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Tesi di dottorato di ricerca

**The ALICE experiment at CERN: development and commissioning
of the cooling and control systems of the Silicon Pixel Detector and
optimization of the LHC Exchange Interface project**

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*A mia moglie Lara
ed alla mia cara nonna Stella*

“El saber no ocupa lugar”

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Introduzione

Durante i tre anni del mio dottorato di ricerca al CERN (European Organization for Nuclear Research) ho collaborato alla messa in funzione dell'esperimento ALICE (A large Ion Collider Experiment), uno dei 4 grandi esperimenti del Large Hadron Collider (LHC), l'acceleratore di particelle costruito in Svizzera, vicino a Ginevra, negli anni '90. ALICE è diventato operativo nel 2008, dopo 20 anni di ricerca, progettazione, costruzione ed installazione delle strutture e degli equipaggiamenti che lo compongono. Questo esperimento fa parte di un ampio progetto di scientifico il cui scopo principale è lo studio del Quark Gluon Plasma (QGP).

Il mio lavoro ha riguardato tre compiti principali: il sistema di raffreddamento e di controllo del dispositivo di rivelazione a pixel di silicio (SPD) e il progetto LHC Exchange Interface.

Per quanto concerne SPD ho contribuito alla fase di progettazione, installazione e controllo del sistema di raffreddamento che, come sarà spiegato in dettaglio in questa tesi, è di fondamentale importanza per il funzionamento del rivelatore stesso.

Quando ho iniziato a lavorare su SPD nei primi mesi del 2008, la fase di commissioning in laboratorio era stata completata ed il rivelatore era appena stato installato nella caverna dell'area sperimentale di ALICE.

Relativamente al sistema di raffreddamento, ho partecipato alla progettazione ed installazione di alcuni componenti. Inoltre il lavoro che ho svolto ha permesso di ottimizzare l'impianto di SPD in quanto ho eseguito diversi tests per migliorarne le prestazioni, ho aggiornato il sistema di monitoraggio dello stesso, ho installato dei sensori che permettono di ottenere misurazioni molto accurate ed infine mi sono occupato della manutenzione del sistema durante tutta la mia permanenza.

Il secondo compito che ho portato avanti è consistito nello sviluppo di parte del Detector Control System (DCS) tramite l'utilizzo di un software SCADA (Supervisory Control and Data Acquisition) che offre un duplice vantaggio in quanto permette il controllo totale del rivelatore ed allo stesso tempo si integra perfettamente con il sistema di controllo generale di ALICE.

In questo contesto ho implementato il read-out hardware e software dei sensori di pressione e temperatura delle linee di raffreddamento e ho elaborato un dispositivo che permette il collegamento diretto tra il sistema di controllo ed il Configuration Database (CDB) del rivelatore.

Ho collaborato ad implementare il progetto LHC Exchange Interface (LHC_EI), in particolare l'esecuzione del sistema di controllo che costituisce la connessione tra l'esperimento ed il collisionatore. La maggior parte del lavoro ha riguardato l'ottimizzazione di fasi molto delicate di sincronizzazione tra ALICE e LHC per le quali ho elaborato diversi strumenti d'analisi che riguardano luminosità, intensità e background dei fasci collidenti all'interno dell'esperimento stesso. Inoltre, nel momento di avvio di LHC ho supervisionato in qualità di esperto le operazioni di iniezione del fascio in ALICE e di scambio dati con l'acceleratore.

Questa tesi è composta da 4 capitoli: il primo introduce brevemente il CERN, gli esperimenti e gli scopi che la fisica delle particelle si è prefissa di raggiungere grazie ad LHC.

L'esperimento ALICE è descritto in questo capitolo e particolare attenzione è stata data al Silicon Pixel Detector.

Il capitolo 2 riguarda il sistema di raffreddamento di SPD e le sue caratteristiche principali. La fase di commissioning del sistema, l'evoluzione delle prestazioni ed i test eseguiti sia sul detector reale in caverna che sul settore replica sono descritti nella seconda parte di questo capitolo.

Il terzo capitolo concerne gli aspetti principali del sistema di controllo generale di ALICE e dei rivelatori che lo compongono. Particolare attenzione è stata data al pacchetto software che ho utilizzato (PVSSII) ed alle strategie adottate per ottimizzare le risorse disponibili (JCOP framework). Inoltre, descrive il funzionamento della Finite State Machine (FSM) che ha permesso di integrare i sistemi di controllo di molteplici rivelatori. In questo capitolo sono spiegate anche alcune caratteristiche importanti per il DCS di SPD.

Il capitolo 4 è completamente dedicato al progetto LHC Exchange Interface le cui peculiarità e struttura complessiva sono brevemente spiegate, mentre gli aspetti legati ai processi operativi più cruciali ed alle fasi di sincronizzazione tra ALICE ed LHC sono descritti in modo più approfondito.

Introduction

During my three years of research doctorate at CERN (European Organization for Nuclear Research) in Geneva, I cooperated in making the ALICE experiment (A large Ion Collider Experiment) operative. This is one of the four large experiments of the Large Hadron Collider (LHC) the particle accelerator that was built in Switzerland, in the Geneva area, in the 90s.

ALICE became operative in 2008, after 20 years of research, designing, building and installing all the equipment and devices it consists of. It is part of a wide research project whose main role is the study of the Quark Gluon Plasma (QGP).

I dealt with three main tasks: the cooling and control systems of the Silicon Pixel Detector (SPD) and the LHC Exchange Interface project.

As concerns the Silicon Pixel Detector (SPD) of ALICE I collaborated in the designing, installation and control of the cooling system which, as will be explained in details throughout this work, is a fundamental component for the running of the detector.

When I started to work on SPD at the beginning of 2008, the commissioning in the test laboratory was over and the detector had just been installed inside the experiment the cavern. Therefore I joined in when its commissioning in the experimental area was about to start. As regards the cooling plant I took part in the designing of some components and in their installation.

My work allowed to optimize the cooling system of SPD since I performed several tests to improve its performance, I upgraded the monitoring of the cooling system, I installed some sensors that are necessary to carry out more accurate measurements and I also took care of the maintenance of the overall system.

I developed part of the Detector Control System (DCS) using a software SCADA (Supervisory Control and Data Acquisition) which provides a double advantage since it allows to fully control the detector while it perfectly integrates in the ALICE general control system.

I implemented both the hardware and software read-out of pressure and temperature sensors for the cooling lines and worked out a device that provides direct access between the control system and the detector Configuration Database (CDB).

I have also taken part in the implementation of the LHC Exchange Interface project (LHC_EI), particularly in the execution of the control system that is the link between the experiment and the collider. For the most part I worked on the optimization of some of the most delicate synchronization between ALICE and the LHC. I realized several analysis tools concerning the luminosity, intensity and background of the beams colliding inside the experiment. Therefore during the LHC start-up phase I was assigned the task of expert in charge of the beam injection operations in ALICE and of the data exchanged with the accelerator.

This thesis consists of 4 chapters: the first one briefly introduces CERN, its experiments and the major aims that particle physics is supposed to achieve thanks to the LHC. The ALICE experiment is also explained and particular consideration is given to the Silicon Pixel Detector.

Chapter 2 deals with the cooling plant of SPD and its main characteristics. The commissioning stage of the system, the evolution of its performance and the tests carried

out both on the detector in the cavern and on a dummy sector are described in the second part of this chapter.

The third chapter is about the most important features of the ALICE general control system and of its detectors. Particular attention is given to the software package that I used (PVSSII) and to the strategies adopted to optimize the available resources (JCOP framework). Moreover, it describes the working of the Finite State Machine (FSM) which allows to integrate several detector control systems. Some important features that I implemented for the DCS of SPD are also explained in this chapter.

Finally chapter 4 is fully dedicated to the LHC Exchange Interface Project. The project main characteristics and overall structure are briefly explained while the aspects linked with the most crucial operating phases and synchronizing steps between ALICE and the LHC are described more in details.

Chapter 1

Overview of ALICE at the LHC

1.1 The CERN Laboratory

CERN, the acronym for Conseil Européen pour la Recherche Nucléaire, is one of the most important and forefront centres for scientific research in the world. It was founded in 1954 by 12 states. Presently it counts 20 member states.

Its main commitment is to pursue the quest to understand the basic laws of Nature.

Here the world's largest and most complex scientific instruments were built in order to discover and study the behaviour of the fundamental constituents of matter. Such instruments are particle accelerators and detectors. Accelerators speed up beams of particles to a given energy before making them collide against each other or against fixed targets. The outcome of the collisions at such energies (~ 10 TeV) consists of a huge number of particles with different masses and charges that demand complex detection systems and well defined analysis strategies to get deeper insight in the behaviour of fundamental forces.

CERN is not only concerned with scientific research but also with technology (one example for all: the World Wide Web was invented here in 1989 by Tim Berners-Lee) and with education by spreading knowledge and training tomorrow's scientists, as well as with international collaboration by gathering together people from all over the world.

1.2 The Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator located near Geneva which consists of a ring positioned 100 m underground (average depth), with a circumference of nearly 27 km.

Beams of subatomic particles, protons or ions¹ travel inside the LHC in separate beam pipes in opposite directions and are accelerated to energies of ~ 10 TeV before colliding. The beams are piloted inside the ring by a magnetic field (8.4 T) created by the superconducting electromagnets which are cooled at around -271°C . Most of the ring is made of 1232 NbTi superconducting magnets.

On the 23rd November 2009 the first p-p collisions were detected by the LHC experiments at an energy of 900 GeV. In 2010 protons have been colliding at 7 TeV; the design energy of 14 TeV will be reached when a new upgrade of the accelerator is performed in 2012.

Fig. 1.1 shows a layout of the LHC injection and acceleration system. Protons are introduced into the 50 MeV proton linear accelerator (LINAC). Then, they are injected into the 1.4 GeV Proton Synchrotron Booster and from there inside the Proton Synchrotron (PS) which accelerates them to 25 GeV and subsequently releases a beam made of 135 bunches, containing $\sim 10^{11}$ protons. The beam is sent to the Super Proton Synchrotron

¹ The particles that undergo the strong interaction are called hadrons (i.e.: protons, neutrons...)

(SPS) which accelerates the protons to 450 GeV before injecting them into the LHC. Bunches of protons separated by 25ns and with 75mm of RMS (root mean square) intersect inside the four experiments placed along the LHC ring.

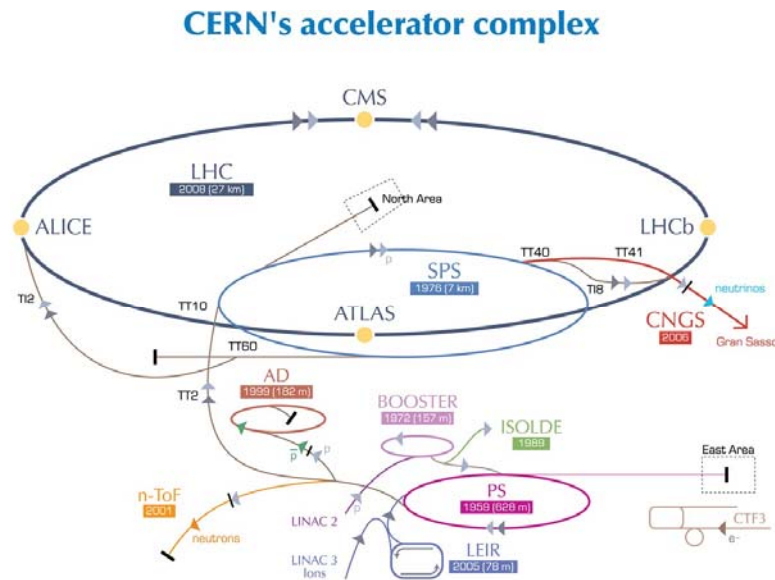


Fig. 1.1: LHC injection scheme

When running at full capacity the LHC energy will be 300MJ. To provide such energy the superconducting electromagnets will be powered by 12000 A in order to produce a magnetic field of about 8,4 T. Not only is this performance necessary to reach the design energy but also to hold the beam trajectory more steadily. If the beam went out of control it could damage the accelerator and the equipment connected with it. Making such a complex machine work properly and efficiently required great commitment and outstanding efforts in all engineering fields.

1.2.1 Physics at LHC

Modern physics still has to provide explanations to several phenomena, however the most important pending issues that scientists are studying are three:

1. The origin of mass;
2. What dark matter and dark energy are composed of;
3. The confinement of quarks;

The LHC and its experiments were actually built to answer to these questions. Protons and lead ions will collide at energies that have never been reached before thus providing the opportunity to extend scientific research into unexplored fields.

The most accredited theory of fundamental interactions is the Standard Model. It describes the elementary particles as well as 3 of the 4 main forces that constitute Nature (the strong force, weak force and electromagnetic one).

This model is consistent with the relativity theory and with quantum mechanics. However the Standard Model has never been regarded as a complete theory of fundamental physics because of its incompleteness concerning the following points:

1. it includes 19 free parameters, such as the masses of particles that must be experimentally proved, as well as 9 more parameters regarding the masses of neutrinos. All of these masses cannot be calculated separately from one another therefore a connection among them must exist which has not been foreseen by the Standard Model.
2. it does not include the gravitational force.
3. it does not provide for the existence of dark matter which forms most of the existing matter in the universe.

The Higgs field was introduced in 1964 to go round one of the weak points of this model (named after Peter Higgs, the first physicist who suggested it). According to this theory the Higgs field would permeate through the universe and provide mass to the other elementary particles. The Higgs boson is the particle, only supposed up to now, that carries the force of this field.

However, the Higgs boson solves the problem of the Standard Model only partially since it would explain why particles have mass but it doesn't explain why their masses are exactly the observed ones. If the Higgs boson does exist and is characterized by a rest energy included in the range anticipated by the theory, then it should be possible to observe it as the product of collisions among protons at 14 TeV as scheduled by the LHC management after 2012.

The latest measurements show that dark matter accounts for the 23% of the energy of the universe but the composition of 80% of its mass is still unknown. The so called supersymmetric particles are supposed to explain this issue and one of the aims of the LHC is to prove their existence. The theory of supersymmetry (SUSY) anticipates the existence of a supersymmetric partner (superpartner) for every particle included in the conventional Standard Model. It also foresees heavy stable particles which interact very weakly with ordinary matter.

The existence of the six quarks (Up, Down, Strange, Charm, Beauty and Top) has been recently ascertained. They have always been observed confined inside hadrons. Whether they can be free and which the properties of that state would be, is one of the main contemporary issues of physics.

It is believed that the early universe, about 10^{-6} s after the Big Bang, under extreme conditions of mass and energy density was in the form of a de-confined state of quarks and gluons, namely a Quark-Gluon Plasma (QGP) [1]. The main objectives of heavy-ion physics at CERN are to reproduce that state, study its properties and explore the Quantum Chromo-dynamics (QCD) phase transition of ordinary matter to the QGP. By colliding heavy ions at ultra relativistic energies one would expect to reach and exceed the critical temperature ($T_c \sim 170$ MeV) at which the system phase transition is supposed to form the QGP.

In November 2010, the LHC delivered the first heavy-ion collisions at an energy almost 15 times higher than any previous attempt. Scientists believe that exploring these phase

transitions within the QCD theory will help them to understand global features like baryon asymmetry or the large scale structure (galaxy distribution).

Four experiments were installed along the ring of the LHC accelerator: ALICE, ATLAS, CMS, and LHCb (Fig. 1.3)

Details concerning the detectors are given in the technical design reports: ALICE [2], ATLAS [3], CMS [4] and LHCb [5].

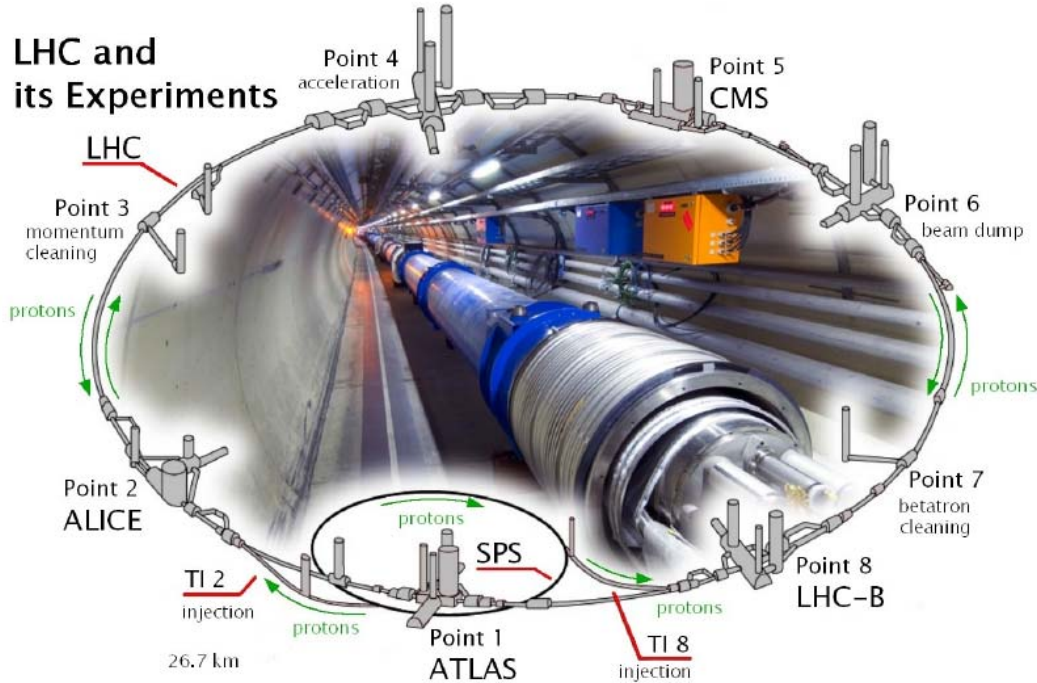


Fig. 1.3: Experiments at the LHC and their location

ALICE is the experiment dedicated to heavy ion physics. Its primary goal is to study the properties of hadronic matter in extreme conditions of temperature and density.

Two huge experiments, ATLAS and CMS, are composed of general-purpose detectors whose aim is to determine the broadest range of signals generated by the collisions in the accelerator. The main goal of these detectors is to search for the Higgs boson and for proofs of physics beyond the Standard Model such as extra dimensions, SUSY and the research concerning dark matter.

LHCb will measure the parameters of CP (Charge-Parity²) violation in the interactions of b-hadrons (heavy particles containing a bottom quark).

² CP is the product of two symmetries: C for charge conjugation, which transforms a particle into its antiparticle, and P for parity, which creates the mirror image of a physical system. The strong and electromagnetic interactions seem to be invariant under the combined CP transformation operation, but this symmetry is slightly violated during certain types of weak decay. Historically, CP symmetry was proposed to restore order after the discovery of parity violation in the 1950s.

1.3 ALICE: A Large Ion Collider Experiment

The ALICE experiment was designed according to the physics and the conditions expected during the collisions at the LHC. The strictest limit is the large particle multiplicity that could be three orders of magnitude bigger than in usual p-p interactions at the same energy. The ALICE detector (Fig. 1.4) was built by a collaboration currently counting in more than 1300 physicists and engineers belonging to 115 Institutes from 33 countries (July 2010). Its overall dimensions are 16m (width), 16m (height) x 26m (length) and its total weight is around 10.000 tons.

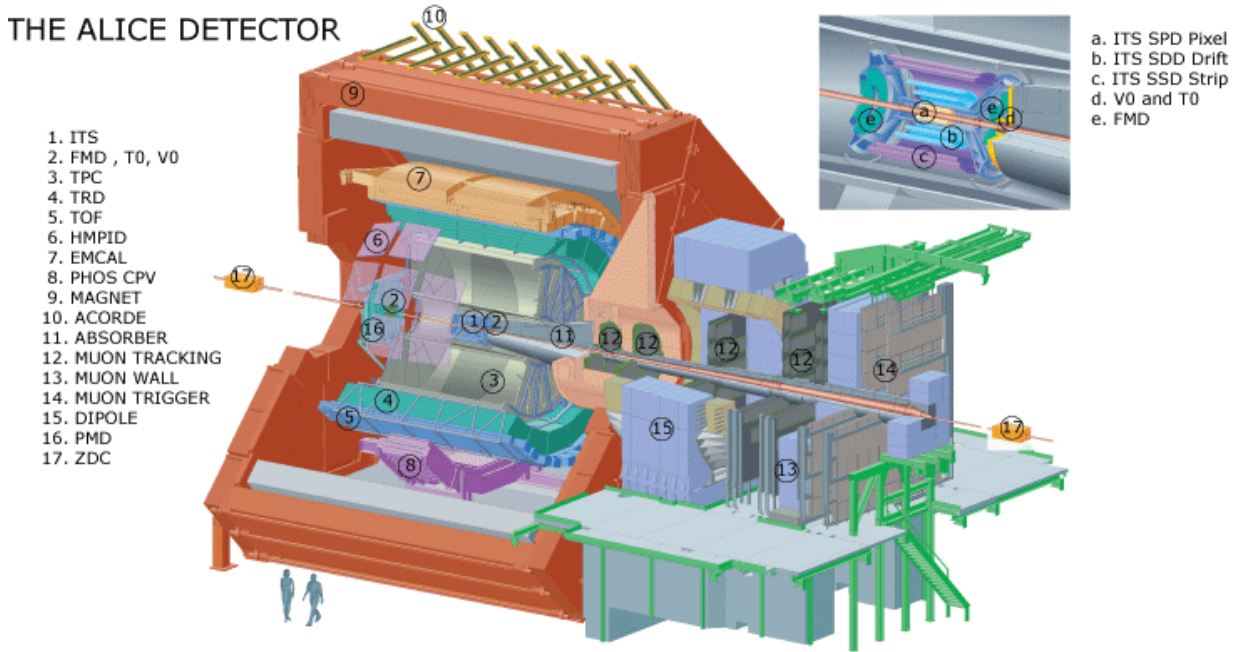


Fig. 1.4: Scheme of the ALICE detectors

ALICE consists of a central barrel part and a forward part. The central part covers polar angles from 45° to 135° ($\eta < 0.9$) over the full azimuth. It is contained inside the L3 solenoid magnet.

