with each other through the bus which is located on the backplane. For safety reasons, signals are not connected directly to extension cards but through the Phoenix modules (Fig. 3.7) via cables to the I/O cards. Every module is equipped with a electrical fuse, which ensures the security of all the electronic control devices in case of power surge and other electrical anomalies. Each digital I/O Phoenix module has thirty two channels, analog I/O modules has only eight of them. On the bottom of a rack there is a Burndy Plate, where all the process signals are located and the branch of power supply for the Phoenix modules and PLCs. The signals (sensors, requests, alarms etc.) from the test station are wired to the electrical cabinet, where they are put together in groups and transmitted as a Burndy plug (Fig. 3.8) to the rack located in a control room in SM18. The control signals from the PLC's modules are connected via cables to the Phoenix modules, then they are wired to the Burndy plate and are transferred outside the rack to the electrical cabinet, where they control executive modules such as valves, pumps, heaters, relays etc.

Data exchange between sensors and PLC is managed by Front End Computer (FEC) with a special software developed at CERN. Description of software frameworks used in this project can be found in Chapter 4. All devices are connected with each other using CERN Technical Network (Subsection 3.3.2).

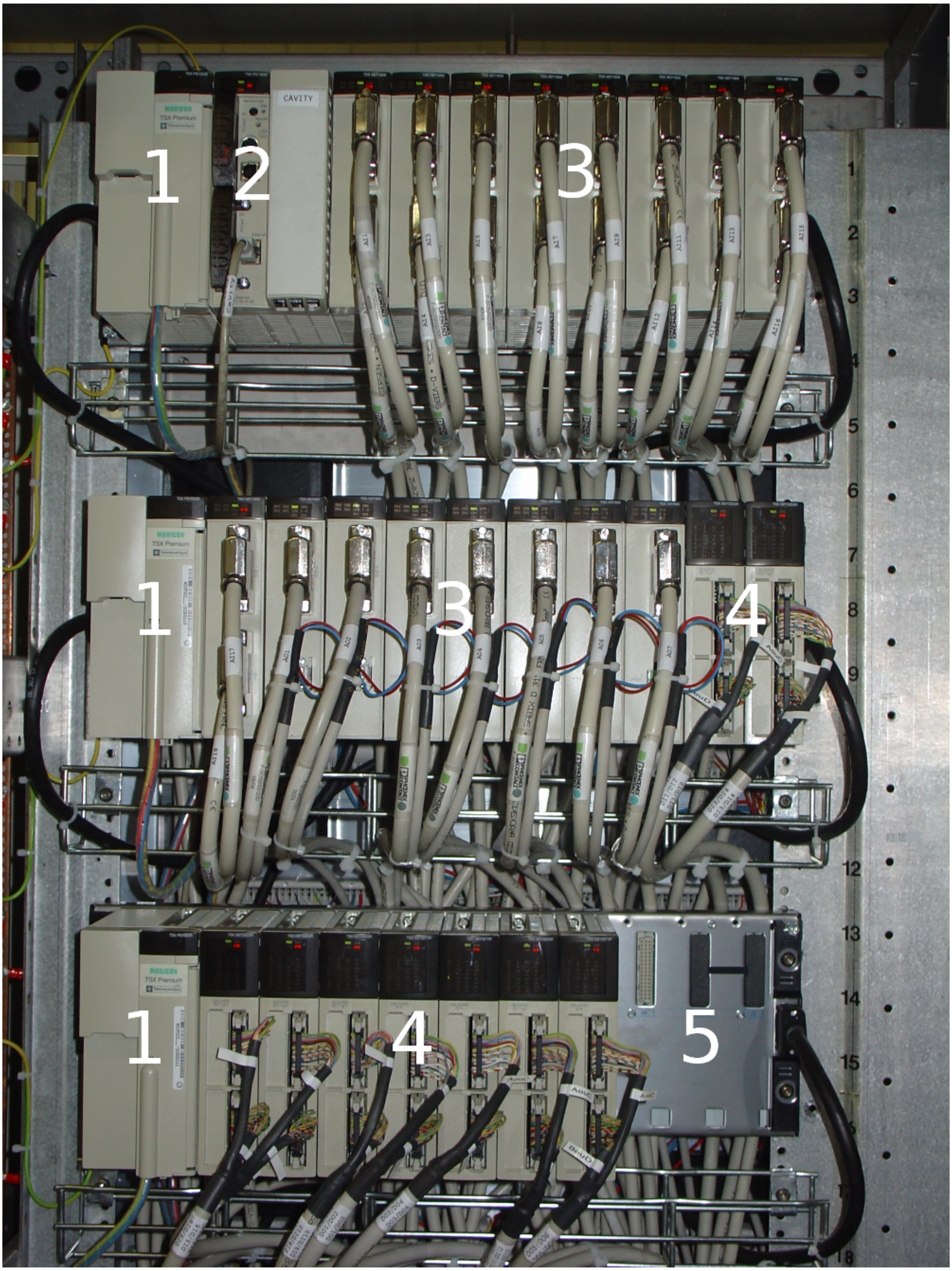


Figure 3.6: Arrangement of I/O modules. 1 – Schneider Electric Power Supplies; 2 – Schneider Electric Premium CPU; 3 – Analog Input/Output modules; 4 – Digital Input/Output modules; 5 – Backplane with three free slots.

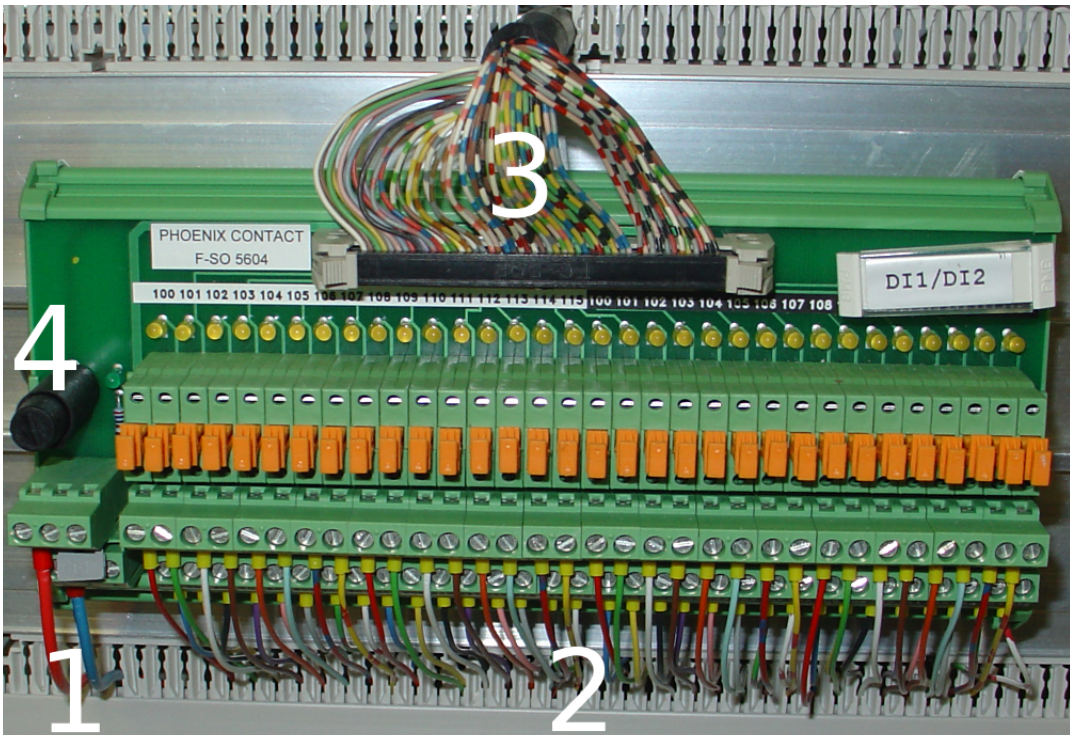


Figure 3.7: Phoenix Digital Input module. 1 – power supply for module; 2 – digital signals from test bench; 3 – connections via cable to PLC DI module; 4 – fuse.

Figure 3.8: Burndy plug and slot.