The barrel contains an Inner Tracking System (ITS) composed of six planes of high-resolution silicon detectors: pixel (SPD), drift (SDD), and strip (SSD). The barrel is surrounded by a cylindrical Time-Projection Chamber (TPC), three particle identification arrays of Time-of-Flight (TOF), a Ring Imaging Cherenkov HMPID (High Momentum Particles Identifiers Detectors) and a Transition Radiation Detector (TRD). The outer layer is composed of two complementary electromagnetic calorimeters PHOS (Photon Spectrometer), EMCal (Electromagnetic Calorimeter).

Smaller detectors ZDC (Zero Degree Calorimeter) PMD (Photon Multiplicity Detector) FMD (Forward Multiplicity Detector), T0 and V0 are placed at small angles and large distance from the interaction point to be used for global event characterization and triggering. Outside the L3 magnet there is ACORDE (A Cosmic Ray Detector) and the forward part is composed by the Muon arm (Muon Chambers and Muon Trigger). The first

is a scintillator used to trigger cosmic rays while the latter is made of a large dipole magnet and a sequence of absorbers and fourteen planes of tracking and triggering chambers. Further technical details concerning the detectors can be found in appendix A.1.

Physics signatures relevant to the study of the QGP imply the challenge to find 2 correlated tracks in a sample of about 1500 (fig. 1.5 and 1.6).

Being ALICE a heavy-ion dedicated detector, it was especially designed to manage high multiplicities.

The actual multiplicity value of the charged particles used in the simulation studies is 1.2×10^3 in the central barrel. This was a reference parameter when the detectors were built since it affected the adopted technologies, the required granularity level as well as the wide range of possible strategies to identify the particles. Moreover, the detector designing had to comply with restrictive identification thresholds so as to enhance the identification of particular trails among the thousands generated by each event.

Such requirements unfortunately involved a disadvantage since some of the detectors are relatively slow thus affecting the selection of real-time events (trigger) and the lack of a calorimeter. Later it was decided to install an electromagnetic calorimeter (EMCAL) to fill the gap and provide a way to measure the energy of the particles that pass through it. The installation of EMCAL will be completed in 2011.

A basic element of the ALICE experiment is the trigger system which is split into 3 levels (Level 0, Level 1, Level 2). SPD is the main detector of 'Level 0'. The three levels select events according to requirements that become more and more restrictive from level 0 to level 2. The trigger main task is to discriminate meaningful events (p-p or Pb-Pb collisions) from negligible one (i.e. reactions between beam and gas residuals in the beam pipe). It also selects events characterized by a specific topology or combinations of tracks and/or picks them according to their momentum which depends on the rare physical phenomena to be studied.

Since the trigger uses time acquisition windows, an important function is the so-called 'past-future protection': it can determine and exclude rare cases in which two collisions took place in a same time window (for details see [6]).

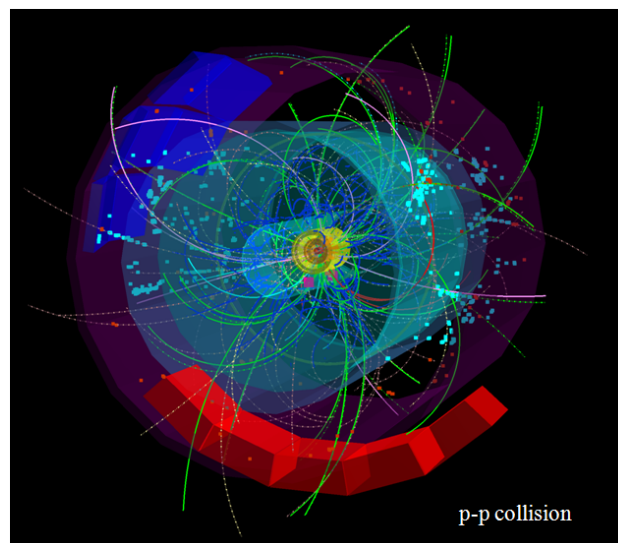


Fig. 1.5: p-p event displayed on 23rd November 2009

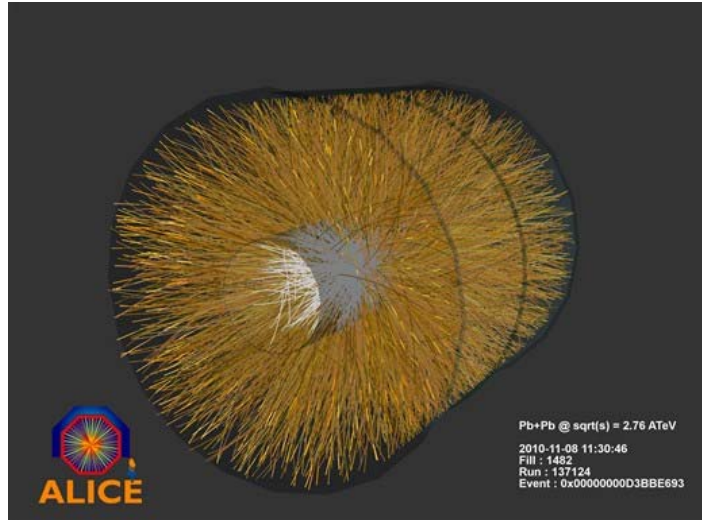


Fig. 1.6: first ion collision in ALICE (8/11/2010)

The interaction rate with nuclear beams at LHC is low (10 kHz for Pb–Pb) and radiation doses are moderate (< 3000 Gy), thus allowing the use of slow but high-granularity detectors.

1.4 The Silicon Pixel Detector

The Silicon Pixel Detector constitutes the two innermost layers of the ALICE experiment. In figure 1.8 it is shown as a part of the Inner Tracking System (ITS). It was conceived to run in a region where the track density can be as high as 50 tracks/cm². To deal with such densities it is necessary to use high precision and high granularity detectors.

The pixel layers are exposed to highest doses of radiation and the integrated levels (10 year run) of total doses and fluency concerning the inner layer are estimated to be respectively around 2.7 kGy and $\sim 3.5 \times 10^{12}$ n/cm² (1MeV neutron equivalent). Several test have been performed in the laboratory of Legnaro (Italy) and the relevant details can be found in [7].

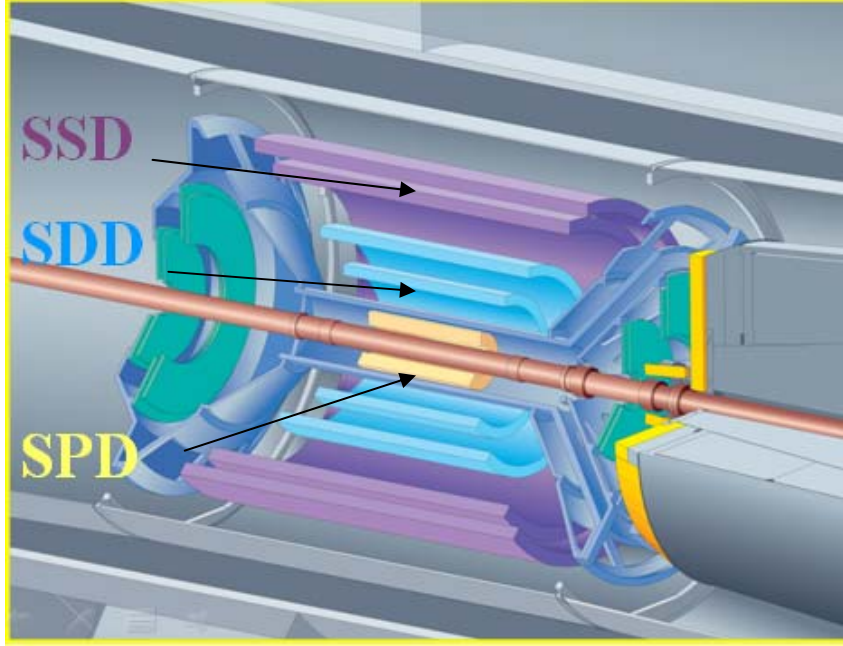


Fig. 1.8: arrangement of the sub-detectors that make up the ITS; SPD constitutes the two innermost layers.

The SPD is meant to supply, with high precision, position determination at high track density in the region close to the interaction point. The three detectors that make up the ITS (SPD, SSD and SDD) can reach a primary vertex resolution of $\sim 10 \mu\text{m}$ (fig. 1.9). In the $r\phi$ -direction the resolution of the SPD nearly reaches $12 \mu\text{m}$.

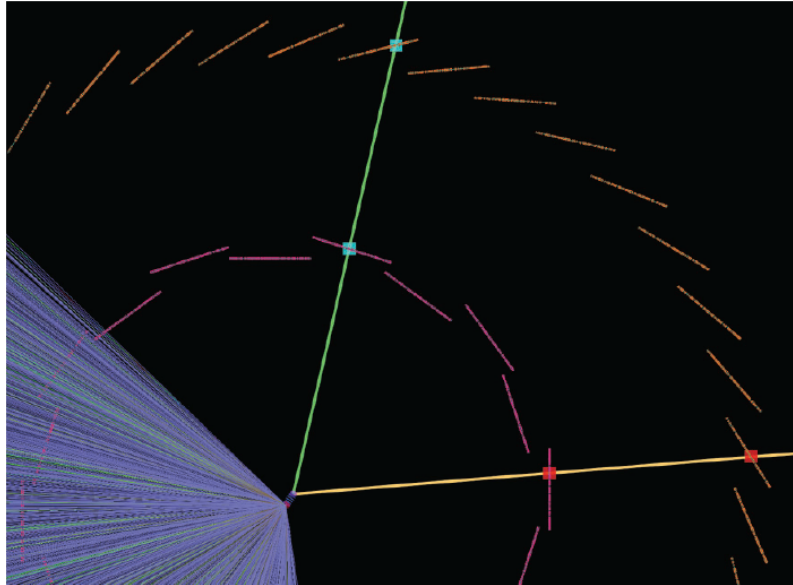


Fig. 1.9: Topology of a $D^0 \rightarrow K^- \pi^+$ decay in a central Pb–Pb collision in transverse projection. It shows the digits in the two layers of the Silicon Pixel Detector. The background signals of the particles sprang from the Pb–Pb collision are visualized only for a limited azimuthal angle (left bottom). The value of the magnetic field is set to zero.

The following paragraphs deal with the architecture and the individual components of the Silicon Pixel Detector.

1.4.1 SPD components

The SPD consists of 120 half staves (HS) installed on 10 carbon fibre support sectors (Fig. 1.10). Each half stave is made of two ladders, a Multi Chip Module (MCM) and an aluminium-polyimide multilayer bus. Each ladder consists of 5 front-end chips which are flip-chip bonded to a silicon sensor that is 200 microns thick [8].

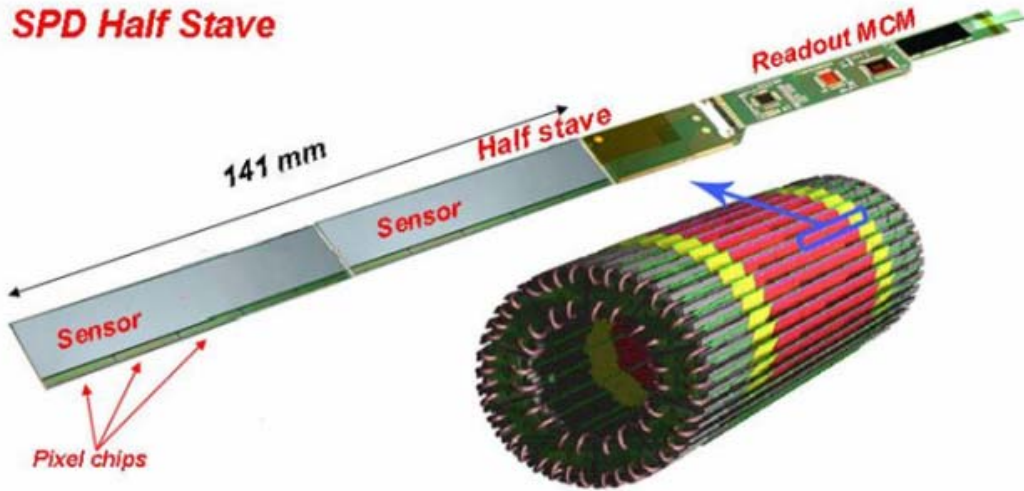


Fig. 1.10: Schematic view of the SPD barrel and its main constituent: the Half Stave

The sensor matrix is made of 256×160 cells that measure $50 \mu\text{m}$ (rp) by $425 \mu\text{m}$ (z).

In the boundary region longer sensor cells are used to ensure the coverage between the readout chips. The sensor matrix is characterized by an active area of 12.8mm (rp) $\times$ 70.7mm (z) and a thickness of $200 \mu\text{m}$.

The front-end chip is $150 \mu\text{m}$ thick and it reads out a sub-matrix of 256 (rp) $\times$ 32 (z) detector cells. The multi-chip module is at the end of the half stave and it controls the front-end electronics; it is connected to the off-detector readout system thanks to some optical fibre links. Two half-staves are attached head-to-head to a carbon-fibre support sector along the z direction; the MCMs are at the ends in order to build up a stave.

Each sector consists of six staves, 4 on the outer layer and 2 on the inner layer. The 10 sectors were assembled around the beam pipe to close the barrel. Totally the SPD is made of 120 half staves, 240 ladders with 1200 chips (9.8×10^6 cells).

The average reading of the inner layer is about 3.9 cm while the outer is 7.6 cm (figure 1.11).

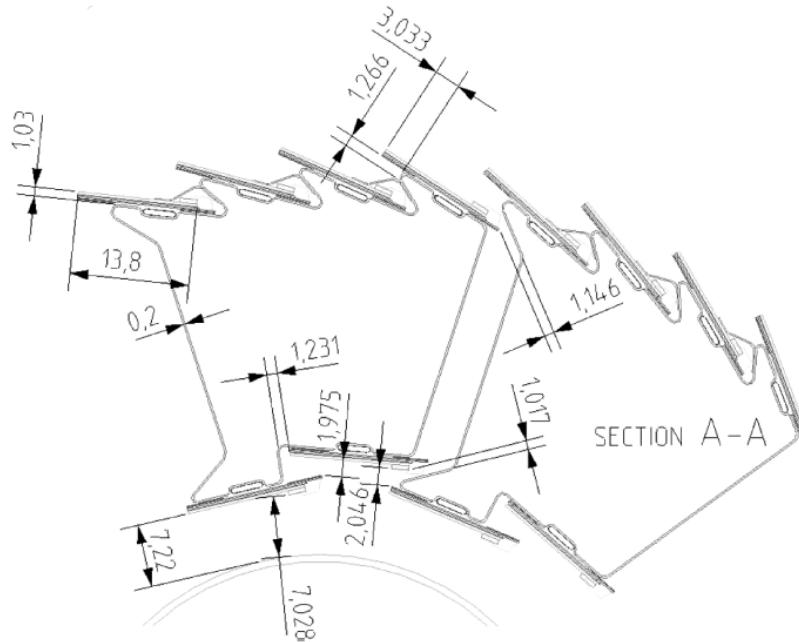


Fig. 1.11: A draw of the transversal section of two adjacent sectors.
On the bottom the beam-pipe is visible and its diameter is 59.7 mm.

The front-end on detector electronics dissipates ~ 1.35 kW. The cooling system is an evaporative type that uses C_4F_{10} . Cooling ducts are embedded in the sector supports and they run under the staves (one per stave). High thermal conductivity grease transfers the heat from the front-end chips to the cooling tubes.

Since the cooling system of this detector has been a majority task for my PhD activity, the relevant details and information will be given in chapter 2.

An al-coated carbon-fibre external shield surrounds the SPD barrel not to affect the SDD layers with heat radiation.

Figure 1.12 shows an assembled half-barrel ready to be integrated in the pixel mechanics.

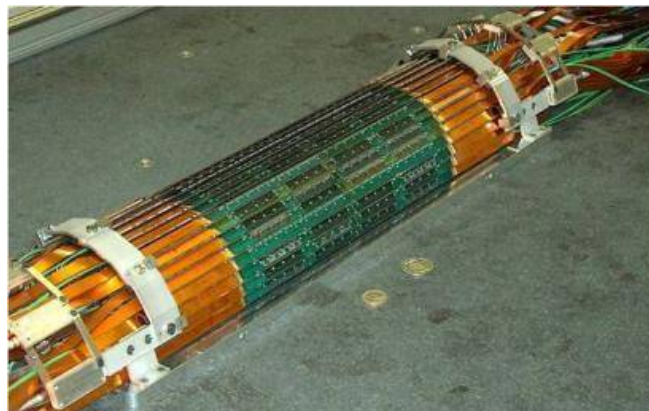


Fig. 1.12: Half barrel assembled

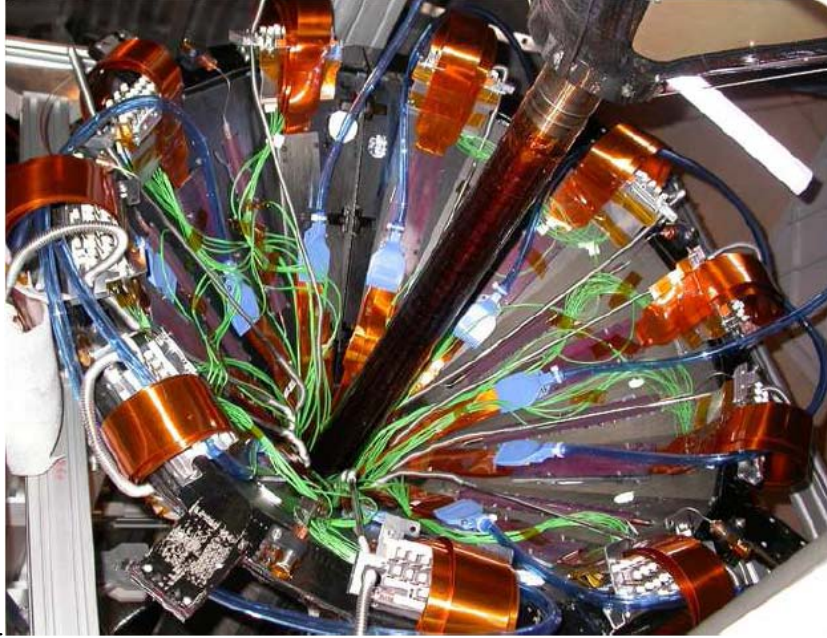


Fig. 1.13: The SPD installed around the beryllium beam pipe in the ALICE experiment

Half Staves (HS) are the basic active element of the SPD. They consist of an MCM and two sensor ladders which are glued on a Pixel Bus [9] (fig. 1.14).

The Pixel Bus, the readout chips and the MCM are connected by ultra-sonic wire-bonding by means of 10×103 (32 data lines, 71 lines for control, test and power purposes) aluminium wire bonds whose diameter is $25 \mu\text{m}$. The edge of the pixel bus is connected to the MCM which manages any communication from/to the off-detector electronics. The HS has an aluminium/polyimide laminate grounding foil (respectively $25 \mu\text{m}$ and $50 \mu\text{m}$ thick), fastened between the readout chip and the carbon fibre, which provides common ground and electrical insulation to the HS itself. Two copper/polyimide laminates, connected to the MCM and the Pixel Bus supply the external connection to the readout electronics and the sensors.

The half staves are mirror fastened, head-to-head along the z direction, to a carbon-fibre composite support sector (CFSS) (fig. 1.11). Every sector supports a total of six half staves, 4 on the outer layer and 2 on the inner layer. The staves are supplied with $2.6 \text{ V} / 0.5 \text{ A}$ for the MCM and $1.85 \text{ V} / 5.5 \text{ A}$ for the Bus [10].

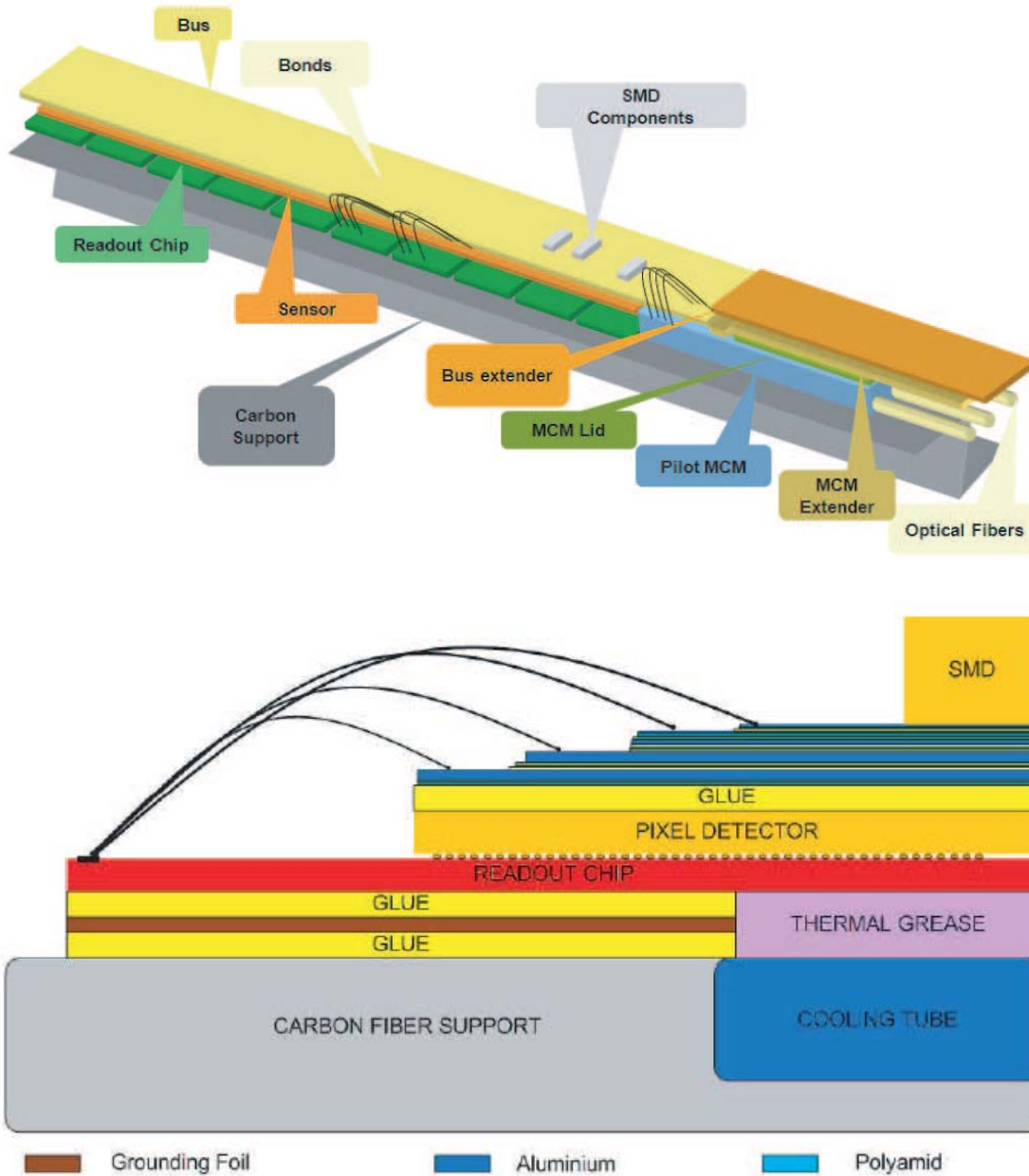


Figure 1.14: The HS structure (top) and cross section (bottom).

A distinctive characteristic of SPD is the Pixel Trigger (PIT) in which a signal called Fast-OR (FO) is triggered any time a hit produces a pulse above the threshold. This signal is generated according to the threshold discrimination and sent to the off-detector electronics without being further processed in the readout cells. The individual cells are ORed together to generate a Fast-OR pulse per chip. This way SPD can provide 1200 independent Fast-OR signals which can be logically combined to obtain a number of conditions, effective at the L0 trigger [11]. This feature is unique among vertex detectors at the LHC.

1.4.2. SPD Off detector electronics and power supply

The ALICE SPD off-detector electronics manages, configures and reads out the detector via bidirectional optical links. Twenty read-out modules process the front-end data streams (fig. 1.15). These modules are based on FPGAs and each one carries three 2-channel link-receiver daughter cards. Figure 1.15 shows the SPD electronics system.

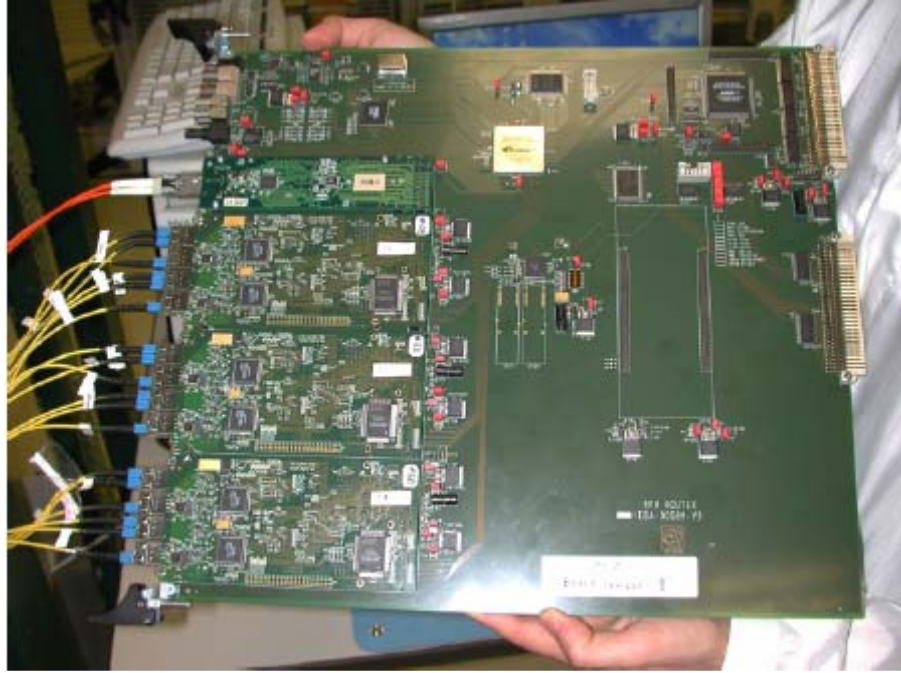


Fig. 1.15: router and three link receiver cards, optical fibers connect the half-staves; the card above the link receiver card is the DDL unit.

The on-board TTCrx chip [12] of the ALICE Central Trigger Processor (CTP) sends the control signals to the router which forwards the trigger commands to the pixel detector. When an L1 trigger signal is received, the router sends trigger signals to the detector; the pixel data are copied into multi-event buffers on the pixel chips. After receiving a positive L2 decision the router starts to check the event-ready flag in the status register of the link receivers; when the flag appears it reads the data from the link-receiver dual port memory. The 120 Half-Staves are read out in parallel. The system can read out data with an average rate of $\sim 3.3\text{KHz}$.

The pixel chips of a half-stave work with a voltage of 1.8V and a current absorption of 5.5A. The MCMs are powered with 2.6V/0.5A. The LV Power Supply (PS) System consists of 20 CAEN A3009 LV dc-dc converter modules (12 independent LV channels each) arranged in 4 CAEN Easy3000 crates. The LV PS is about 40 m away from the detector. Each Half-Sector is powered by a LV module: six channels are necessary to supply the MCMs and the others for the pixel bus). The detector bias voltage (50V standard setting) is provided by CAEN A1519 modules: 12 independent HV channels placed in a CAEN SY1527 mainframe on the surface at a distance of about 120 m.

Each sector uses a HV module. The SY1527 mainframe is the system basic element and it communicates with the software layer via Ethernet (TCP/IP, OPC protocol).

The SPD control system downloads the devices configurations in the mainframe and the latter configures and supervises the system. Should any error occur (over-current, over-voltage, trip, etc...) the mainframe turn off the corresponding channels or boards. A CAEN A1676 branch controller provides the SY1527 communication with the LV modules.

1.4.3 Interlock and Cooling system

The design of the cooling system has been driven principally by the following constraints: low material budget, long-term stability against corrosion, chemical compatibility, minimal temperature gradients and cooling duct temperature above the dew point.

Several possible solutions based on different coolants were considered [13]. An evaporative system with C_4F_{10} as coolant was chosen bearing in mind the fact that the detector has a very low mass and that every HS dissipates ≈ 12.5 W (equal to about 1.5 kW for the whole detector). The C_4F_{10} follows a Joule-Thomson cycle (rapid expansion at constant enthalpy and subsequent evaporation).

A detailed description concerning the cooling system will be given in the chapter 2.

A PLC controls the cooling plant and it communicates with the control PC via Ethernet (TCP/IP) through an OPC Server-client protocol.

Should the cooling system be suddenly switched off, the temperature rise in the half-staves would increase by 1°C/s and this would irreparably damage the detector in a very few seconds. Two interlock levels (hardware and software) act in parallel to switch off the power supply in case of malfunction. The Hardware interlock reacts very quickly (few microseconds) switching off the concerned half sector; the software interlock is slower ($\sim 1\text{s}$) and it acts only on the half staves. Further details regarding the interlock system will be given in the following chapter.

Chapter 2

The SPD cooling system

The first part of this chapter deals with the technical and design characteristics of the SPD cooling plant, while the second one explains in detail the commissioning stage which has been one of the main tasks of my doctorate activity at CERN.

2.1 The SPD cooling system overview

The cooling system is essential for the Silicon Pixel Detector to run. Poor performance will immediately result in a loss of efficiency. Running without cooling would cause a rise in temperature of 1°C/s and the consequent destruction of the detector in less than a minute.

The ASIC, which at nominal working conditions generates $\sim 0.9 \text{ W/cm}^2$, is responsible for this rise in temperature. The total power dissipated by SPD is $\sim 1.5 \text{ kW}$.

The cooling system is an evaporative one which makes use of C_4F_{10} as cooling fluid [13]. The choice was dictated by the performance demand of the SPD and by the detector structure and environmental conditions:

- the temperature of the HS's must be close to the room temperature, no condensation;
- minimize the temperature gradient along the staves;
- keep the material budget as low as possible;
- high chemical and electrical compatibility;
- no corrosion by the cooling fluid;

Several tests were carried out before choosing the kind of cooling system to be used. At the beginning water was taken into consideration on account of its good thermal and hydraulic characteristics but its advantages had to confront with the necessity of having a leak less system which is difficult to handle in such small pipes. Besides it had to face the consequent increase in material budget when a reasonable safety factor is required to provide efficient cooling. Other dielectric fluids, such as demineralised or deionised water and fluorocarbons (C_5F_{12} , C_6F_{14} e C_4F_{10}) were weighed up [13].

The choice among these fluids was made bearing in mind the thermodynamic performance and the chemical compatibility with the metals used in the circuit. The external connection surface of the capillaries was treated like it was done for the cooling ducts. C_4F_{10} was chosen because of its favourable equation of state (i.e.: 15°C at 1.92 bar) and because its molecular structure does not contain hydrogen which participates in the formation of hydrofluoric acids which are extremely corrosive for Phynox, when it is exposed to ionizing radiation.

On the contrary the thermal and hydraulic performance of C_4F_{10} in its liquid phase, compared to water, is quite poor, as it is for most dielectric fluids due to their little thermal

capacity and to a considerable loss of load. Therefore, in order to remove the dispersed heat properly along the staves a substantial pressure difference at the ends of the little tube would be necessary.

An evaporative cooling system was decided on as it offers a very high thermal capacity with small quantities of fluid.

Such a choice was also accounted for the following reasons:

- constant temperature along the staves
- restriction on strains induced on the tube thanks to a minor pressure drop;
- smaller mass flowing in the system due to the coexistence of both phases, not only the liquid one. Each input line should keep a liquid flow of 0.06 l/h, while in the return ones the gas flow should be around 4.4 l/h;
- it allowed small cooling duct dimensions;

The inlet and return pipes (out/in = Ø 12/10 mm) are in stainless steel 316 L, the cooling ducts under the staves are made of a an alloy called Phynox and the input/output capillaries consist of a copper-nickel alloy (40% Co, 20% Cr, 16% Ni and 7% Mo).

Every stave is cooled thanks to the evaporation of the C_4F_{10} contained in the cooling ducts which lay inside the proper cavities of the carbon fibre supports. (fig 1.14). The ducts are made of Phynox, an austenite alloy which is highly resistant against corrosion. The wall thickness of the ducts is 40 μm and their initial diameter is 2.6 mm squeezed down to flat profile (fig 2.1), whose overall thickness is 600 μm in its thinnest part. Phynox can be suitably hard, even if it is very thin, and it is also corrosion-safe when there are no aluminates or silicate inclusions.

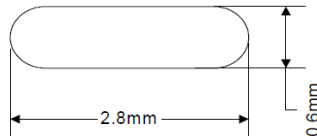


Fig. 2.1: the cooling tube cross section.

The duct surface was treated with Ni (around 1 μm thick) and Cu deposition (around 5 μm thick) by induction head ($T \sim 230^\circ\text{C}$) to be better soldered (fig. 2.2), to the copper fittings. These fittings are CuNi welded to the capillaries (inlet) and to the small ducts (outlet) thus connecting them to the collector boxes (fig. 2.2 left).



Fig. 2.2: The cooling collector and the Phynox tube with the Cu fitting

The input lines are supplied by input capillaries whose inner and outer diameters are respectively 0.5/0.85mm and whose length is 550 mm as required by the pressure drop that is necessary to bring the fluid to the coexistence phase. The output capillaries inner and outer diameters are 1.5/1.8 mm and their length is 90 - 120 mm.

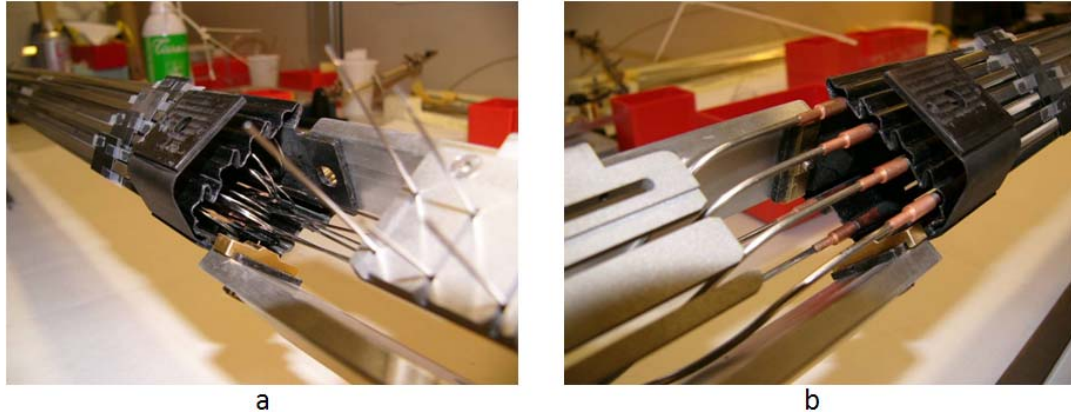


Fig. 2.3: The hydraulics at the inlet (a) and at the outlet (b) of the sector

Evaporation due to forced convection takes place in the area of the little tubes that are under the staves. In such a condition, the warmed fluid is two-phase since it is a mixture of liquid and steam. This mixture can be characterised by different motion conditions which may considerably affect the value of the heat exchange coefficient.

2.1.1. Principle of operation and Plant Description

This cooling system is based on the Joule-Thompson thermodynamic cycle (fast expansion at constant enthalpy) shown in figure 2.4. The cycle based on the Joule–Thomson effect which describes the temperature change of a gas or liquid when it is forced through a valve (or the capillaries in our case) while kept insulated so that no heat is exchanged with the environment (the gas does not work and absorbs no heat, so the internal energy is conserved).

The scheme of the plant is illustrated in figure 2.5. The most important points of the plant inlet and return cycles are highlighted in capital letters in both figures. The diagram in figure 3.4 shows the theoretic cycle of the system.

The 10 inlet tubes (out/in = Ø 6/4 mm) are 50m long and the maximum difference in height between the inlet point and detector is 8m. The return tubes (out/in = Ø 12/10 mm) are 35m long and their difference in height is around 6m because the compressors were placed on the upper part of the plant.

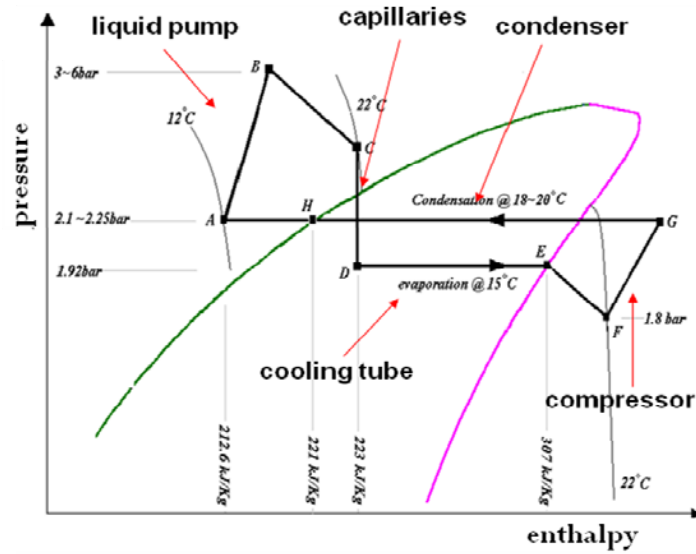


Fig. 2.4: The principle of operation of the SPD cooling system.

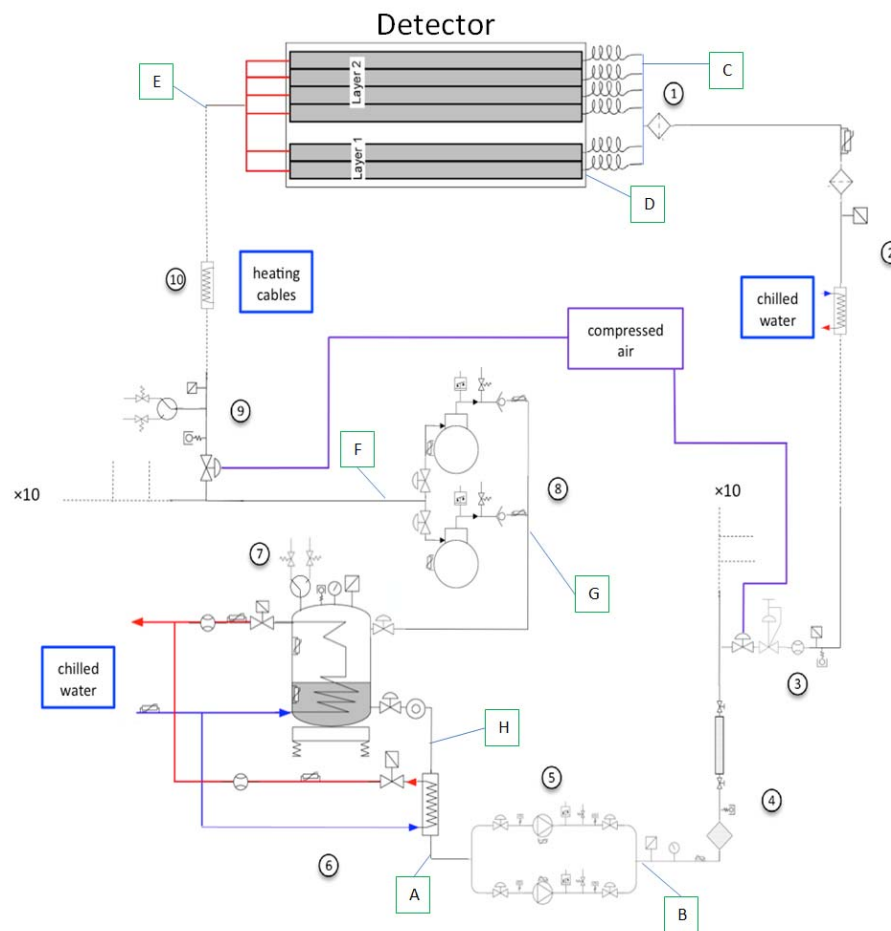


Fig. 2.5: The scheme of the plant

The explanation of the circuit starts from point H where the saturated liquid is collected at the bottom of the condenser. It is then cooled by a water chiller at 6°C using a cold water heat exchanger (point A) in order to prevent the pump cavitation. The condenser is equipped with double pressure-relief valves which are used one at a time. A manual ball valve allows switching between the two. In case of overpressure, one of the valves can be opened and a constant small leak may occur because the valve is only partially closed due to the hysteresis of its spring. This provides for the possibility to switch to the second valve when access is allowed.