3.3.2 CERN Technical Network

At CERN there are two ethernet networks: the General Purpose Network (GPN) and the Technical Network (TN). GPN is deployed over the CERN facility and provides accesses to the Internet. The second one has restricted access and it is used only to control the equipment and does not have a link to the Internet. TN is highly subnetted, routed network based on fiber optical Gigabit Ethernet. The core is build of two redundant backbone routers located in the CERN Computer Center and in the Prévessin control room. These routers are interconnected in a redundant way with the series of regional routers [26].

The control system for the Radio Frequency Cavities test bench relies on the CERN Technical Network. The addresses we used in the project are from the range 172.18.xxx.xxx (mask 255.255.0.0), which prevents any direct connections between the Technical Network and the Internet. The TN infrastructure has a direct link to the GPN, so the communication from the inside of the Organization is still possible, but it can be forbidden if needed. All the network equipment is installed with a double power supply connected to two independent power sources, in order to provide proper connectivity even in situations of power cut.

3.3.3 Communication and data exchange

Status of cryogenic process in the Radio Frequency Cavities test station is provided by sensors measuring temperature (TT), pressure (PT) and the level of liquid helium (LT). The process is managed by analog/digital cryogenic valves and analog heaters. In addition, the process control is appointed with a few type of diagnostic devices and hardware interlocks, which are represented by digital signals.

Figure 3.9 presents the overview of data exchange between sensors, secure signals and process control devices. The measuring probes to communicate with the upper level of the control system need industrial computer gateways, called Front End Computers (FEC). These machines capture raw signals from the detectors and convert them to physical sensor information, including the calculation of individual non-linear transfer functions, moreover, they are also capable of conveying the commands for electrical heaters (EH). The sensing equipment is connected through the remote I/O FIP crate to the FEC using World Factory Instrumentation Protocol (WorldFIP). These type of communication was selected because of its high radiation tolerance as well as resistance to electromagnetic noise, and it is used whenever the front-end could not be moved away from disturbances. Furthermore, this protocol allows deterministic data transfer over long distances at high data rates up to 2.5Mbits. This feature is ensured by the fact that access to the medium is managed by a master node, which means that slaves can transmit only when they are requested by the master. This warrant, that in the worst case delays in message transmission will not exceed real time deadlines [27, 28].

The status of the sensors are send to the FEC (with FESA framework — Section 4.1) and then they are propagated through the ethernet connection (Subsection 3.3.2) to the PLC, which is responsible for the cryogenics of the Radio Frequency Cavities test station.

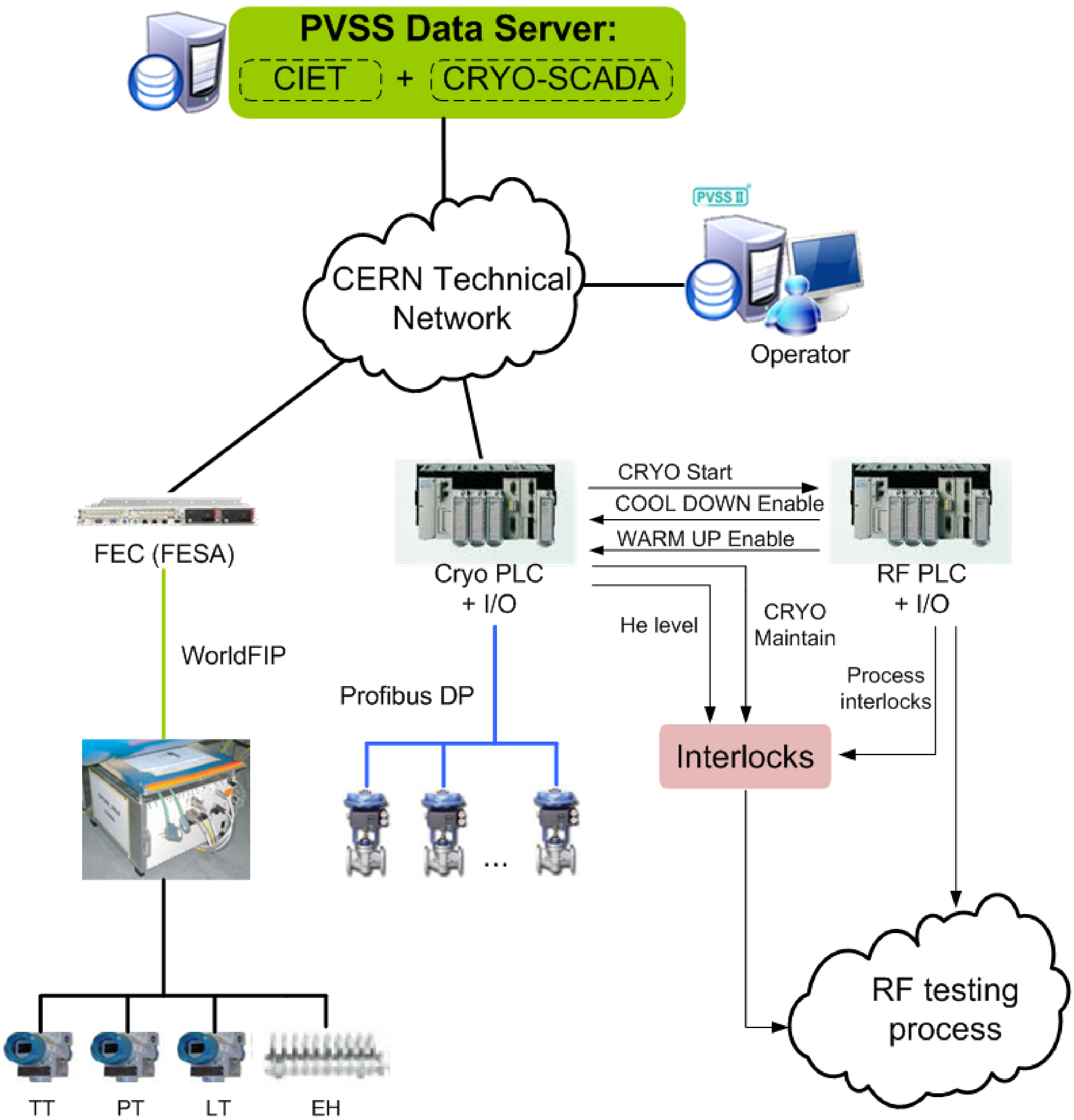


Figure 3.9: Communication structure of the RF test station.