A pressure transmitter and a temperature sensor deliver the information needed to regulate the pressure inside the condenser to the control PLC (as previously explained) through a proportional–integral–derivative controller (PID loop³) which acts on a regulating valve.

The pump raises the liquid pressure (point B) which, thanks to some manual pressure regulators, is adjusted differently in each line (fig. 2.6).



Fig. 2.6: Swagelok pressure regulators and Bronkhorst Coriolis flowmeter

These regulators were installed at the end of 2009 together with 10 flowmeters in order to control the inlet parameters loop by loop (pressure and flow).

The working principle of the flowmeter is based on the Coriolis effect (fig. 2.7): each flowmeter contains two parallel tube loops which are part of an oscillating system. When a fluid flows through the tubes, Coriolis force causes a variable phase shift between the two loops that is detected by sensors and fed into the internally mounted pc-board. The resulting output signal is proportional to the real mass flow rate, whereas thermal mass flow meters are dependent on the physical properties of the fluid.

³ A proportional–integral–derivative controller is a generic control loop feedback mechanism (controller) widely used in industrial control systems – a PID is the most commonly used feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a desired setpoint. The controller attempts to minimize the error by adjusting the process control inputs.

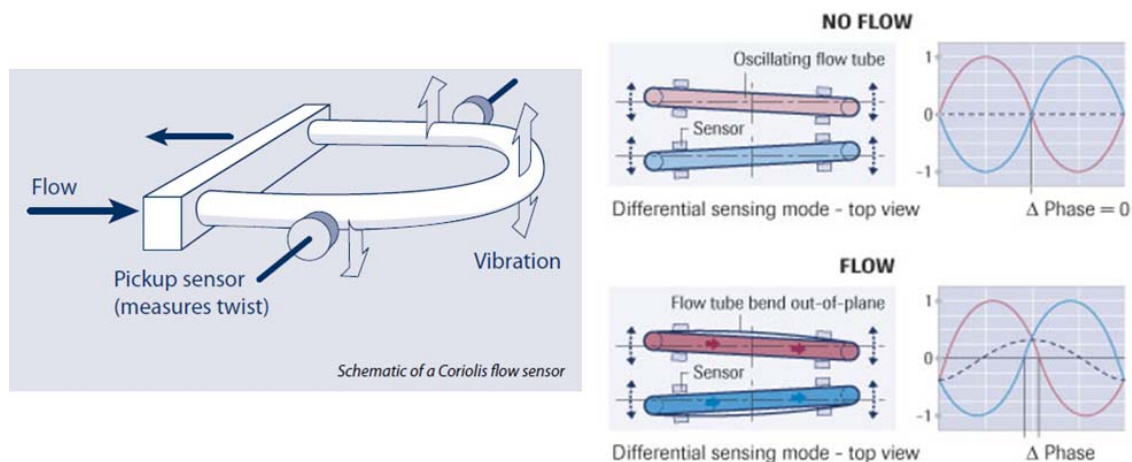


Fig. 2.7: Coriolis flowmeter: operating principle

As I will explain in details later on, the working conditions of the detector change from sector to sector and this is the reason why it was deemed necessary to control the loops one by one.

A transmitter measures the inlet pressure and sends it to a PID loop implemented in the PLC. A frequency inverter converts the PID output into pump speed. The two rotary vane type pumps are characterized by a relatively low NPSH (net positive suction head), which is a basic requirement to prevent cavitation during normal operations.

A parallel second pump was also installed because, in case of cavitation, some parts may wear out very quickly making it necessary to switch to the second pump. This operation can be carried out remotely.

Zone 4 (fig. 2.5) is equipped with 2 filters: one is a “hydrofilter” dedicated to the removal of traces of water and HF compounds, while the second one is an Oxysorb which assures purity of $\text{H}_2\text{O} < 20 \text{ ppb}$ and $\text{O}_2 < 5 \text{ ppb}$.

Zone 3 is the point where the supply line of the plant divides into 10 lines. Each of them consists of a pneumatic valve, a pressure regulator (to fine-tune the flow in each sector), a flowmeter, a pressure transmitter and a Schrader valve used as a vacuum plug. The 10 lines outstretch for about 30 m and after them 10 heat exchangers, fed by water at 7.5°C , were installed (zone 2) in the area inside the magnet called “patch panel 4” (PP4). Pressure and temperature sensors are installed about 2 m downstream the heat exchangers. This is the closest point of measurement to the SPD. Given the very small inner diameter of the capillaries, two filters with granularity of $60 \mu\text{m}$ were placed at the end of each supply line (zone 1) and $\sim 8 \text{ m}$ upstream (zone 2) to protect the circuit downstream from possible contamination of the fluid. The capillaries are after the last filter (Point C). The expansion at the capillary outlet brings C_4F_{10} to pressure and temperature conditions where the liquid and vapour phases coexist (point D).

Inside the detector C_4F_{10} vaporizes at 15°C at a pressure of 1.92 bar. At some point after the detector, the fluid can be regarded as saturated vapour (point E). In the return leg a pressure jump brings vapour to a thermal balance with the room temperature inside the cavern ($\sim 22^\circ\text{C}$) where the detector is hosted.

At approximately halfway between the detector and the cooling plant, about 10 m of the return pipes were equipped with a self-regulating heating cable (total power per line ~ 600

W) which completely evaporates the liquid left over in the lines. This prevents any excessive pressure drop along the return path (which makes it difficult to control the evaporation temperature at the detector) as well as any liquid from getting in contact with the compressor membrane, which could cause serious damage.

In 2008 a second compressor was installed in order to provide a redundancy system. Both compressors can be remotely operated.

A manifold close to the plant hosts the ten lines equipped with pneumatic shut off valves, pressure transmitters, vacuum plugs and two pressure relief valves that can be alternatively selected. All this was thought necessary for the same reasons previously explained about the condenser. The pressure relief valves take care of the safety of the SPD as the pressure drop along the return lines is small and nearly constant (~300 mbar) from the cooling duct below each stave.

In the return manifold the pressure is measured by a transmitter and then fed back into a PID loop implemented in the PLC. The PID controls the speed of the compressor through a frequency inverter. When operations are in a steady state, the incoming vapour flow is constant and the compressor stabilizes at a given constant speed between 30 and 50Hz. In order to make the compressor work in stable conditions, it is also necessary to keep constant the pressure at its outlet. Therefore, it is important for condensation pressure to be kept steady (PID loop) no matter what variation in the incoming vapour flow occurs.

Several pressure and temperature sensors on the plant monitor the thermodynamical conditions of the fluid and assure safe running parameters. The pressure switches after the pumps switch off the frequency inverter in case of overpressure. Pressure relief valves are placed in each sector of the plant (which can be divided by pneumatic valves in four separated volumes) and a number of Schrader valves provide plugs for such operations as vacuum, nitrogen ventilation, freon refill and recovery.

The interlock system consists of a hardware interlock that acts directly on the power supply of the half sector in a very fast way (around few μ s) and a software interlock that reacts more slowly and only at the level of the HS. Two redundant chains of 5 temperature sensors (Pt1000) are installed on the upper surface of the half staves in order to provide the relevant temperature for the interlock system. A chain is directly connected to the PLC analog input modules, while the second one is read out through the MCM that sends the temperature values to the routers. In case a half-stave exceeds a threshold temperature value (usually set at 40°C) the hardware interlocks act on the Low Voltage (LV) board switching off the concerned half-sector.

The cooling plant is equipped with a further interlock system that consists of 11 hardware interlock channels. One of them acts on all the low voltage modules and turns off the whole detector in case of cooling plant failure (i.e.: pressure instability, high temperatures in the boosters, etc...). The remaining channels instantly switch off only the corresponding single sector if the relevant cooling line is faulty.

The main difference that distinguishes the hardware and software interlocks is their reaction time. The hardware interlocks very quickly react switching off the power supply of the whole detector or, in case of temperature spike in a HS, they turn off the power supply of the half sector that houses it.

Two levels of software interlocks were implemented: their reaction time is slower than the hardware ones because they are sent through the communication protocols of the control system. Nonetheless they offer a great advantage since they can intervene on single half-

staves. The first software interlock level does not allow operators to switch on a HS if the measured temperature is higher than 22°C; the second level switches off single HSs in case their temperature is higher than 38°C. These operations can be carried out thanks to a background script that individually intervenes in the channels of the LV supply module.

2.1.2. Design parameters

The saturation pressure of C₄F₁₀ at 15°C is 1.92 bar. The flow required for each stave depends on the ratio between the power dissipated and the difference between the enthalpy of the fluid at point D and E in the thermodynamic cycle. To calculate this we used a safety factor equal to 2, therefore the considered power is twice the nominal one:

$$\dot{m} = \frac{\text{power / stave}}{h_D - h_E} = \frac{50W}{307 \text{ kJ/kg} - 223 \text{ kJ/kg}} = 0,595 \text{ g/s} \quad (1)$$

The following table shows the design parameters of one sector and of the whole detector:

Density at 15°C(Kg/m ³)		Flow / stave			6 staves (one sector)			60 staves		
Sat liquid	Sat vapour	g /s	L/h		g /s	L/h		g /s	L/h	
			in	out		in	out		in	out
1536	20.75	0.6	1.41	104.1	3.6	8.44	624.6	36	84.4	6246

Table 2.1: C₄F₁₀ flow rates at 15°C for a stave, a sector and the whole SPD

With the applied safety factor a flow of 36 g/s is enough to cool the whole detector. Knowing this datum allows to calculate the power to be removed in the condenser (G-F leg in the thermodynamic diagram) and for the sub-cooling (H-A leg in the thermodynamic diagram):

$$(h_G - h_H) \dot{m} = (310 - 220) 0,036 = 3240W \quad (2)$$

$$(h_H - h_A) \dot{m} = (220 - 212) 0,036 = 288W \quad (3)$$

The Darcy-Moody correlation was used to determine the length of the capillaries (fig. 2.8):

$$\Delta p = 0,316 \text{Re}^{-0,25} \frac{1}{2} V^2 \frac{L}{D} \rho \quad (4)$$

Where ρ is the density of the cooling fluid (1530 kg/m³), D and L are the inside diameter (0,5 mm) and the length of the capillaries, while V is the speed of the fluid. Re is the Reynolds number which can be calculated from the following relation:

$$\text{Re} = \rho \frac{v_m D}{\nu} \quad (5)$$

where ν is the kinematic viscosity which is equal to $1,62 \times 10^{-7} \text{ m}^2/\text{s}$.

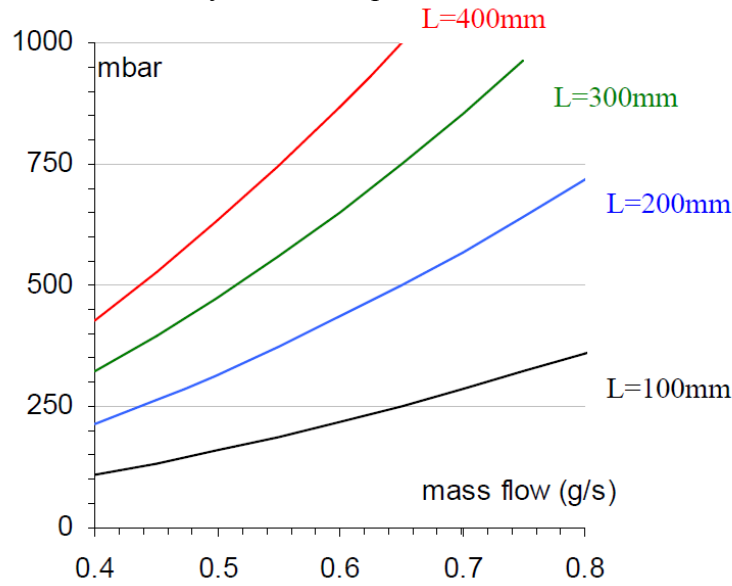


Fig. 2.8: Capillary Pressure drop-Length correlation

A theoretical estimation of the frictional pressure drop for a two-phase flow is a complex task and unfortunately it results far from accurate, whereas a coarse estimation can be made averaging two hypothetical cases:

- a) assuming 100% of the mass flow as liquid
- b) assuming 100% of the mass flow as vapour along the stove

The flow is laminar in case (a) and turbulent in case (b). Since the length of the staves is small ($L=288 \text{ mm}$) the approximation adopted here will be to take the arithmetic average between (1) and (2). At 15°C densities are equal to 1536 kg/m^3 for saturated liquid and $20,75 \text{ kg/m}^3$ for saturated vapour, while kinematic viscosity goes from $1,62 \times 10^{-7} \text{ m}^2/\text{s}$ in the first case to $5 \times 10^{-7} \text{ m}^2/\text{s}$.

A 15°C the variation in the evaporation temperature with reference to the evaporation pressure is:

$$\left(\frac{\Delta T_{EVAP}}{\Delta P_{EVAP}} \right) = 0,0149 \text{ } ^\circ\text{C} / \text{mbar} \quad (6)$$

Table 2.2 shows an estimation of the pressure and temperature drop along a stove with regard to two different flows.

	Reynolds (if only liquid)	Reynolds (if only vapor)	pressure drop - if only liquid (mbar)	pressure drop - if only vapor (mbar)	Average (liq+vap)/2 (mbar)	Tevap drop along the stave (K)
0.6g/s (50W)	1536	36805	6	214	110	1.6
0.3g/s (25W)	767	18400	2.7	62	32	0.5

Table 2.2: estimated temperature and pressure drop along the stove

These estimations suggest that it is necessary to keep the mass flow in a given range and to carefully adjust it to respect a certain degree of temperature uniformity. An excessive mass flow leads to a higher gradient along the staves. Therefore mass flow is tuned by varying pressure with the pressure regulators at the plant. The SPD temperature is monitored as an average value along the staves, therefore it is not possible to monitor its uniformity.

The Darcy-Moody correlation allows to estimate also the pressure drop along the inlet and return lines between the plant and the detector (assuming a state of saturated liquid in the inlet line and one of saturated vapour in the return one) [13]. This calculation provides the minimum pressure required to get 2.43 bar before the capillaries, which is 3.3 bars. This value takes into account either the leaks in the lines and the height difference between the plant and the detector (~ 8 m). The pressure drop in the return line is not as remarkable as the one in the inlet ones (120 mbar), therefore the evaporation pressure to be set for the plant is around 1.8 bar.

2.1.3. The commissioning phase: plant performance in 2008-2009

The first commissioning stage of the cooling plant was carried out in the Departmental Silicon Facility (DSF) at CERN. Efficiency tests were performed on all the SPD sectors. The plant that was used was the same one that was later taken to the experimental cave in ALICE.

The tests in DSF gave satisfactory results: even if the system in the laboratory allowed to switch on only 5 sectors (half barrel) at a time, 100% efficiency was checked with an input pressure of around 3 bar. With the difference that the plant in the cave is about 50m away from the inlet point in the capillaries and the fact that it is 8 m further down, such parameters were nevertheless taken into account during the designing stage.

At the beginning of 2008 we run into the first problems which were especially focused on sector 9, in fact only 50% of its half staves could be switched on because the other half was not sufficiently cooled.

The working parameters were changed in the summer of 2008 in order to circulate more cooling fluid inside SPD ($P_{liq}=4$ bar e $P_{gas}=1,9$). We managed to improve the situation partly and for the first official run of LHC in September 2008 the Silicon Pixel Detector worked at an efficiency of 86% with 17 half staves switched off (14 due to cooling problems and 3 because of electronic related issues).

Figure 2.9 shows the way the switched off half staves were distributed in the detector (labelled in red): side C shows SPD from the inlet cooling side, while side A is the exit. This figure clearly illustrates that most of the problems took place in sector 9 and that, in general, side A is the most affected. This is due to the fact that the flow goes from side C to side A, therefore an early dry-out effect mostly influences the HS on side A.

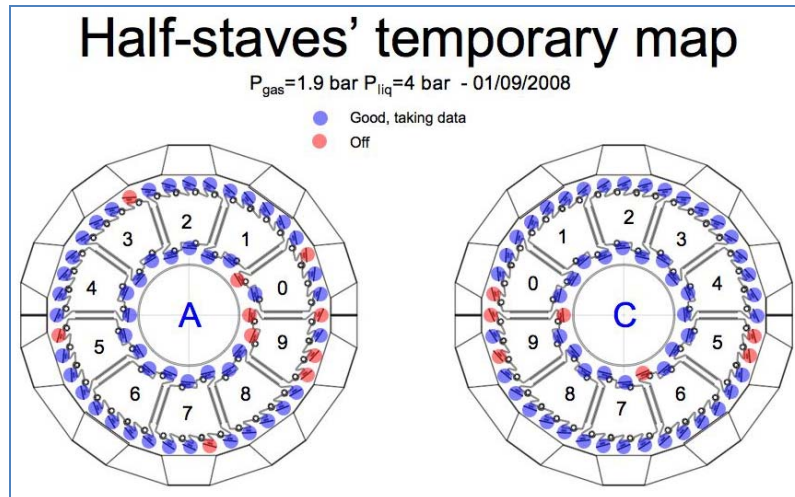


Fig. 2.9: SPD situation in September 2008

During the shutdown of nearly one year between October 2008 and August 2009 the access to the ALICE experiment was allowed again. We took the opportunity to disconnect the cooling pipes on the gas side (after the detector) so that the miniframe could be removed (metal structure pointed out by the blue arrow in fig. 2.10). It is used to connect various services to the detectors inside the L3 magnet.

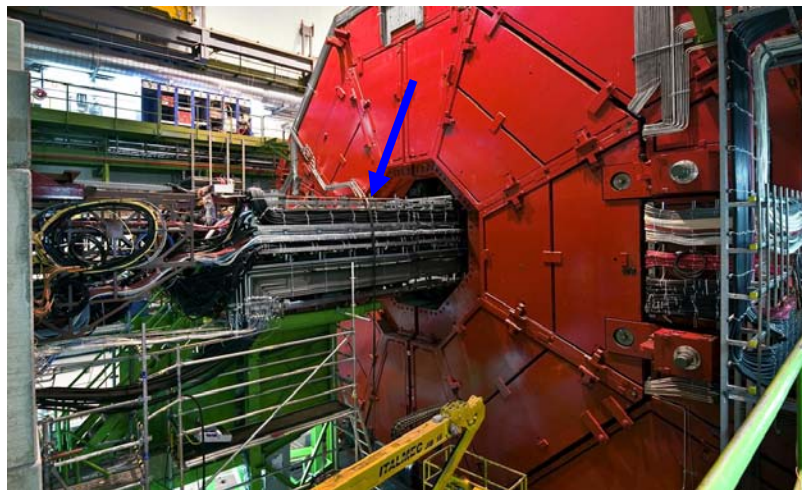


Fig. 2.10: ALICE front view

In such cases the cooling pipes coming from the detector are stopped up in order to prevent any contamination by external agent such as dust or impurities of any kind. The miniframe was serviced during a few months and in July 2009 it was repositioned in the cave. After that it was possible to reconnect the cooling pipes on the gas side. During the stop some changes in the plant were made:

- a filter within $1 \mu\text{m}$ granularity was installed after the pump;

- a heat exchanger was installed between the tank and the pump to prevent any pump cavitation at different working conditions;

The plant was switched on again on 12th August 2009 and at the first detector's run we clearly noticed that the cooling performance had worsened (fig. 2.11) because only 71% of the detector was working and 32 half staves were off due to high temperature.

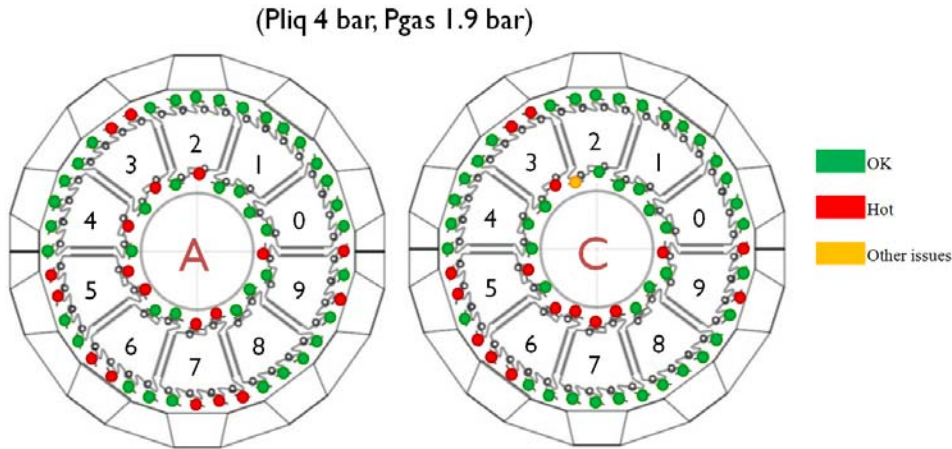


Fig. 2.11: SPD situation in August 2009

While the performance of sector 9 was as poor as before, the warming conditions of sectors 3, 5, 6 and 7 were clearly worse. Moreover, a few half staves that were switched on were supplied by reduced power to prevent them from becoming too hot, even if this affected the efficiency and the noise level.

The situation was critical enough to decide to carry out several tests to investigate the reason for such worsening.

2.1.4. Tests and improvements

We first installed new temperature and pressure measuring points as close as possible to the detector in order to improve the control over the working conditions.

Twenty pressure sensors (Swagelok mod. PTU-F-AC6-11AH) and 20 temperature sensors (PT100 4 wires mod. TRM P1B-30150X) were installed (fig. 2.12): one on each detector inlet (PP4) and outlet (PP1) line. I looked after the installation of the sensors personally.

This operation required careful scheduling since any activity inside the L3 magnet is strictly controlled on account of safety issues and of the concurrence of several groups working in limited space. The pressure sensors were installed in-line thanks to the VCR Swagelok connections. The sensitive elements of the temperature sensors were laid directly on the cooling pipes, they were fastened with aluminium adhesive tape and Armaflex thermal insulation.



Fig. 2.12: temperature sensor Pt100 (left) and Swagelok pressure sensor (right)

The most time-consuming job was the electrical connection and the setup of the read-out system for these sensors. Dedicated screened cables were laid in the proper path, using 4-wires connections for each PT sensor (because of the cable length) and 2-wires connections for the pressure gauges which deliver a calibrated current. The sensors were cabled to a reading board called Embedded Local Monitor Board (ELMB, see chapter 3) which was connected to the SPD control system via CANbus (the details concerning this installation and the readout system will be given in the chapter dedicated to the SPD control system).

In September 2009 the following tests were carried out:

1. liquid (inlet) side pressure increase;
2. pairs of lines were swapped;
3. a stainless steel line was replaced by a multilayer one;
4. the liquid closest to the detector was undercooled;
5. SEM analysis of the filters removed from PP4;

Test no. 1: the flow increased as the inlet pressure increased (from 4 to 5,5 bar). The performance of the critical sectors improved but unfortunately the set values were much above the standard working ones. Therefore we chose to equip the plant with some manual pressure regulators (as mentioned in paragraph 2.5.1) in order to be able to adjust pressure line by line instead of applying high pressures even in the sectors that didn't need it, obtaining a better flow balance between lines with different impedance.

At this stage we decided to equip each line also with flowmeters to monitor the flow. In general we noticed that when pressure on the plant was increased the one detected in PP4 increased quite consistently on the bad sectors. Instead, a pressure drop was more evident in the good sectors: i.e, adding 1 bar to the plant setpoint made the pressure of sector 2 in PP4 raise of 0,55 bar, while the one of sector 6 nearly caught 1 bar (fig 2.13).

Such result pointed out for the first time the impedance difference between PP4 and the detector for different lines. For mechanical (clogged filter in PP3) or thermodynamic reasons (local proximity to coexistence phase) a kind of barrier between PP4 and the detector sets up. Such effect was never observed during the commissioning in DSF.

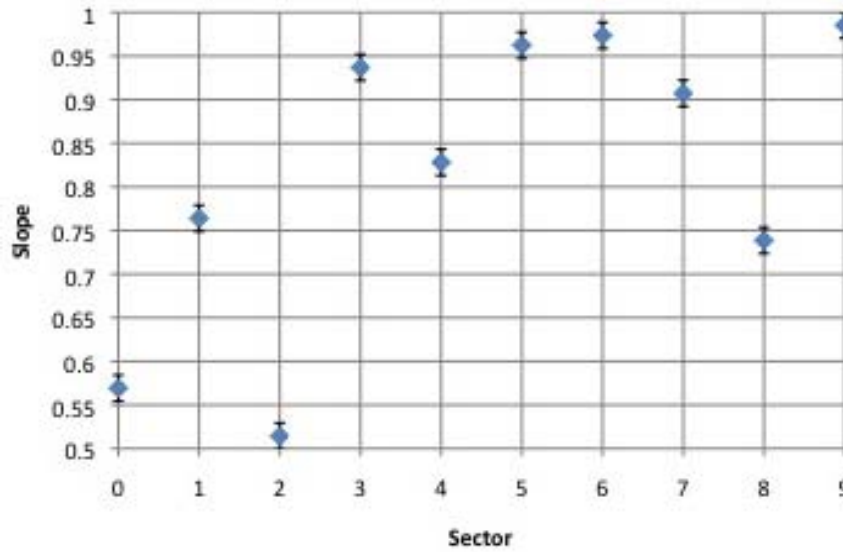


Fig. 2.13: Pressure difference in PP4 after increasing the pressure at the plant

Test no. 2: since we had the opportunity to disconnect the cooling pipes in PP4 (8m from the detector) we tried to connect the supply line of a good sector to a bad sector in order to check whether the problem was confined along the piping between the plant and the detector. In figure 2.14 the position of the good and bad sectors is shown. In fact 4 less performing sectors out of 5 are on the same side of the experiment (side O = outer part of the LHC ring). We suspected this could be due to the fact that the supply lines on that side are longer than the ones on side I (inside the LHC ring) and they also follow a different path, affected by more bends, elbows and siphons.

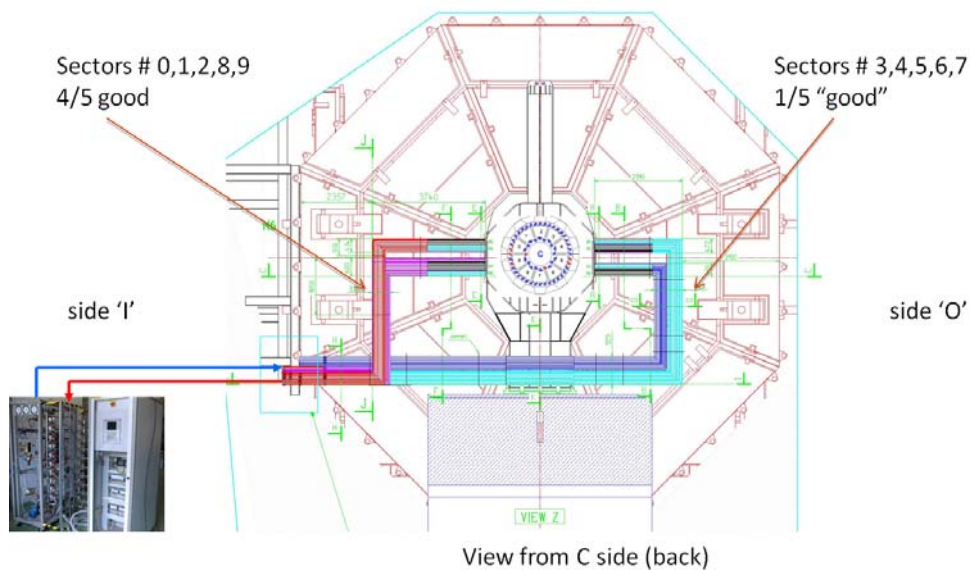


Fig. 2.14: SPD cooling pipes layout (rear view)

The tests proved that the performance improved slightly in a shorter line. Therefore, we decided to lay new supply lines in order to equalize the path among the lines with shorter length, also minimizing the number of bends.

The new lines were laid down in October 2009 after the door of the L3 magnet had been closed (fig 2.15). Because of the forthcoming restart of the LHC in November 2009, we had to choose a temporary path that passed in front of the doors, even if the lines had to be cut to be able to open the magnet's doors. Therefore they will have to be installed according to a permanent layout during the long LHC shutdown.

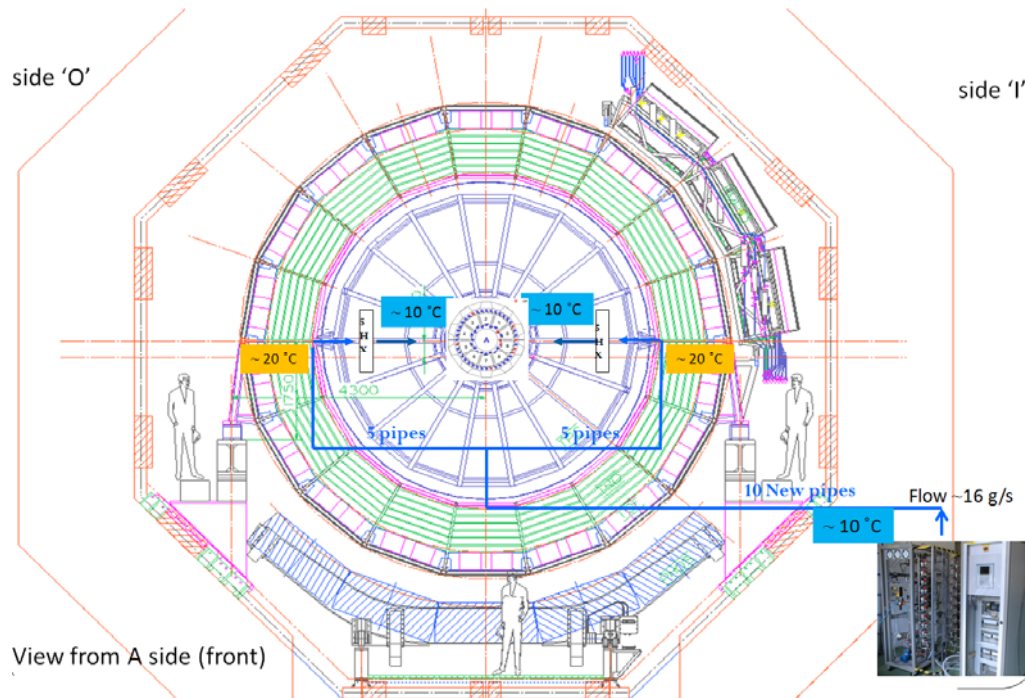


Fig. 2.15: SPD new cooling pipes layout (front view)

Test 3: we decided to replace the stainless steel pipe with a temporary one made of multilayer material (polyethylene on the outside, an aluminium layer and polyethylene copolymer on the inside). The results of this test were not interesting as far as the performance was concerned. We tried to thermal insulate with Armaflex the whole length of the supply line in order to keep the liquid temperature as low as possible until it reached the detector. Unfortunately the fluid speed was so reduced that the surface effect prevailed anyhow. So the idea of thermally insulate the supply lines was discarded.

Test no. 4: to prove if the thermodynamical conditions of the liquid close to SPD were unfavourable due to the heating caused by exchange with the environment along the supply lines we conceived a special test using ice; we dipped 8m of plastic hose (6/4mm o/i diameter) in a basin full of ice in order to cool the liquid in PP4, the accessible point closest to the detector. The freon temperature was then lower than 8°C. We carried out some switching on tests on the critical sectors 5 and 6 and we noticed that the flow

increased by 50% and the cooling efficiency improved remarkably even if the fluid viscosity increases as temperature lowers.

Therefore we decided to install 10 heat exchangers in PP4 (one per line, fig. 2.15) and to cool the liquid close to the detector.

The HSs are fed with water at $\sim 7,5$ °C by a leak-less circuit (preventing outflow of water close to the many electronic boards installed there).

Unfortunately this solution proved to be more effective in the loops with better flow because the fluid speed in the most critical lines was so slow that just a few meters before the heat exchangers the liquid temperature was again very close to the room temperature.

Test no. 5: the filters used in PP4 for a year were examined under an electronic microscope. The pictures showed a number of particles of various materials sized of ~ 10 - 80 μm in average of the grid of a clean filter. (fig. 2.16).

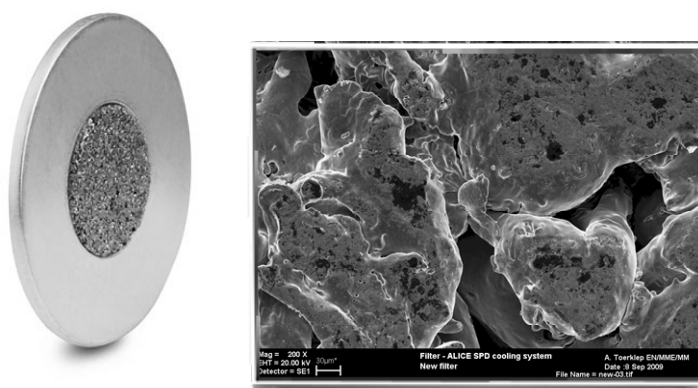


Fig. 2.16: Swagelok filter (left) and its grid microscope view (right)

The analysis carried out at the CERN metallurgical laboratory on the filter taken from sector 7 of the SPD confirmed that the grid was soiled with particles as big as the grid itself (60 μm) (fig. 2.17).

The conclusion of the analysis was the following:

“In the used filters several exogenous fragments were located clogging the filter. There were several fragments containing different composition elements. In addition to elements from the Stainless steel, the following traces of elements were found: O, Al, K, C, Sn, Cu, P, Ca, Cu, Na, Cl and Zn.”

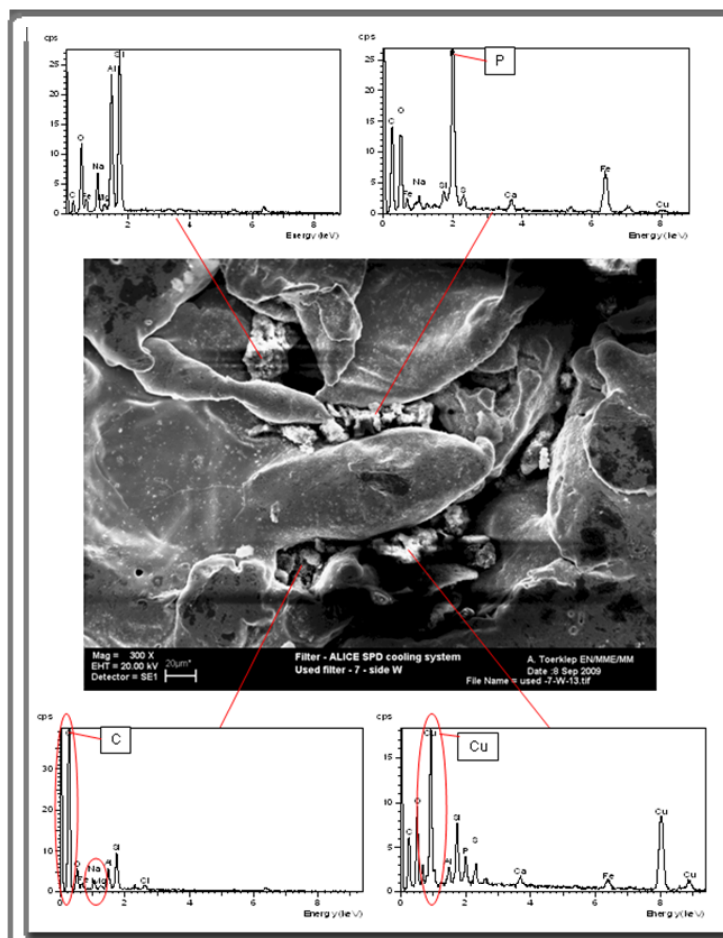


Fig. 2.17: SEM analysys of the filter of sector 7

This result was essential to confirm the hypothesis that a significant number of particles passed through the first filter (PP4) and then stopped on the surface of the following one (PP3) where a certain clogging mass may have piled up and hinder the fluid flow causing a serious pressure drop.

Since the filter in PP3 is not currently within reach we decided to carry out several cleaning cycles by fluxing a solvent called Metklene C3 (used by industrial factories to clean cooling systems, 90-100% diclorinemethane and 3-5% (R)-p-menta-1,8-diene) inside the circuit in the opposite direction at a pressure of 1.8 bar not to damage the detector. The second cleaning cycle was carried out using C_6F_{14} in a cleaning machine (fig. 2.18) equipped with a frequency inverter to adjust the cleaning flow. We could take advantage of the friction of the fluid against the filters thanks to its high density at room temperature.



Fig. 2.18: the cleaning machine

Summarizing, we took the following actions:

- we installed a sub-cooling which consists of 10 heat exchangers in PP4 (one per line);
- each line was equipped with a manual pressure regulator and flowmeter;
- new supply lines were installed: shorter and more symmetrical path with regard to sides O and I of the plant;
- 24-48h cleaning cycle per line;

The results of the cleaning cycles were encouraging: we recovered 14 HSs which, together with the ones already working, totalled 101 out of 120. After the sub-cooling was installed in November 2009 the total rose to 110 which is 91,6% and a record of only 9 HSs were off due to cooling problems.

Unfortunately this situation worsened as time went by and now it takes a few days before the plant becomes stable.

At the beginning of December 2009 the detector lost 8% of its efficiency (100/120 HSs) and held to this value.

The sectors affected by cooling related problems are always the same even after the new piping was laid out. As a matter of fact the new flow data (fig. 2.19) clearly showed that the performance of sectors 3, 5, 6, 7 and 9 are below the minimum ones foreseen by the design parameters (1,8 g/s).

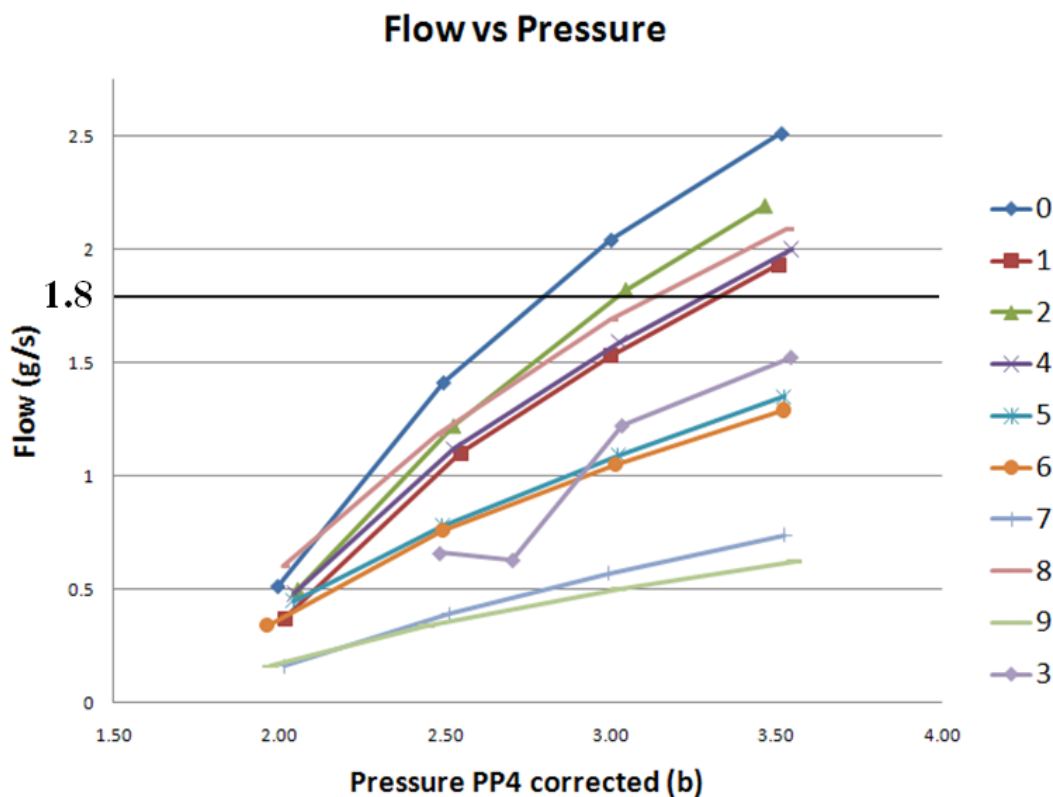


Fig. 2.19: Flow measurement on the detector

The diagram in fig. 2.19 shows the result of a test during which the supply pressure was increased line by line. The sectors were tested one by one and only one loop was opened while all the others were kept closed in order to undo any possible influence among the loops.

2.1.5. Actual performance and flow instability

In February 2010 the situation was very promising, in fact when we turned on the detector after the winter shutdown (December 2009 – January 2010) 108 HSs were switched on and stable (fig. 2.20). On 30th March 2010 the LHC produced collisions at an energy of 7 TeV. Since then, any access to the cavern was authorized only during a scheduled technical stop (4 days every 5 weeks). During the stops in 2010 I attended to the maintenance and restart of the plant. I was also “on call” SPD cooling expert 24h/24 during 2009 and 2010.