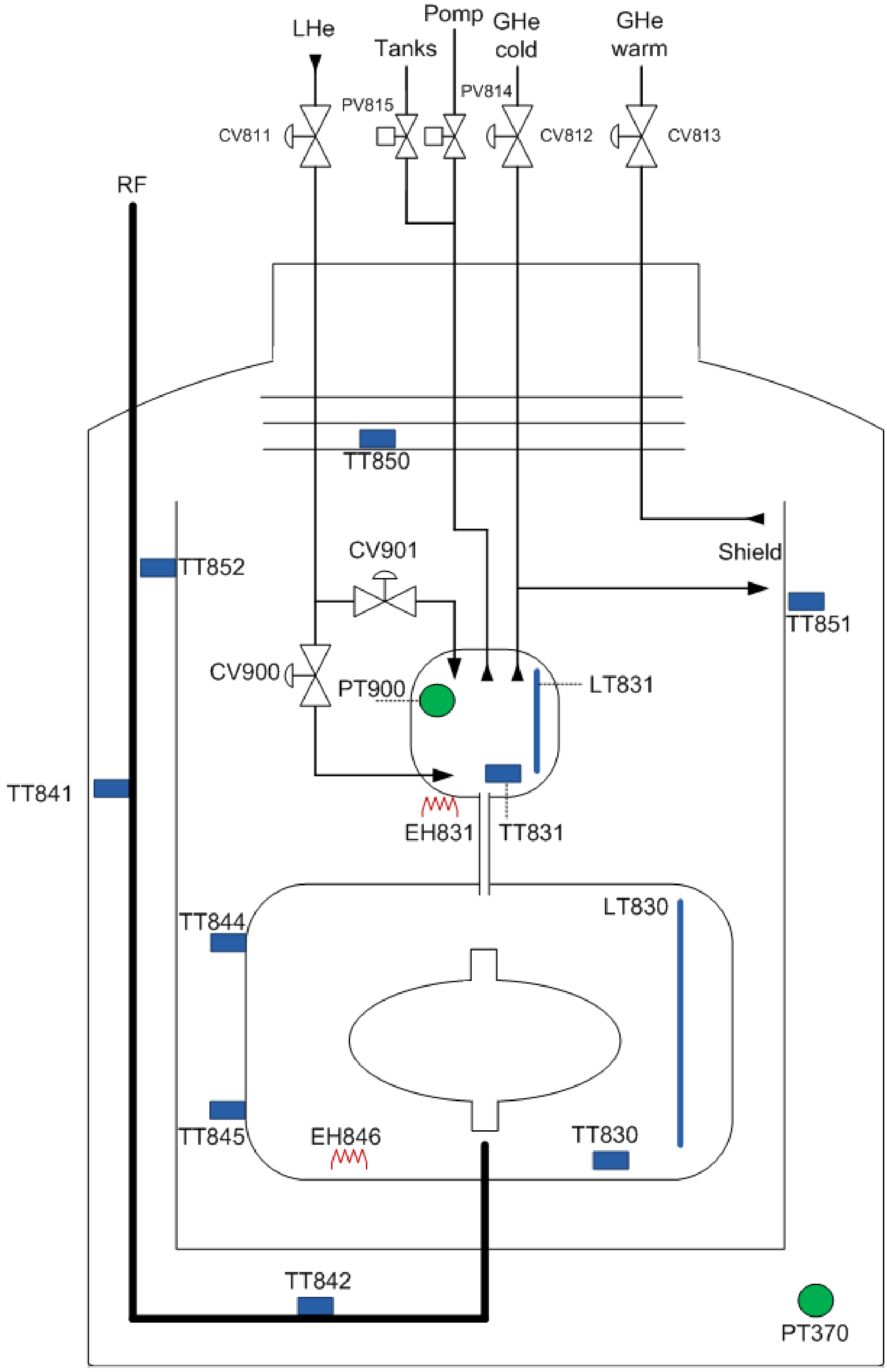


Figure 3.10: Cryostat (number 3) for the cavity.

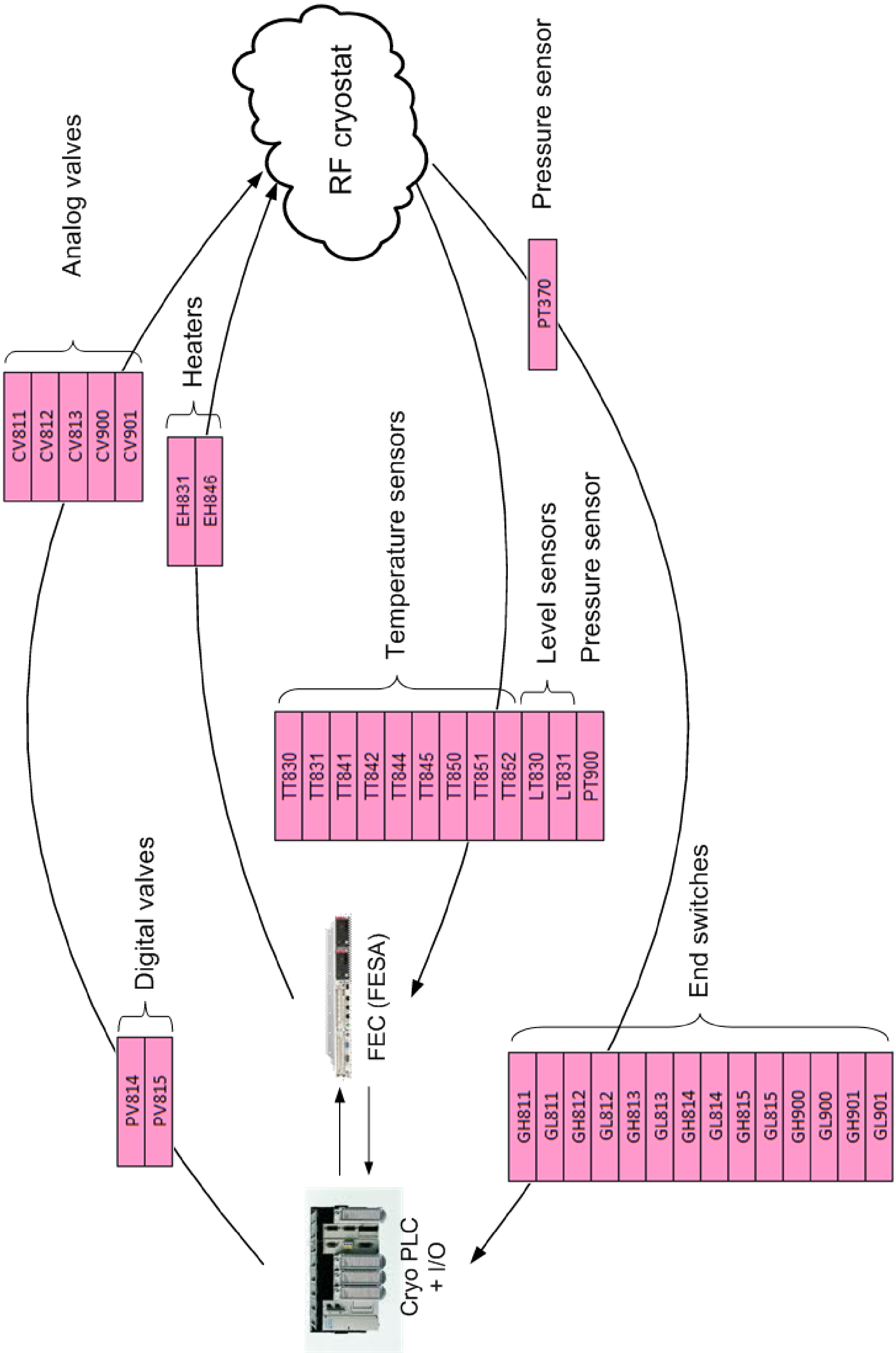


Figure 3.11: Structure of data exchange in the RF Cavities test station.

There are four additional signals, which help to control process correctly. The first one is an analog output, which holds the information about the level of liquid helium. Such solution was mandatory, because if there is not enough coolant in the cryostat, it assures that the process does not start or when it is already running, cancels it immediately. For security reasons, it is very important to have certain amount of liquid helium, otherwise high currents flowing in the circuits can damage the test bench. Another two important digital output signals for the control process are CRYO Start and CRYO Maintain. The first one checks if all condition for starting the process are met and if it is true, it gives logic 1 to the output. The second one controls if the conditions for safe tests are kept, if not, it stops the whole process. There are also two digital input signals — COOL DOWN Enable and WARM UP Enable. Every one of them sends request to cryogenic PLC to embark certain action. The Profibus network is used to send requests to the on-off valves (PV) and to read the feedback from the analog valves (CV).

The human-machine interface is based on two SCADA (Supervisory Control and Data Acquisition) systems — CIET (Cryogenic Instrumentation Expert Tool) and CRYO-SCADA — built with PVSS and running on data-servers hosted in the CERN Control Center (CCC). CIET is used by the control experts to remotely monitor, configure, parametrize, and reset the WorldFIP read-out channels, while CRYO-SCADA allows operators to access data and commands relevant to the cryogenic process. It consists of synoptic panels, which provide navigation, monitoring and control for all instruments. It also handles alarms, interlocks, real-time and historical trends, data and event logging and archiving [29]. The data for CIET are obtain directly from FESA by sending requests to it, SCADA gathers information from the cryogenic PLC.

Chapter 4

Frameworks and software production for the Radio Frequency Cavities test station

This Chapter presents the frameworks that were used in the Radio Frequency Cavities test station project, as well as the code and synoptic production procedure.

4.1 FESA software framework

Front End Computer executes the equipment access software for the Radio Frequency Cavities test station. It is capable of accessing data from the hardware interface boards and providing the information to any software agent in the control system.

The software running in FEC was developed using a specific framework, known as FESA. It is a complete environment for the equipment specialists to design, develop, test, and deploy real time control software. The repetitive components of the equipment control software have been formalized into a generic model, which defines the structure of the real time part of the software. It manages hardware and interrupts, together with the structure of the server tasks that handles external requests.