During such stops the cooling plant was put in standby (loops closed) and it underwent only minor interventions such as equipping the manifold on the gas side with double safety valves. The plant also stopped a few times (alarms) due to power cuts or to a failure in the chilled water system. The PLC, as previously mentioned, is equipped with safety systems that automatically close the loops and switch off the pump in case of emergency. The plant was restarted after it had been reset and, once it was running again, all the loops were opened one by one.

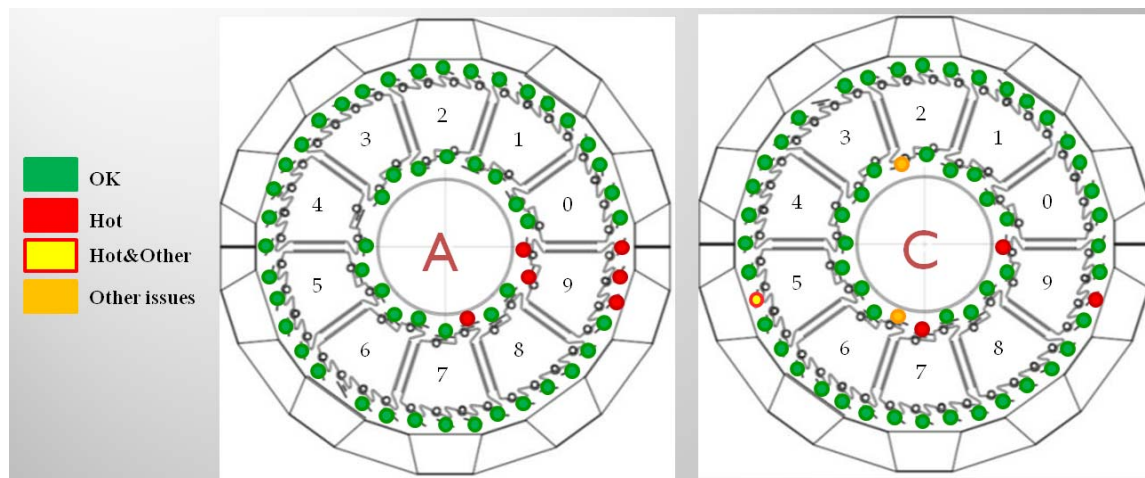


Fig. 2.20: SPD situation on February 2010

After such events we noticed that the flow performance radically change and the trend was getting worse.

Table 2.3 summarizes the most significant flow data measured during some plant restarts.

Sector	25-Feb	17-Mar	25-Mar	28 Apr
0	2.40	2.26	2.36	2.21
1	2.00	1.97	2.00	1.93
2	2.24	2.24	2.24	2.16
3	1.45	0.74	1.20	1.20
4	1.83	1.66	1.70	1.78
5	1.58	1.45	1.42	1.43
6	1.54	1.43	1.38	0.94
7	1.01	0.90	0.98	0.65
8	2.10	2.00	2.09	1.94
9	0.78	0.56	0.56	0.62
Tot flow	16.93	15.21	15.93	14.84

Tab 2.3: Flow data after cooling interruptions (flow in g/s)

The value measured on 25th February concerns the plant performance after the first restart at the beginning of the same month; on 16th March a chiller water failure triggered the interlock system and the day after the flow in sector 3 had decreased by 50% and less, though considerably, also in other sectors.

During the technical stop on 25th March the plant was intentionally switched off in order to refill the tank. When it was switched on the flow had further decreased and in an attempt to start again from a condition similar to the one at the beginning of February, where, all the cooling lines were completely emptied and vacuumed (10^{-5} bar). This procedure slightly improved the flow performance in sector 3, while the one of sector 9 was unchanged.

During the following technical stop the plant was switched off as usual for normal maintenance. When it was switched on again we found that the flow had worsened, therefore it was necessary to reopen the critical lines and vacuum them. Unfortunately this operation didn't increase the flow in sectors 6 and 7. This had never happened during the commissioning in 2008-2009.

Such flow instability has eventually deteriorated the performance of SPD that is at present running with only 94 HSs on. This means that only 78,8% of the whole detector can operate at design conditions. The most affected sectors are still number 3, 6, 7 and 9 which respectively correspond to loops 5, 2, 1 and 6.

The distribution of the dissipated power and the HSs temperature is summarized by the charts in fig. 2.21 where the blue column shows the design condition. All of the HSs are underpowered with reference to the design power and the average temperature is 5° above the design one. In some cases it even gets near the interlock limit which is 38°C.

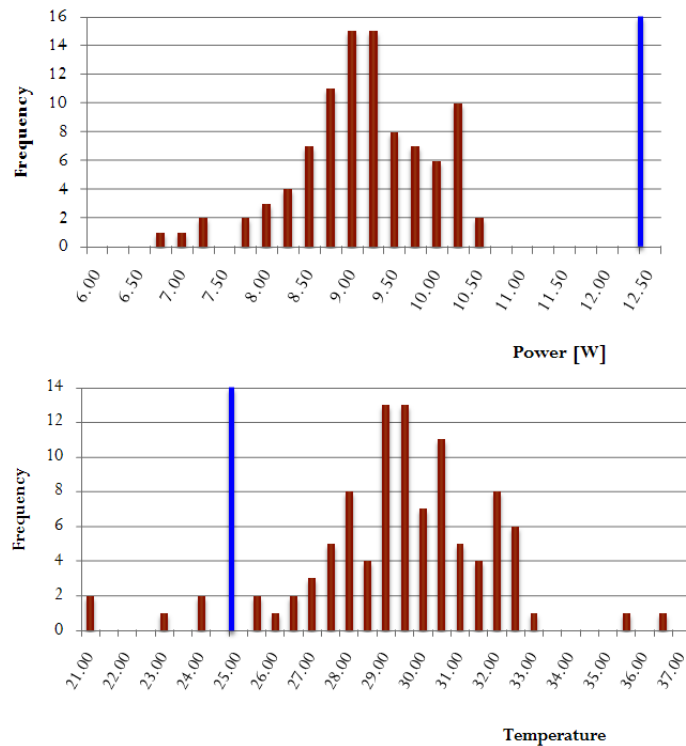


Fig. 2.21: Power dissipation and temperature (°C) distribution

2.5.6. Thermosiphon Test bench

The tests carried out up to now have not provided completely satisfactory evidence of what the real problems that affect the system are. Any hypothesis which, in such complex system, has to rely on untrustworthy calculations has to be experimentally confirmed. Therefore we decided to build a test bench to investigate the issue in the laboratory.

Our aim was to reproduce the same poor flow conditions that characterize some of the sectors of SPD. We meant to study this circumstance in order to find what the most likely causes may be and schedule an improving intervention to be carried out during the shutdown foreseen for the year 2012 (or 2013).

To accomplish this task, we built a sector that is identical to the ones installed in SPD. However, the half-staves are replaced by a 3-layer sandwich that reproduces approximately the thermal properties of the real HSs using a resistance instead of the chip to simulate the heat dissipation. Another fundamental component of this test bench is the kind of cooling plant used. At the beginning we chose a small plant similar to the working one. Several issues, mainly concerning the available cooling power and other minor details, convinced us to build an exact replica of the real plant, which is actually being built.

In the meantime we used a thermosiphon plant built by EN-CV-DC (ENgineering Cooling - Ventilation – Detector Cooling) and based on a different working principle that can deliver C_4F_{10} at working conditions identical to the nominal ones.

We started to build the test bench at the end of last summer and in the meantime we thought it right to take advantage of the months until it was finished to carry out preliminary tests using a dummy sector of SPD. Therefore in co-operation with the CERN group of ENgineering Cooling and Ventilation (EN-CV) connected the dummy sector to an already working thermosiphon plant that had been tested with C_4F_{10} .

The dummy sector is provided with the same hydraulic equipment as a real sector of SPD. The only difference is that its carbon fibre supports do not house HSs but heating elements powered by a common power supply.

The thermosiphon is a bi-phase system that circulates a cooling fluid without the aid of any mechanical equipment such as pumps or compressors. The fluid is condensed at a temperature and pressure lower than the evaporation ones and at a higher height than the evaporation point in the testing sector.

Figure 2.22 (a) shows the thermosiphon working principle and (b) the relevant p-h diagram. The fluid circulates in a natural way since gravity makes it fall to the bottom of the plant; its pressure is raised by hydrostatic pressure during the descent. At the bottom of the plant the fluid evaporates on contact with the sector it is supposed to cool. The evaporation pressure in the sector is slightly higher than the condensation pressure at the top of the plant; this difference makes the gas rise back to the top.

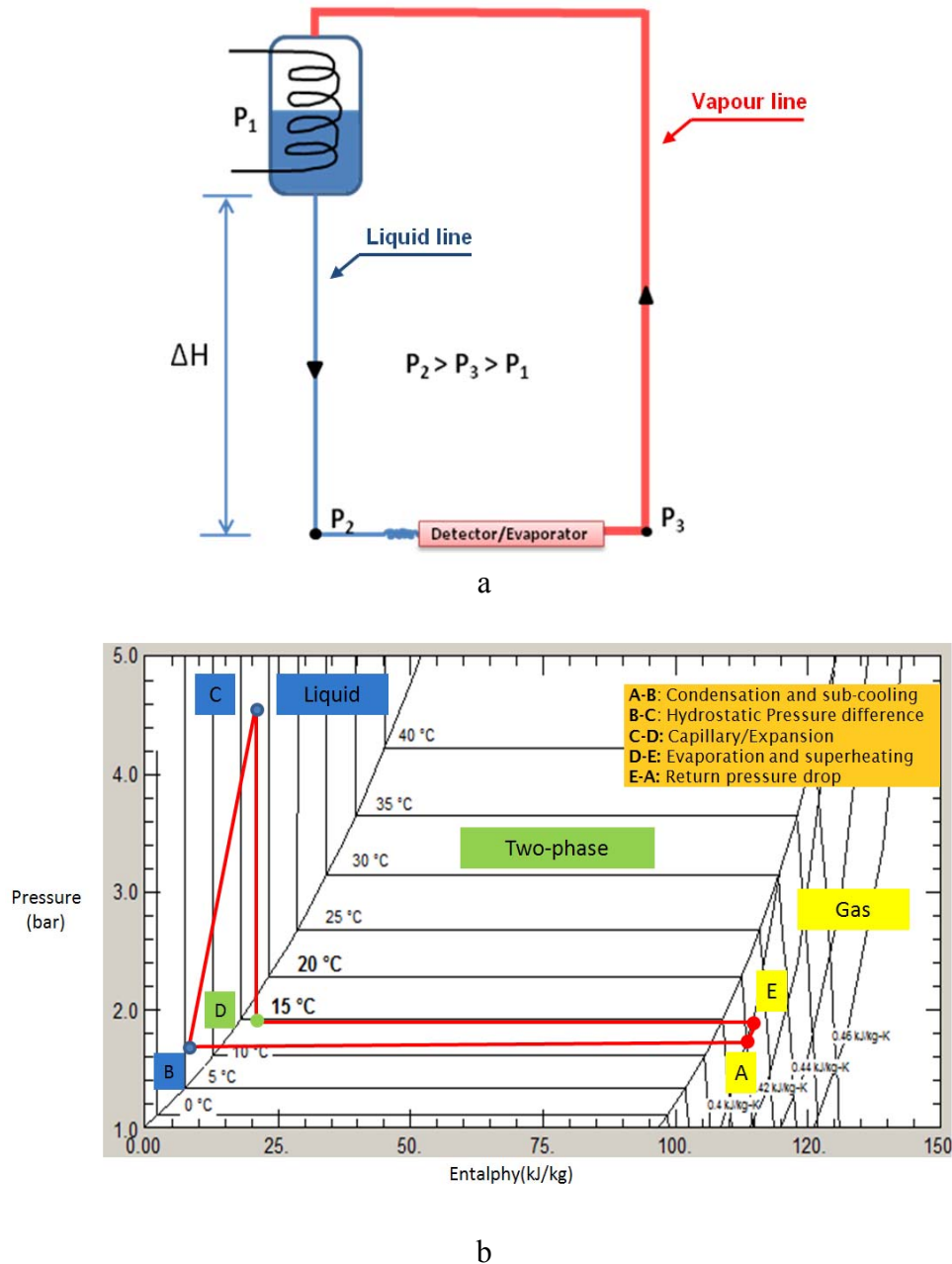


Fig. 2.22: Thermosiphon system (a) and C_4F_{10} p-h diagram description (b)

The fluid inside the dummy sector evaporates at a slightly higher temperature than the one inside the condenser; due to such difference the evaporation pressure outgoing from the evaporator is a little higher than the one at the entrance of the condenser and this is what makes the gas rise back to the top along the return pipe. The evaporation pressure inside the sector depends on the saturation pressure inside the condenser.

The system can work only if the hydrostatic pressure difference between the condenser and the entrance of the sector is higher than the pressure difference between the sector inlet and outlet points.

In this particular situation a ΔH of 18 m provides a pressure difference between P_2 and P_3 of about 2,5 bar (P_{in} 4.2 and P_{out} 1.7) which is suitable to our requirements. Our dummy sector was connected to the thermosiphon as shown in figure 2.23.

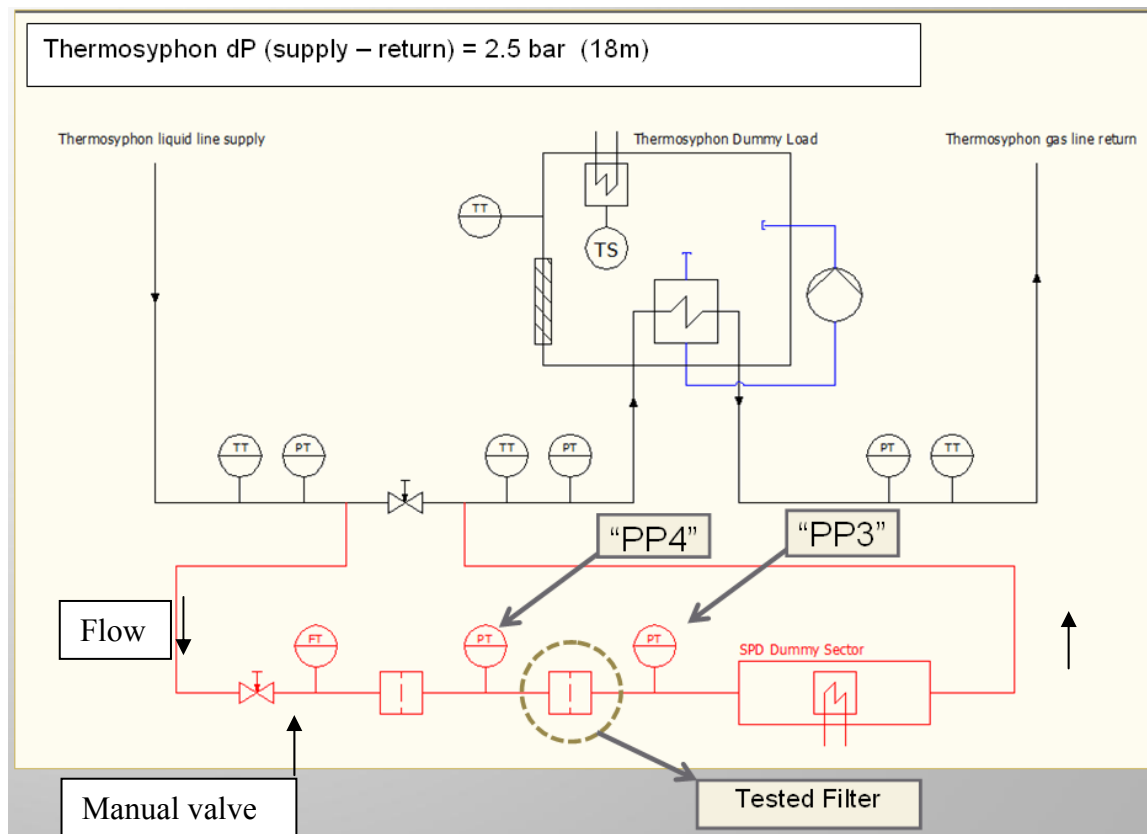


Fig. 2.23: Thermosiphon test bench scheme

The two filters were installed in series and two pressure transducers (one was set up between the filters and the other one after the second filter) allow us to determine accurately the fluid pressure depending on its different conditions. This configuration also matches the position of the filters in the cavern even if the distance between the two filters is shorter. For the sake of convenience we decided to name the two filters as follows: the first one is called “filter in PP4” while the second one is the “filter in PP3”.

As illustrated in the above figure, the first transducer supplies pressure in PP4 whereas the second one provides pressure in PP3.

The Thermosiphon test bench is controlled by a PLC and it can detect pressure along the test line and other data (pressure and temperature) at different spots thus allowing us to monitor the whole fluid path from thermodynamic point of view.

We carried out several test sessions with inlet pressure of 4.2 bar and outlet pressure of 1.7 bar:

1. pressure drop trend in the filter in PP3 in different flow conditions with the following configurations (different flows were set by operating the manual valve):

➤ circuit set without filters

- circuit set with a 20 μm filter in PP3
 - circuit set with a 60 μm filter in PP3
 - circuit set with two 60 μm filters (1 in PP4 and 1 in PP3, as in the cavern)
 - circuit set with two 60 μm filters in PP3.
2. After classifying the results of the above tests, we studied the performance of 60 μm filters in PP3 which had been partially shadowed with epoxy glue laid on the 50%, 75% and 90% of the filters;
 3. We finally let in the circuit some carbon dust calibrated as follows:
 - (0,4-12 μm)
 - (20-50 μm)
 - (80-200 μm)
 - sample of dust calibrated at max 75 μm

We used these samples according to the following procedure: we started by introducing a small quantity (less than 1g) of very thin dust in order to check the effectiveness of the 60 μm filter. The dust thickness was then increased step by step until an 80-200 μm sample was used. We finally carried out some mixed tests making use of dust of different sizes.

2.5.6.1 Results

The first results concern the flow tests carried out depending on the position of the manual valve at the circuit inlet (fig 2.24). When the manual valve is fully open (position 0) the flow is very close to the design one.

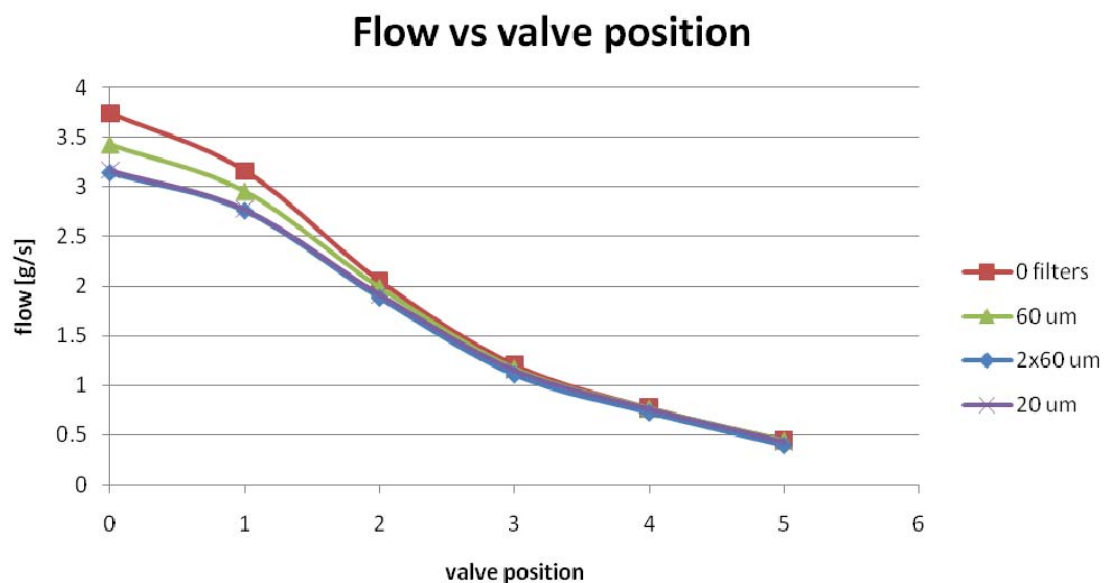


Fig. 2.24: Flow test at different manual valve positions

The values are between 3,74 g/s when the circuit is set without filters (red line) and 3,17 g/s with the 20 μm filter (violet line). The nominal design flow is 3,6 g/s.

As the manual valve is closed the value of the flow decreases according to a regular trend until reaching 0,5 g/s in position n. 5. The diagram shows that the effect obtained using only a 20 μm filter is the same as with two 60 μm filters in series (blue line). The green line shows the performance using a 60 μm filter; it clearly evidence that its trend is intermediate compared with the one of the circuit working without filters or with two filters of the same size.

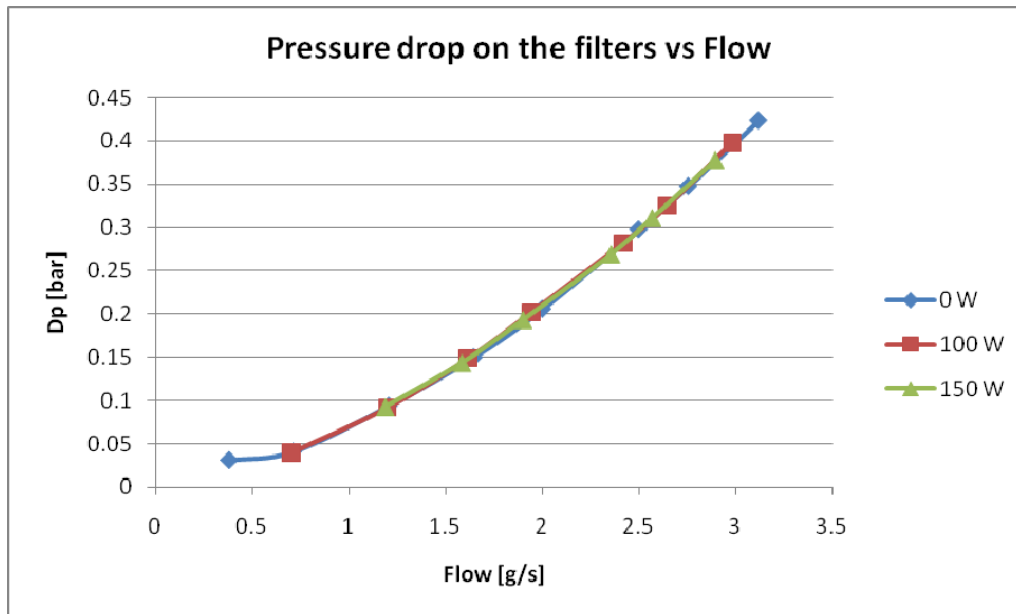


Fig. 2.25: Pressure drop in PP3 with different flow and different power applied to the sector.

In the upper part of the diagram in figure 2.25 some data concerning the pressure drop in inside the filter (clean) in PP3 are enhanced. The circuit was configured with two 60 μm filters in series and different flow rates were set by applying a power of 0, 50 and 150 W. At about 3.2 g/s, the pressure drop is around 350-400 mbar and it decreases as the flow is reduced. The pressure drop in PP3 decreases also as the power applied to the sector increases. Such behaviour is illustrated more evidently in figure 2.26.

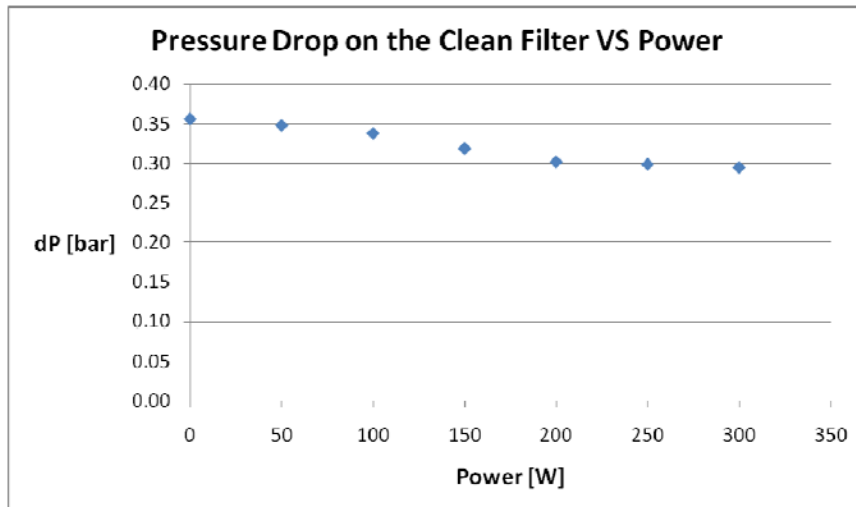


Fig. 2.26: Pressure drop and flow test at different power applied to the sector

The above figure clearly evidences that the impedance of the sector rises as the applied power is increased. Being the manual valve position the same, the flow decreases from nearly 2,9 g/s when 0 W are applied to less than 2,6 g/s at 300 W.

We also notice a reduction of 50 mbar in the pressure drop in the filter in PP3 during the lapse of time between the beginning and the end of the test. This effect is correlated to the flow reduction. The pressure drop for a 60 μ m filter is around 350 mbar.

Figure 2.27 shows the filters that we clogged with epoxy glue. We decided to put the glue on different parts of the surface of the filters in order to check the pressure drop in several conditions. The photo presents three filters 50% (lower part), 75% (in the middle) and 90% (upper part).



Fig. 2.27: Filters clogged using epoxy glue on different surface portion of the filters

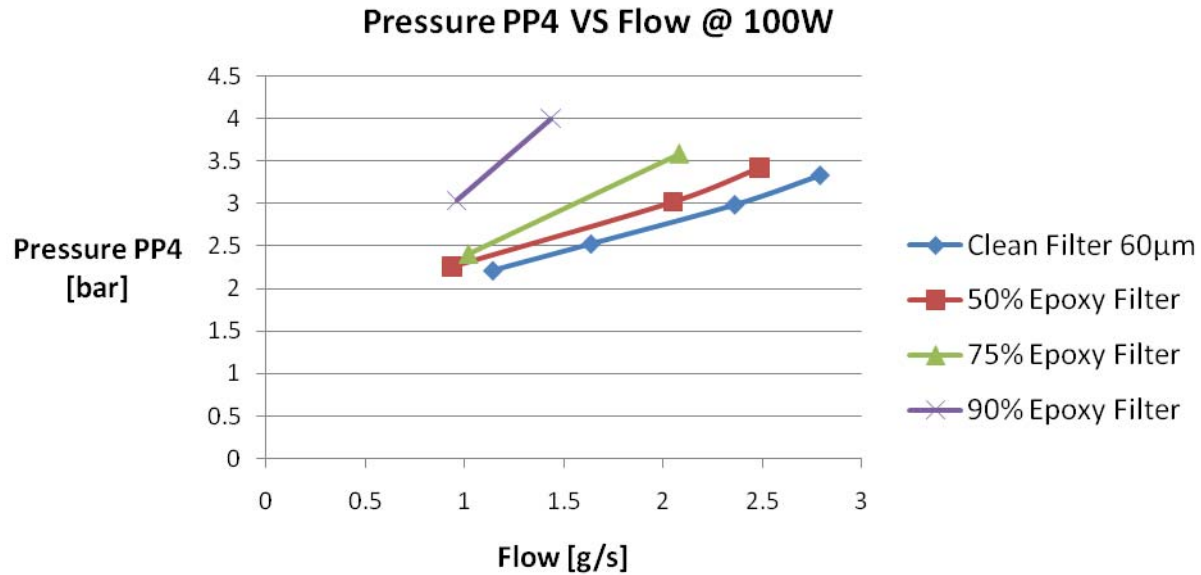


Fig. 2.28: Pressure in PP4 with clogged filters

Figure 2.28 shows the pressure trend in PP4 according to the flow rates of the clogged filters when a 100 W power was applied to the sector. The blue line, representing the trend with the 60 µm clean filters, was added for comparison. As can be noticed the filter with a 50% clogged surface (red line) does not evidence a clear pressure rise and the flow loss is around 10%. The only case in which the effect of the impedance rise is more obvious is when using a 90% clogged filter (violet line). The maximum flow we managed to reach in that situation is 1,43 g/s. The flow in worst performing sectors of SPD is less than 1 g/s. This is a plain proof of the fact a simple shadowing of the surface of the filters cannot explain by itself the effects observed in the “real” system.

Finally we carried out tests using carbon powder of different calibres in order to check how it affected the flow decrease. We decided to use this kind of powder since the blades of the pump installed in the cavern are made of the same material and the analysis of the filters in PP4 in the cavern evidenced the presence of carbon powder in great quantities.

To carry out these tests we prepared several samples each weighing 0.25g and we used them on the 60 µm filters in PP4 and PP3. We weighed the filters before and after the tests. The first test was carried out by putting the content of the 0,4-12 µm powder sample in the circuit between the flowmeter and the filter in PP4. Since it was very difficult to handle the powder, only 70 % of the sample could actually be used.

When the inlet valve was opened we evidently observed that some of the particles passed through the two filters and reached the sector. Even if the quantity of powder was really small and, despite the fact that some of it stuck to the sides of the plastic flexible pipes between the two filters, it affected the flow in an unmistakable way.

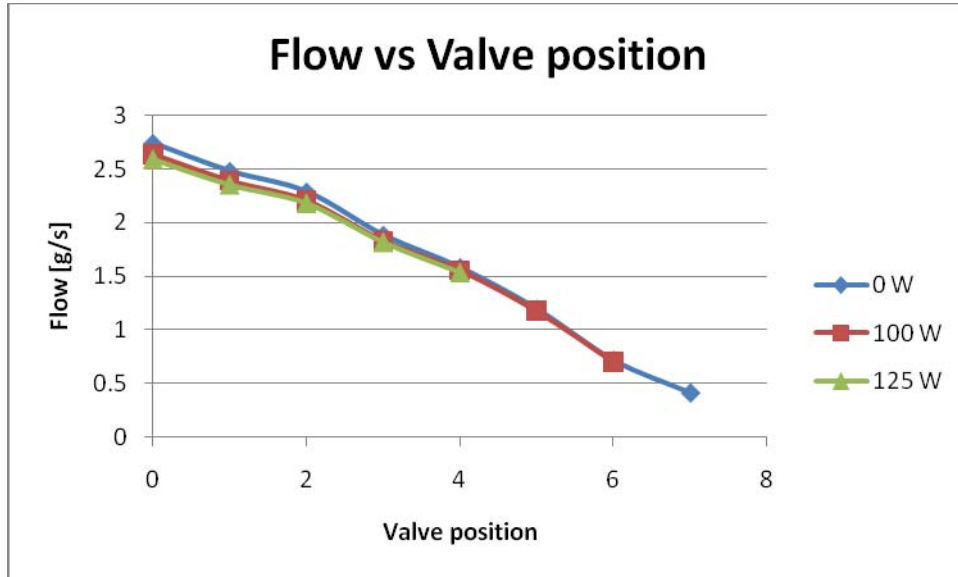


Fig. 2.29: Flow rates of the filters clogged with 0,2 g of carbon powder (0,4-12 μm)

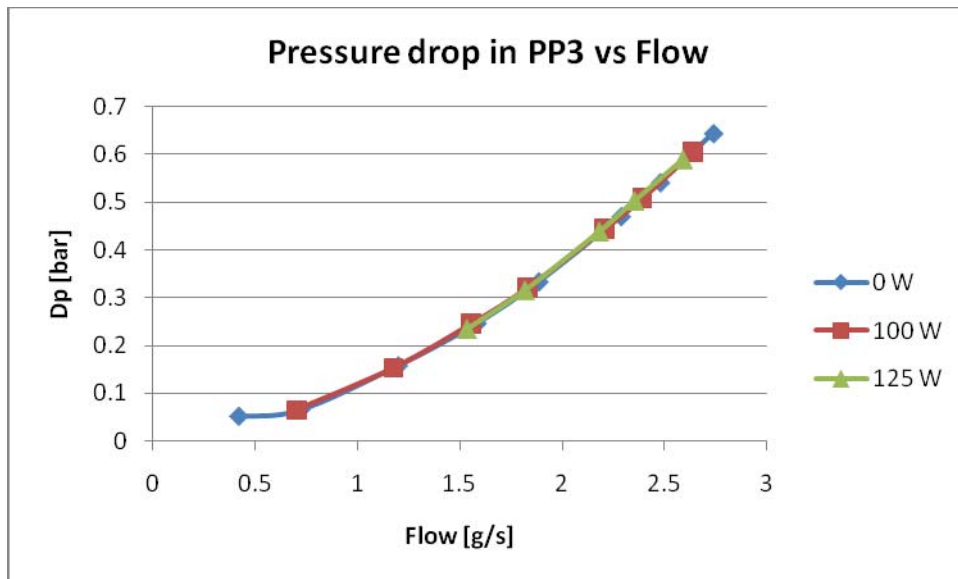


Fig. 2.30: Pressure drop in PP3 with filters clogged with $\sim 0,2$ g of carbon powder (0,4-12 μm)

As evidenced in figure 2.29, the flow clearly decreased: around 2,8 g/s compared with 3,2 g/s for clean filters. The pressure drop in the filter in PP3 increased by 50%: 644 mbar instead of ~ 400 mbar. (fig. 2.30 compared to table 2.4). This result is quite unexpected since the size of the powder we used is remarkably smaller than the matrix of the filter. When power was applied to the sector we noticed a further decrease in flow compatible with the drag offered by the sector.

Both filters were removed after the tests in order to weigh them to assess the quantity of powder collected. The filter in PP4 weighed 0,0012 g more while the one in PP3 had taken up 0,0007g.

This proves that a very small quantity of powder is enough to cause remarkable flow problems. The filters were visually analyzed with an Electron Microscope (SEM). Figures 2.31 and 2.32 show the conditions of the filters in PP4 and PP3. It must be noticed that the powder is evenly distributed on the surface of the filter in PP4 while only a small part of the filter in PP3 is clogged. The latter is nevertheless affected by a pressure drop twice as big as the one that occurred with clean filters. The size of the grains is highlighted in Figure 2.33 and it is easy to notice that agglomeration occurred. A picture of the filter in PP3 examined under the microscope is shown in fig. 2.34.

Supposing that some powder could also have settled between the filter in PP3 and the sector we decided to replace the plastic sections of the pipes, the stainless steel connections and to install two new clean 60 μm filters. When the test was resumed we found out that the original flow data were the same ones we noticed when the test was started (3,1 g/s; 400 mbar pressure drop in PP3). This leads us to exclude the possibility that the particles confined in the last portion of the pipe before the capillary could affect the flow.