To build the control software, the set of configuration tools for the creation and evolution of any FESA component was provided. They were used to define internal data structures, syntax of external commands, links between hardware events or external requests and treatment code. External requests are handled by dedicated server tasks that fully implement the device access model of the Controls Middleware (Section 4.2).

Some system level services are provided for the operation of the FEC, such as handling errors from the equipment, monitoring of the processes, etc. These services cause the real time behavior of the FEC. In addition they support remote control for adjusting parameters — such as the trace level of a task — or executing corrective action.

The developers and the users (equipment specialists, operators, and maintenance team) has also a set of interactive tools, test applications and Java libraries, which allow them to test all the functionalities of the software during its development and operation. These instances are all generated in an automatic manner, without any specific code being required [6].

FEC installed in SM18 control room runs a real time operating system called Scientific Linux CERN. The software tools are written in Java, thus they are platform independent.

4.2 Controls Middleware

The Controls Middleware (CMW) is the package of protocols, Application Programming Interfaces (API), and software frameworks, which allow uniform communication between the software entities of the control system. There are two models which are supported: the device access model and the messaging model. Both are briefly described in sections below.

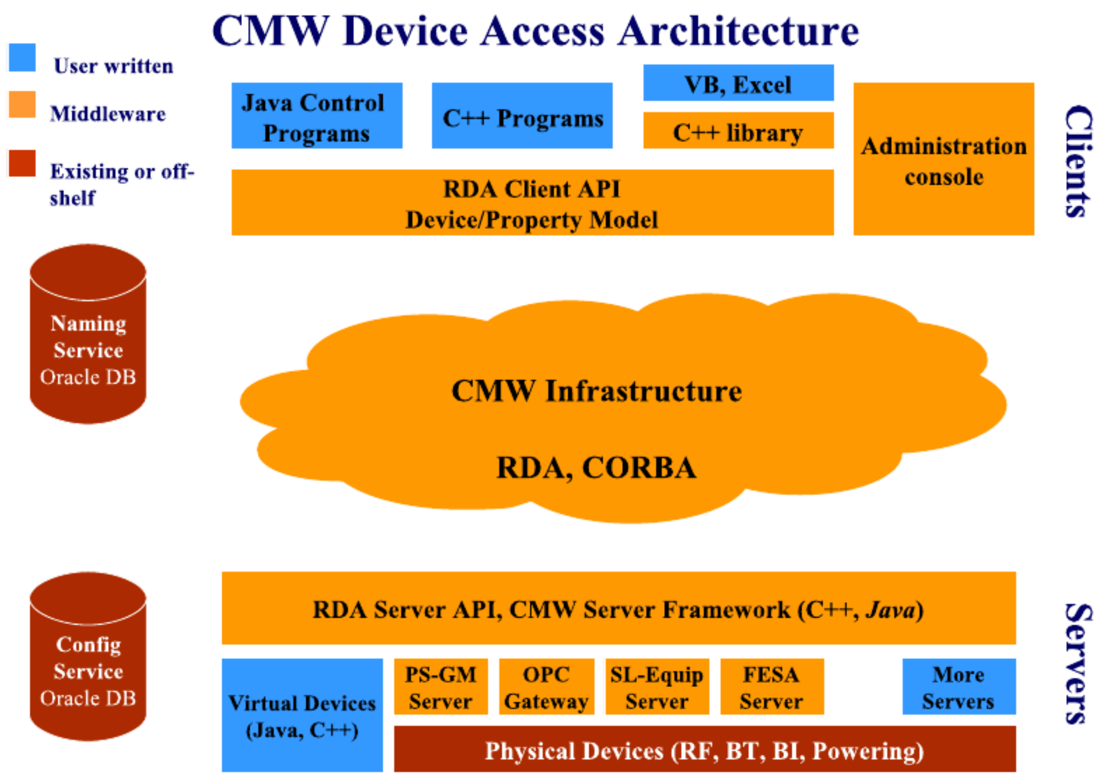


Figure 4.1: The Device Access Model.

4.2.1 Device Access Model

Figure 4.1 presents the full architecture of the CMW Device Access Model. Common use of that kind of communication model is between Java applications and CMW equipment servers running in FECs. These processes communicate with each other through the Remote Device Access (RDA) API, which is available for Java and C++ languages. Inside the device access model, it is possible to access all the equipment as a "device", because every one of them has a named entity within the control system, which corresponds to a physical device or to a virtual controls entity. Each device has a number of properties that characterize its state. The device status can be accessed by reading the value of interesting us property, moreover it can be controlled by setting one of its properties with the required value. "Get" and "Set" value request can be either synchronous or asynchronous. This model gives also an opportunity to monitor changes of values via listeners (callbacks). Sometimes it is needed to specify under which conditions the operation has to take place. These conditions are commonly referred to as context or filter. A list of properties, together with their type description and the semantic of the assessors, is referred to as a contract. They serve a particular purpose, for instance measurements or settings of a device [6].

4.2.2 Messaging model

Complementary to the device access model, the messaging model allows any software process to send and receive asynchronous messages in a loosely coupled way. Many application programs exchange data via asynchronous messages: timing and logging events, notifications, and alarms, those are typical examples of data which are asynchronously generated from a various set of producers, and which is potentially of interest for multiple clients. The software of a control system is build on the Java Message Service (JMS) as the messaging solution for Java based controls application. The JMS specification adds a standard and vendor independent API that enables the development of portable, message based applications in the Java programming language. In addition the JMS is a strategic technology for the Java 2 Platform Enterprise Edition (J2EE). The Alarm Service is a typical example of a messaging system relying on the publish-and-subscribe paradigm: it subscribes to alarm notifications published by several processes, and after processing redistributes the result to dedicated consoles and any other controls software component that subscribed to the appropriate alarm content hierarchy [6].

4.3 The UNICOS framework for industrial controls

The control system architecture is divided in three layers (Fig. 4.2). The first one (field layer) consists of the process sensors and actuators (valves, heaters etc.) which are connected to the control system using PLC I/O modules and/or field buses. Control layer consists of the process logic implemented in the PLCs. The last part of the architecture (supervision layer) provides the monitoring and commands through the Supervision Control And Data Acquisition (SCADA) system. The problem of such type of control system is lack of homogeneity between those layers. The main purpose of the UNified Industrial COntrol System (UNICOS) is to integrate the architecture of the control system. The software design is an arise of an object-oriented philosophy used with earlier control systems. In this framework, each apparatus such as sensor, actuator, or other device included in the process is modelled as an object. It provides methodology, components and tools to design and program industrial control systems. This methodology allows production of a functional analysis by the process engineers, which can be directly implemented in the PLC code by the programmer. UNICOS can be deployed to variety hardware and software items. The control software for FECs, Schneider (but also available for Siemens) PLC, CIET and CRYO-SCADA used in the Radio Frequency Cavities control system is mostly based on the UNICOS framework.

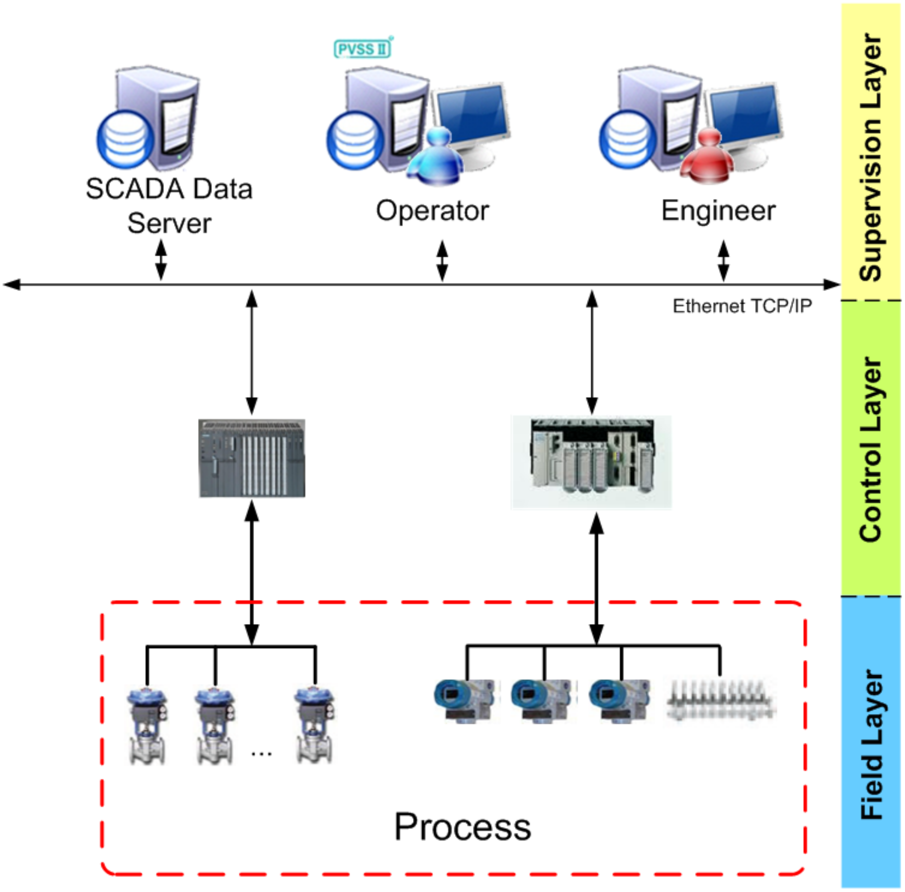


Figure 4.2: Three layer architecture of the control system.

All the objects classes have been designed according to the same principles. The implementation of the objects in UNICOS branch out into two parts:

- the GUI functionality — programmed in the SCADA,
- the process behavior — programmed in the PLC.

SCADA objects were made to help the operator to interact on the process by means of graphical components and dedicated panels called “faceplates”. Their main purpose is to inform the operator of the equipment status, and allows him to send requests to it. All the objects are linked to the plant through I/O channels and they are connected to the PLC via either a fieldbus or a direct I/O connections. The SCADA and PLC object parts are connected together by a communication layer based on the TCP-Modbus protocol. Objects implemented in the PLCs are provided with a proxy in the supervision layer. The UNICOS middleware is responsible for synchronizing the PLC’s objects with their proxies, particularly when the result of each command or process changes. Figure 4.3 presents, that each PLC object has several interfaces and receives the following information:

- requests from the operator via the SCADA object — these orders are transmitted to the PLC by manual requests through the communication middleware,
- configuration parameters (GUI or PLC) set during the programming phase and accessible for modification by a program specialist,
- information from the process (input signals), consisting of analogue or binary values from sensors and status of other objects,
- orders from the control logic programmed into an object of a higher hierarchical level via the Auto Requests.

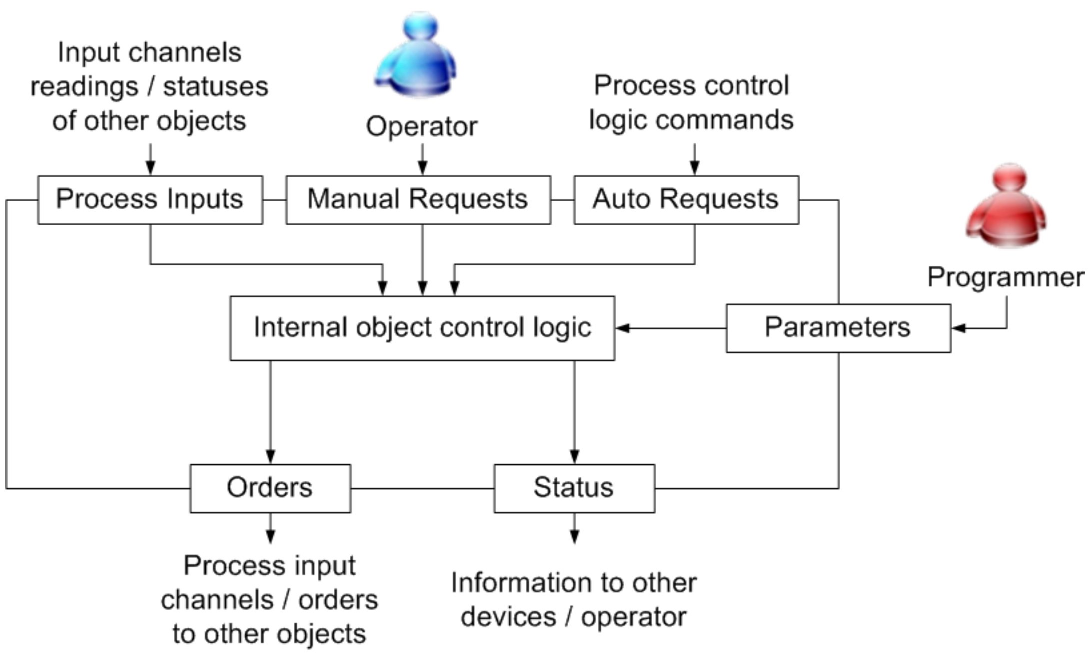


Figure 4.3: PLC object model.

There are three main types of object that are defined in the UNICOS architecture [6]:

- Input-Output Objects provide the interface to the plant. They link the devices and actuators to the control system. Some basic treatments may be embedded in these objects. Input/Output channels are accessed only through such objects,
- Field Objects represent hardware elements, such as valves, heaters, motors, and other process devices. Each type of Field Object has its own associated process logic. This logic integrates specific functions (for instance alarm generation, transition between set points, interlocking),
- Process Control Objects (PCO) control equipment units grouping several Field Objects and/or other PCOs. The process logic of these objects is split between a standard part (insuring a homogeneous interface to the environment) and a specific part to handle the process to control.

The I/O and Field Objects are Control Modules, while the PCOs can be considered as Equipment Modules or Units — depends on the level of complexity they handle.

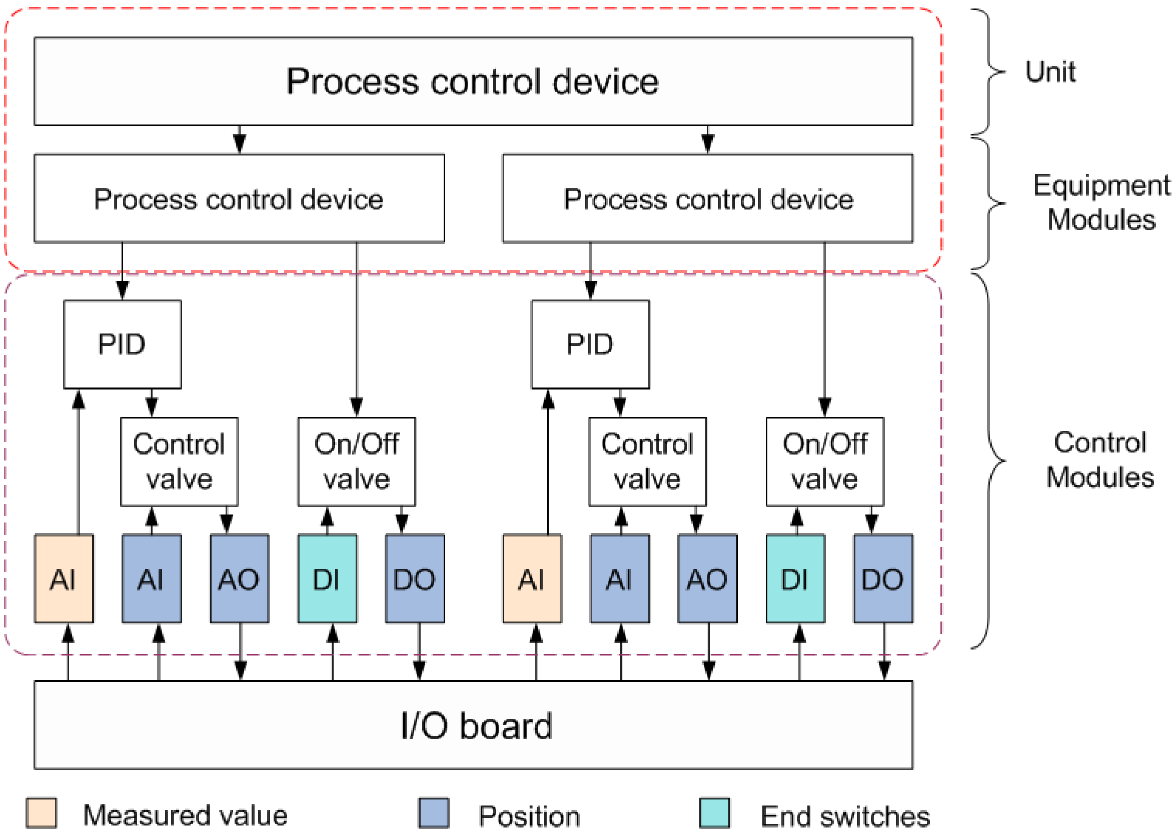


Figure 4.4: UNICOS object hierarchy.

Taking into account the internal states of the object (auto/manual mode, interlocked, started, stopped, forced etc.), the object control logic of the PLC processes all the input signals together with requests and sends orders to the process outputs and/or lower level objects. After that, it distributes the status of the object to inform the other objects and/or operators via the communication middleware.

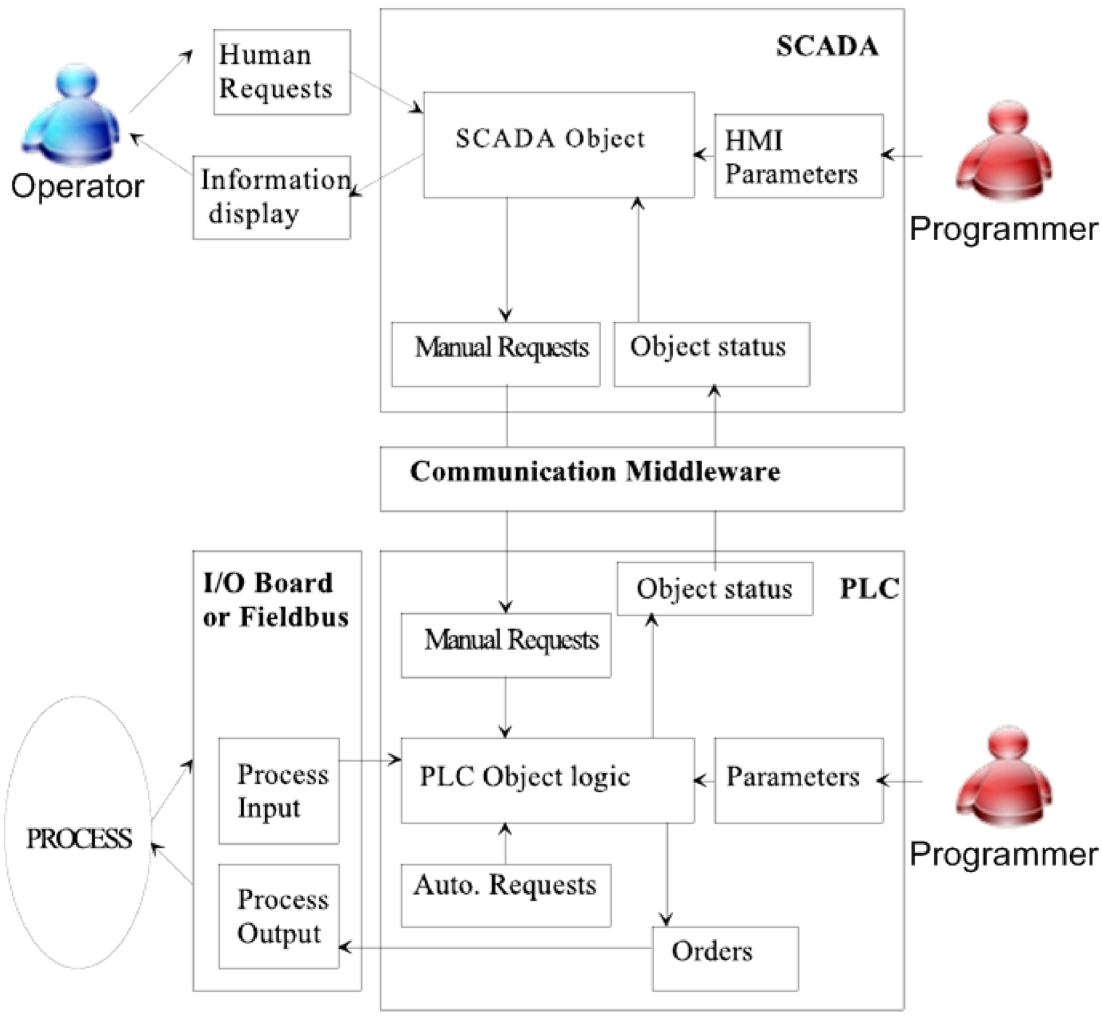


Figure 4.5: The UNICOS object model.

The PCOs are the nodes of the object hierarchy and they need to be versatile to cooperate with the process logic, that is why they provide:

- conditions for the Controlled Stop — it is used to stop the object in a controlled way,
- conditions for the configurable interlocks, to act correctly on the PCOs in case of abnormal situations. There are several interlocks, such as:

  - Start Interlock — avoids starting up but does not stop the running process,
  - Temporary Stop — stops the process in case of anomalies, but allows restarting it when they disappear,
  - Full Stop — it is similar to one above, but the difference is that, the process can be restarted only after operator acknowledgment,

- configurable feedbacks — the on/off status of the PCO depends on the process inputs and states of its child objects,
- global logic — implements the global parameters computation,
- dependant object logic — code which drives each child object of a given PCO. It defines the "auto" requests to be sent according to process inputs and the status of the PCO.

The PCOs are also capable of propagating the alarm acknowledgments and transitions to "auto" mode towards their children. They are also handling the Option Modes, which specify the process current function [30].

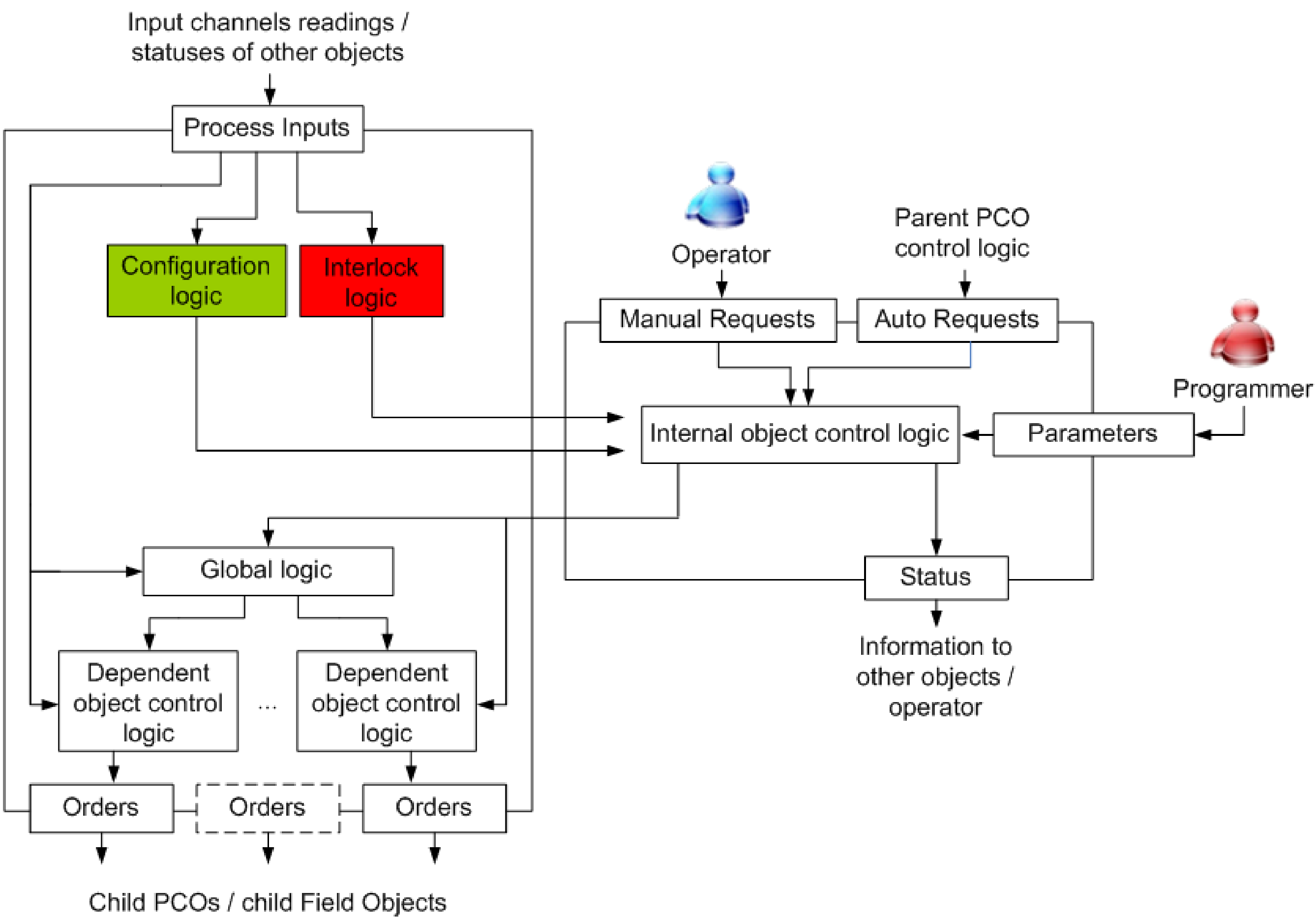


Figure 4.6: UNICOS PCO model.

4.4 Software production

To help application developers in all phases of software production, special set of components and tools supporting UNICOS model have been produced. In addition, to cover all needs of the cryogenic system, a set of field objects have been developed. Process engineers are obligated to verify, if the UNICOS process field object library covers the system demands. In case there are some missing types, the new objects have to be developed for SCADA and PLC layers.

In order to start the programming of the PLC, at first we needed to prepare process functional analysis, it means, that we had to define a hierarchy of the PCOs used in the Radio Frequency Cavities test station (Fig. 4.7). To do that, we needed to identify the different Units and Equipment Modules (PCO) by grouping together Control Modules. This is the most critical phase, because there are no general solutions. The best way to do that, is to identify circuits which are performing different and independent tasks. After we established the hierarchy for each PCO, next step was to define other parameters, such as:

- interlocks and feedback conditions,
- option modes — stand by, cool down, warm up,
- finite state of the machine,
- global parameters computation,
- dependant logic for each child objects — for each PCO we needed to define specific logic, it usually consists of interlocks and the logic used to control dependant objects.

In addition, according to the process specifications, we were obligated to specify the complete list of I/O and field objects. We gathered all relevant information by filling out the provided Excel spreadsheets (Fig 4.8, 4.9). In these parameters were also included process information for the PLC and configuration data for the supervision. All the hardware related information were based on the electrical drawings and Process and Instrumentation Diagrams (P&IDs). After this step, the first phase of coding could start. All the PLC objects and their PVSS proxies had to be created in the two layers. To do that, the Instance Generator (tool developed at CERN) produced — from the filled up Excel spreadsheets — configuration files, which included all the objects for the RF Cavities control system together with their memory assignment in the PLC and the SCADA. Afterwards, these files were imported into the PLC and SCADA, the middleware was automatically configured. This stage allowed us to start the commissioning of the installation from the supervision, down to the sensors and actuators.

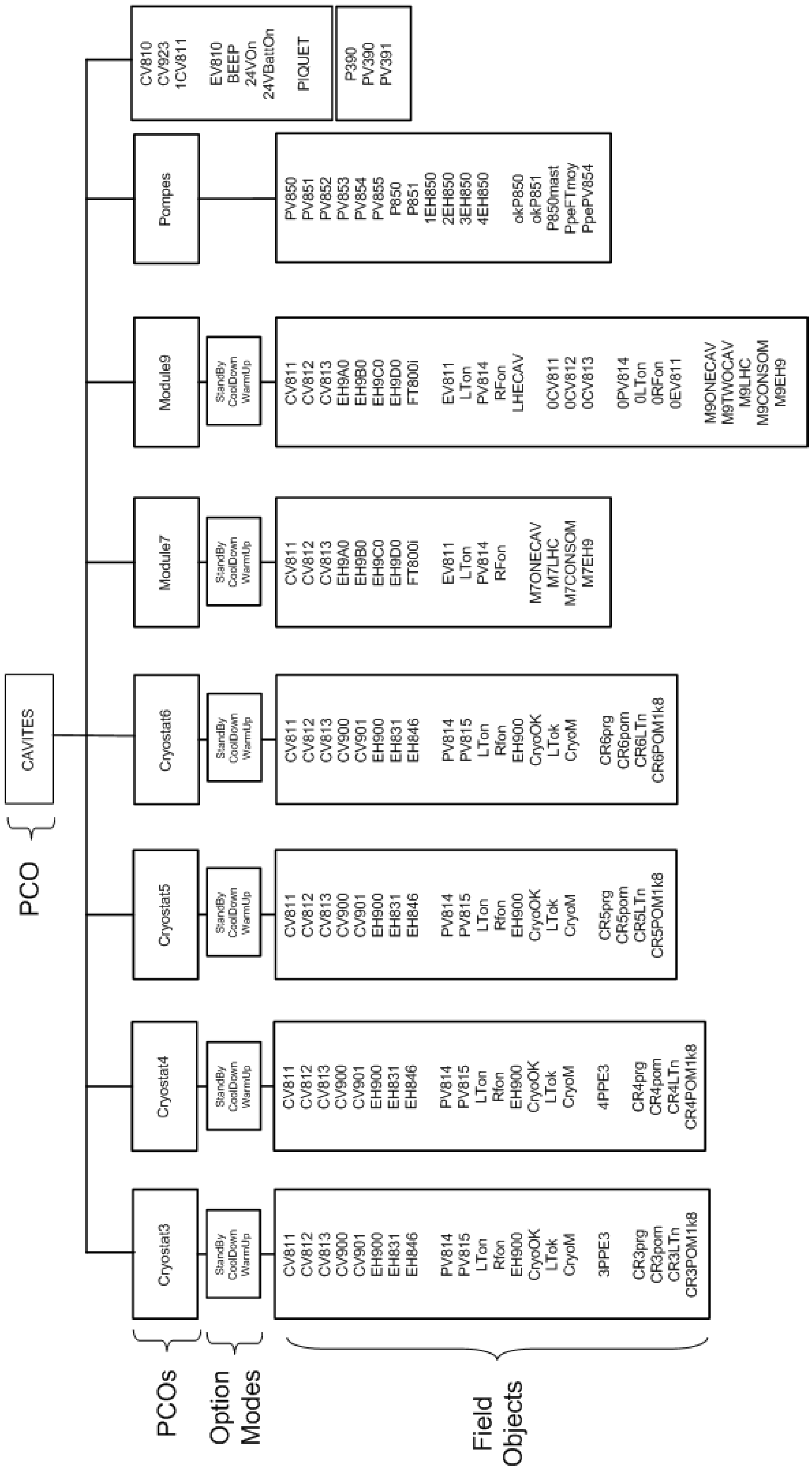


Figure 4.7: PCO hierarchy for the RF Cavities test station.

PLC CHANNEL	ELECTRICAL DIAGRAM	EQUIPMENT	LOCATION	NAME	DESCRIPTION	INSTANCE TYPE	UNIT	RANGE MAX	RANGE MIN
ADDRESS	HARDWARE					AnalogInput_Small			
%IW0.7.3	AI9.3	QLKRF	S	3PT370	ENCEINTE_A_VIDE	AnalogInput_Small	mB	2000.0	0.0

Figure 4.8: Example of the I/O specification for the RF Cavities test station control rack.

EQUIPMENT	LOCATION	NAME	PROCESS INPUT					PROCESS OUTPUT	DESCRIPTION
			FEEDBACK ON	FEEDBACK OFF	LOCAL DRIVE	LOCAL ON	LOCAL OFF		
TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD	TBD
QLKRF	S	3PV814	3GH814	3GL814				3PV814DO	PURGE_OU_ATM Open

Figure 4.9: Example of the devices specification for the RF Cavities test bench control system.

Another phase of coding consisted of producing the application specific PLC code. The Logic Generator (another tool developed at CERN) provided us with the PLC program logic skeleton, which was compliant with the PCO hierarchy (Fig. 4.7). This configuration file defined the order and the relations between PCO-PCO and PCO-Field Objects. After importing it to the program, we were capable of coding the logic into the PLC, using the provided skeleton as a placeholder of the code. No additional code development was needed for the supervision layer.

If there is a necessity of replicating equipment modules or if there is a situation, that there are many equipment of the same type it is possible to replace the manual production of the code by the automated one. In that case, the interlock logic, configuration logic and global dependent child objects logic can be programmed as include files, which will be used later on by the logic generator to produce complete PLC code instead of generic skeletons.

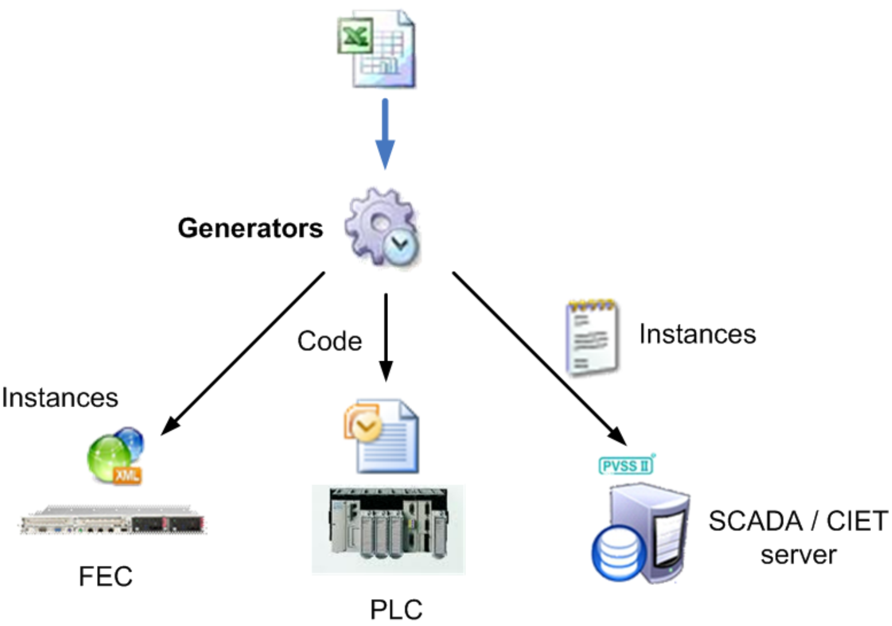


Figure 4.10: Generation mechanism.

4.5 Synoptic panels development

Supervisory Control and Data Acquisition (SCADA) systems are widely used at CERN. To help operators with management of the Radio Frequency Cavities test station cryogenic process, we have prepared a set of graphical panels.

To produce the synoptic views, we used a drag and drop drawing tool. This Graphic Editor allowed us to prepare static and dynamic parts of the panel, by placing the correct widgets — which corresponded to the proper object — on the panel. The panel we have created consist of all the objects used in the process such as sensors, digital valves, analog valves, PIDs, PCOs etc. All of them display animated synoptic of a control process, trend and alarm windows, they are also capable of sending back control parameters as well as operator's commands. In order to do that, the PVSS provides a run time database, which is responsible for storing the data from the devices. Each object has a unique name (Equipment_Location_Name Fig. 4.9) in that DB, and it can be easily accessed for processing, visualization etc. What is more, all this information can be archived for long term storage, and retrieved later by user interfaces or other processes. It is also possible to define the alarms conditions for the data arriving to the database.

Precise set of flags and alarms summarized in one place, help operators in diagnosing the process and in some cases detect the malfunctioning equipment [31]. A great amount of program parameters for the process were customized during the tests through the SCADA application.

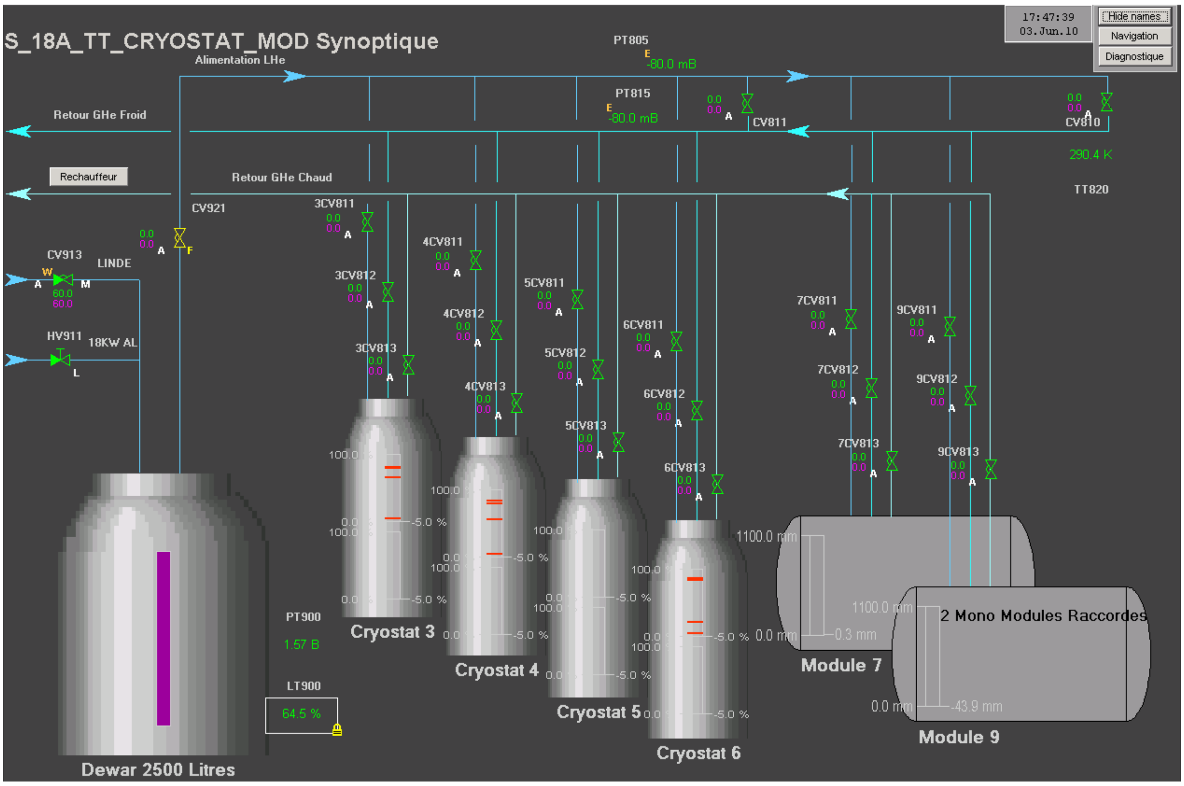


Figure 4.11: Synoptic panel of the Radio Frequency Cavities test station.

Conclusions

Presented production of the Radio Frequency Cavities test station shows the approach to the controls at CERN. To handle such a large scale control system an automatic code generation is necessary. The control software production relies on a set of package of automatic generation tools. They have been developed to create data and code in several steps. Their main advantages are:

- reduced software production time and effort,
- increased code reliability,
- minimized risk of human mistakes and simplified long term maintenance.

The applications we have prepared — which are based on UNICOS framework — proved to be very efficient tools for operators. The process experts are able to interact with any object in the application, through SCADA interface. It gave us a possibility for flexible troubleshooting during tests of the Radio Frequency Cavities test station. What is more, easy creation and modification of synoptic panels does not require programming knowledge, so any additional functions of the panels can be added by operation crew. The concepts of the UNICOS framework have shown their usefulness when developing and changing the applications. It gives the easiness of modification while commissioning thanks to the readability, modularity and reusability of the code. Moreover it ensures excellent stability of the PLC, however the use of the objects cause extra memory usage as well as additional CPU load, that is why it is not suitable for time critical control system (below 10ms).

The performance of the closed control loops depends on the quality of the ethernet communications between PLCs and FECs. Because of the low occupancy and high availability of the Technical Network infrastructure at CERN as well as the optimization of the applications' code and the network topology, the performance of the controls is not violated despite, that the ethernet is not a deterministic network.

Significant improvements have been implemented in the SCADA and cryogenic control system of the SM18. An industrial and an accelerator frameworks have been successfully integrated in control system, showing their highly complementarity.

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