Annex 1: General view of filter pp4

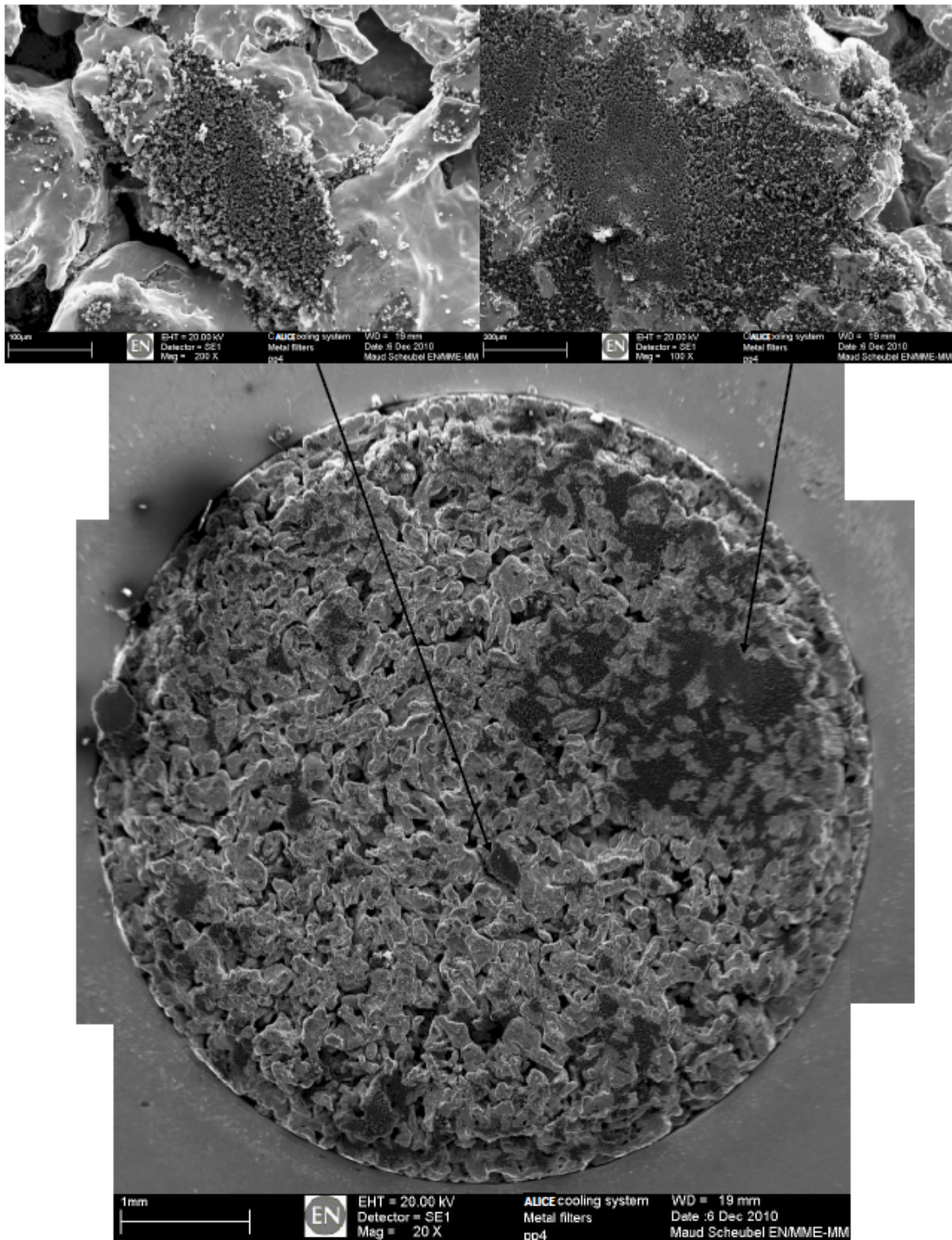


Fig. 2.31: SEM analysis of the clogged filter in PP4

Annex 4: General view of filter pp3

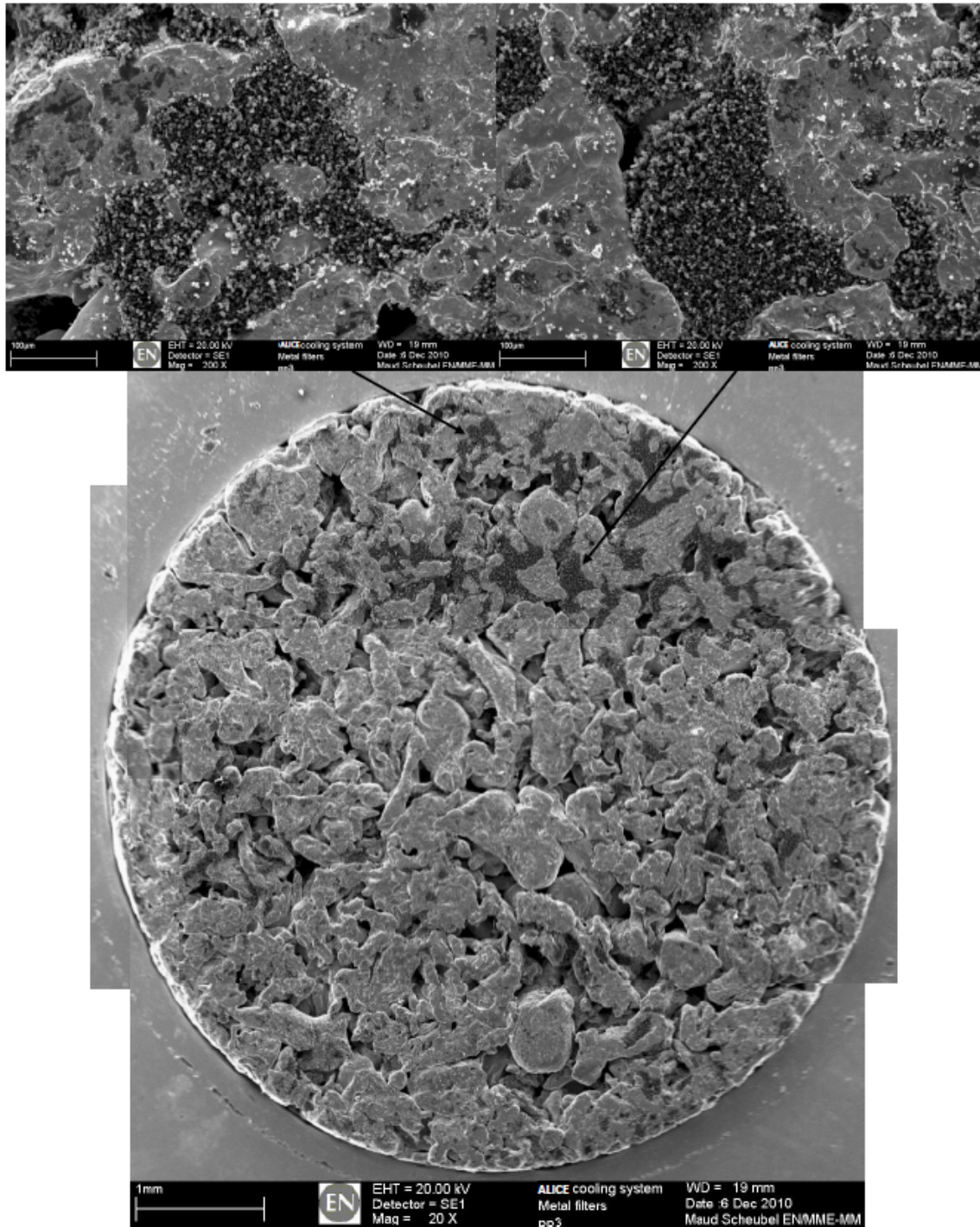


Fig. 2.32: SEM analysis of the clogged filter in PP3

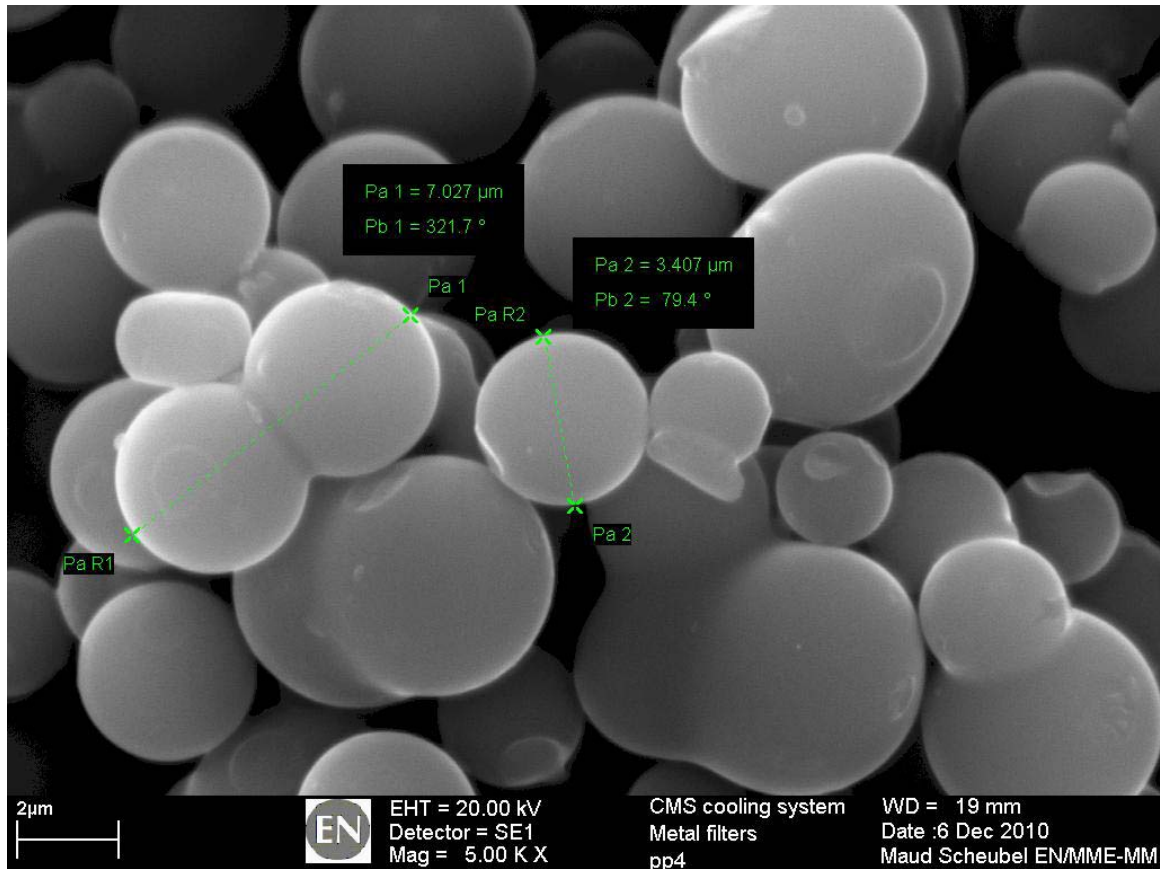


Fig. 2.33: dimensions of the particles in the filters



Fig. 2.34: Filter in PP3 after the test

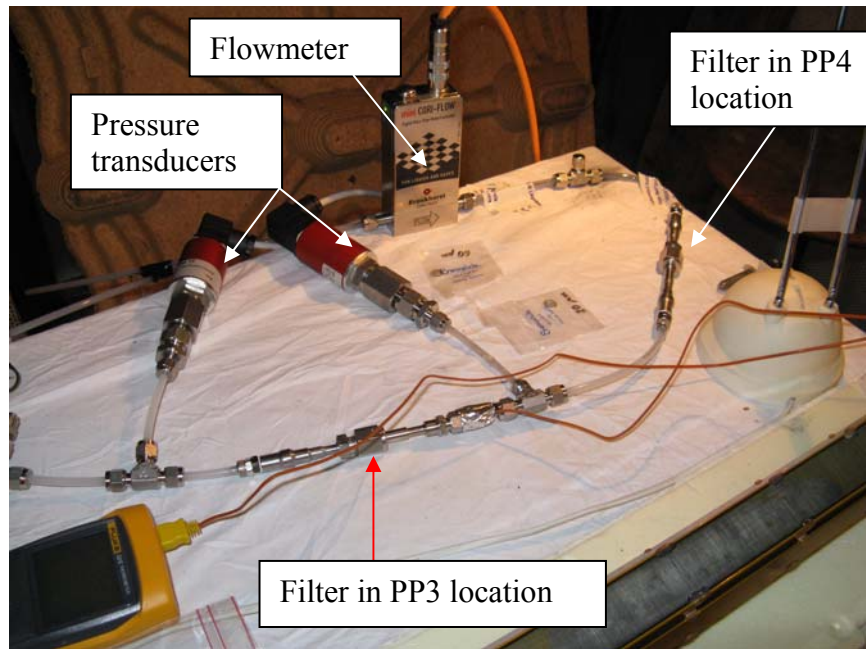


Fig. 2.35: Test section installation

In figure 2.35 the test setup is shown.

Another test was carried out by introducing twice the quantity of powder (0,5 g) having the same diameter ($0,4\text{--}12\text{ }\mu\text{m}$). In this case we had a pressure drop in PP3 of 350 mbar, the flow decreased drastically and stabilized at 1,15 g/s.

This test provided evidence that most of the dust gathered in the filter in PP4 and only a little passed through it. In fact pressure in PP4 was 2,47 bar (tab. 2.4) therefore only 200 mbar higher than the one detected at the same spot with a clean filter and with the same flow value (fig. 2.28); the pressure drop in PP3, instead, had tripled (compare fig. 2.25 with tab. 2.4).

This circumstance was photographed with a thermocamera. Figure 2.36 shows that the temperature in the last part of the sector was around 40 degrees with 150 W applied thus confirming that the sector cannot be used in such condition.

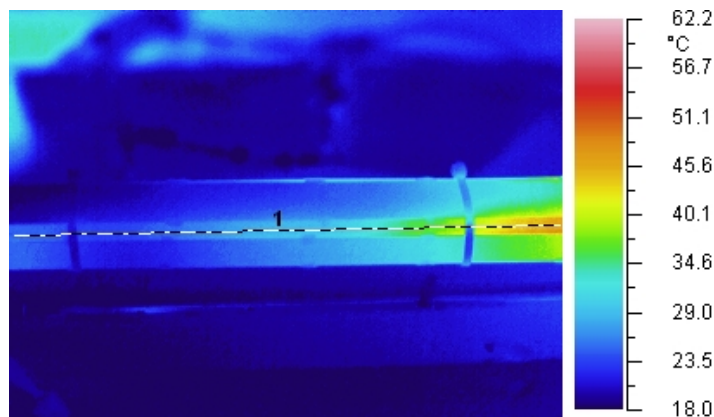


Fig. 2.36: Powered sector photographed with a thermocamera

We carried on further tests with thicker powder. The flow and pressure drop values we measured are reported in table 2.4:

Powder diameter (μm)	Mass (g)	Pressure PP4 (bar)	Δp in PP3 (bar)	Flow (g/s)
0,4-12	0,2	3,44	0,644	2,74
0,4-12	0,5	2,47	0,355	1,15
20-50	0,25	2,168	0,032	0,915
80-200	0,25	2,185	0,073	0,776
max 75	0,25	2,422	0,102	1,487

Tab. 2.4: results of the tests with carbon powder

All these results make it clear that it is more difficult for thicker powder to pass through the filter in PP4 and that it makes the flow decrease without affecting the pressure drop in PP3. Finally we carried out a set of tests with very small quantities of 0,4-12 μm powder ($< 0,1$ g) staggering the starts and stops in order to check if conditions changed in time. The results are shown in table 2.5.

From the table we can deduce that the raise of Δp in PP3 is remarkable and it highlights that fact that at any cycle some particles pass through the filter in PP4 and settle on the following filter. This behaviour is very similar to the one of SPD during the last months. Moreover it is a preliminary, important indication suggesting the possibility that during the first running year the filter in PP3 became dirty since there was no 1 μm filter at the plant. Thus, as time went by, some particles may have come off the filter in PP3 and deposited all over the circuit any time the loop was opened again.

Action	Pressure in PP4 (bar)	Δp (bar)	Flow (g/s)
Stop&start	3,031	0,337	2,495
Stop&start	2,885	0,323	2,238
Stop&start	3,197	0,471	2,590
Stop&start	3,373	0,663	2,489
Stopstar from vacuum	3,162	0,540	2,060
Stop&start	3,413	0,673	2,298
Stop&start	3,463	0,685	2,255
Stop&start	3,474	0,686	2,270

Tab. 2.5: Start and stop cycles with very small quantity of carbon powder (0,4-12 μm)

To conclude we showed that the state of the SPD cooling is strongly affected by a pressure drop along the circuit and that any improvement that was made during the last years allowed to slow down its worsening.

With reference to the commissioning phase, all the tests carried out so far suggest that the loss of efficiency suffered by SPD because of the cooling reduced performance is most probably due to partial clogging of the inline filters. A further series of tests has to be carried out in order to reproduce running conditions as close as possible to the real ones. This can be done using an exact replica of the actual plant.

While performing such tests we also mean to define the range of thermodynamical conditions where the problem is localized and set the best running parameters for future operations at maximum efficiency. This work is preliminary to the one that will be done during the long shutdown of LHC (2012-2013) when any part of the cooling lines will be accessible (included the filters in PP3).

Chapter 3

The ALICE controls and the detector control system of SPD

This chapter describes the ALICE Controls and the Detector Control System (DCS) of SPD. The first part deals with the general characteristics and the tasks of the experiment control system, while the second one explains the main features of the SPD control system and my contribution to its implementation.

3.1 The tasks of DCS

The main task of DCS is to set the ALICE experiment to work efficiently and safely. It controls and oversees the hardware, the facilities of all detectors (e.g. HV, LV, cooling) and the common infrastructures such as racks, environmental conditions and the like.

DCS also operates as an interface to external systems like the CERN Technical Services (e.g. electricity, ventilation) and the accelerator main parameters (e.g. beam conditions and backgrounds). It provides online information concerning the status of the monitored facilities and equipment, with as many details as required by the global system operation.

In order to manage the whole ALICE experiment, which consists of 18 sub-detectors, according to the expected standards of efficiency, the Detector Control System must meet the following requirements:

- Partitionability: it is the ability to cut off a sub-system in order to operate it separately from the rest of the experiment. This operation mode is particularly useful during maintenance or calibration. This characteristic is fundamental considered the number of sub-detectors that form this experiment.
- Modularity: it is provided by the hierarchical structure of DCS.
- Homogeneity: this features helps integration, maintenance and upgrading; the hardware and software comply with this directive.
- Flexibility: it is a very important characteristic since DCS is supposed to manage and monitor several elements whose requirements may vary according to different needs.
- Automation: it carries out normal actions in a very fast way and it prevents human errors which may easily occur when routine is concerned.
- Intuitive User Interfaces— since not all operators are control system experts, user interfaces have to provide a standardized and coherent view of the system and they also must be easy to be used by everybody.

A Detector Safety System (DSS) was implemented in order to supervise and prevent situations that could endanger people and damage the detectors. The DSS consists of a front-end, stand-alone system based on PLCs [2].

The DCS was implemented with PVSS-II SCADA system [14] (Supervisory Control and Data Acquisition) using the Framework (FW) components developed at CERN according to the JCOP (Joint COntrols Project) project. Since several of its functions are required non-stop, the technology and solutions they are based on must ensure a 24-hour working as long as the experiment is running.

Even if it was made of a wide range of components and it was developed by different groups in parallel, the DCS is a coherent and homogeneous system that allows to easily integrate its sections.

Given the large number of sub-detectors and subsystems that need to be controlled, the only way to provide an integrated control system for the ALICE experiment is to use common solutions for common requirements.

As the DCS is expected to be working during all the running phases of the experiment (data taking, shutdown etc.), it must cope with different operational modes and, at the same time, it must allow to control the sub-detectors or any part of them in an independent and simultaneous way.

All the data required to configure the equipment of the ALICE experiment are stored in databases. The records concerning the operation of the experiment are archived and can be available at any time, while the information regarding the physical analysis is stored in a database and can be easily accessed from the offline system.

Since one of the most important tasks of this control system is to assure the integrity of the detectors, this unit must be reliable and allow for both hardware and software interlocks in case of dangerous situations.

The control requirements needed by subsystems were systematically collected by the ALICE Control Coordination (ACC) team, who drew up light weight User Requirement Documents (URDs), so as to determine the ones that were common to all of them. Every URD is equipped with an ‘overview drawing’ that shows the hardware structure of the control system of each sub-detector.

The DCS also takes care of configuring, monitoring and supervising the technical equipment of the experiment such as commercial hardware devices, power supplies, crates and sub-detectors specific equipment like front-end chips, etc. The above also includes computing devices like PCs, PLCs and the software processes running on them. This task is carried out mostly by sending commands and settings to the equipment and by reading back the information received from it.

The control system can also handle pre-programmed decisions and automatic actions, such as recovering from errors, without requiring any operator intervention. Operators can interact with the control system through a user interface that displays the information and allows to issue commands. In fact, the JCOP project provided useful tools to be used to define the kind of alarms (warning, errors or fatal) and to configure them within the DPs structure. This way, through PVSS it is possible to implement some safety devices that are necessary to protect basic equipment and to make the detectors run properly. The control system is endowed with an Error handling feature that allows to detect errors and to attempt to correct them. It is also supposed to inform and give instructions to operators, to record and store information about problems in order to keep statistics for further offline analysis.

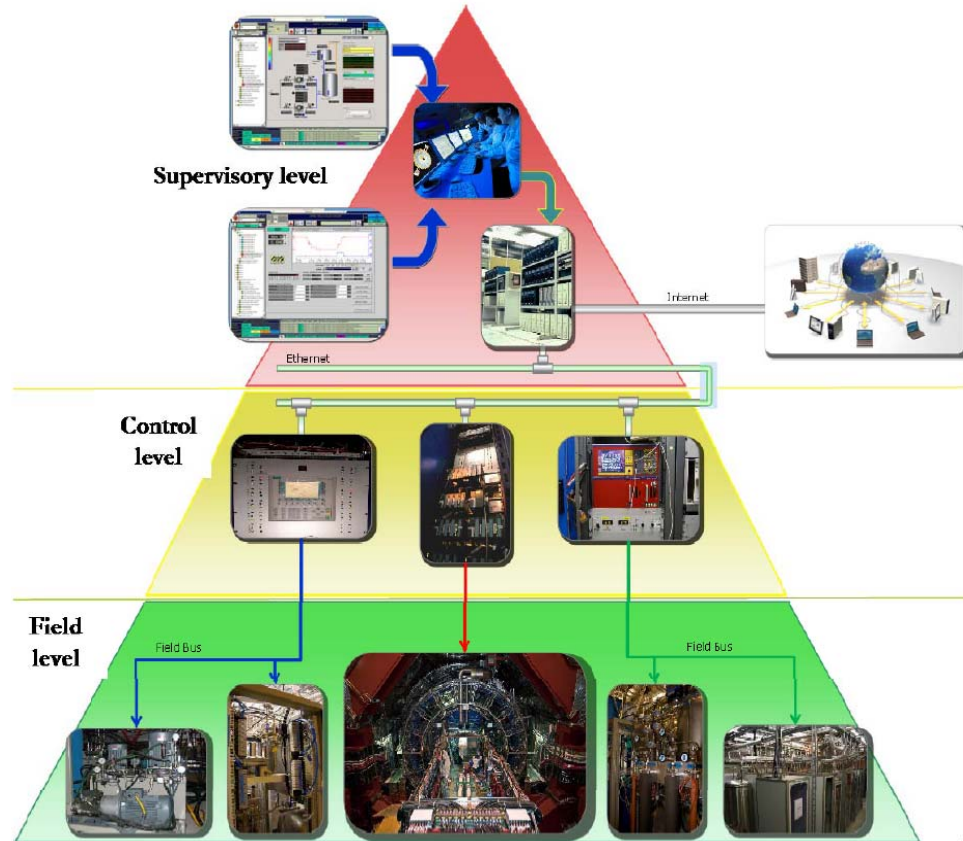


Fig. 3.1: The ALICE hardware architecture

The hardware architecture of the control system can be split into three layers: supervisory, control and field as shown in figure 3.1.

The supervisory layer is composed of a number of computers (Operator Nodes, ON) that provide the user interfaces to the operators. The worker nodes are on a slightly lower level; they interface with the control layer. The supervisory layer interfaces the control layer where drivers, PLC or PLC-like devices communicate with the equipment of the experiment. These devices collect and process information from a lower level, called field layer, and make it available for the supervisory layer. In the meantime the control layer receives information from the supervisory level to be processed and distributed to the devices. The field layer includes all the field devices such as power supplies, fieldbus nodes, sensors, actuators, etc.

Figure 3.2 shows the software architecture: the supervisory layer is divided into two sub-layers, respectively the FSM and the SCADA layers. The software layer will be discussed more in details in the next sections.

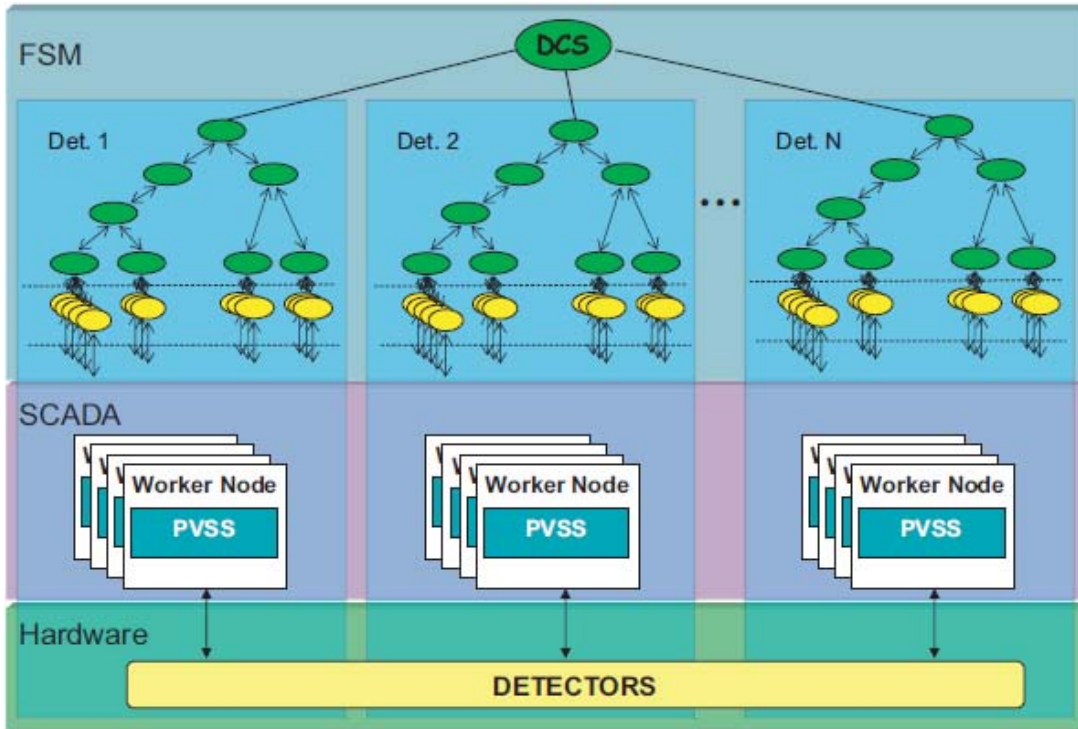


Fig. 3.2: DCS software architecture

3.2 The Finite-State Machine (FSM)

The FSM is a common interface (fig. 3.3) used to integrate the global ALICE DCS control with the one of each detector. It is implemented using the State Management Interface (SMI++) [14].

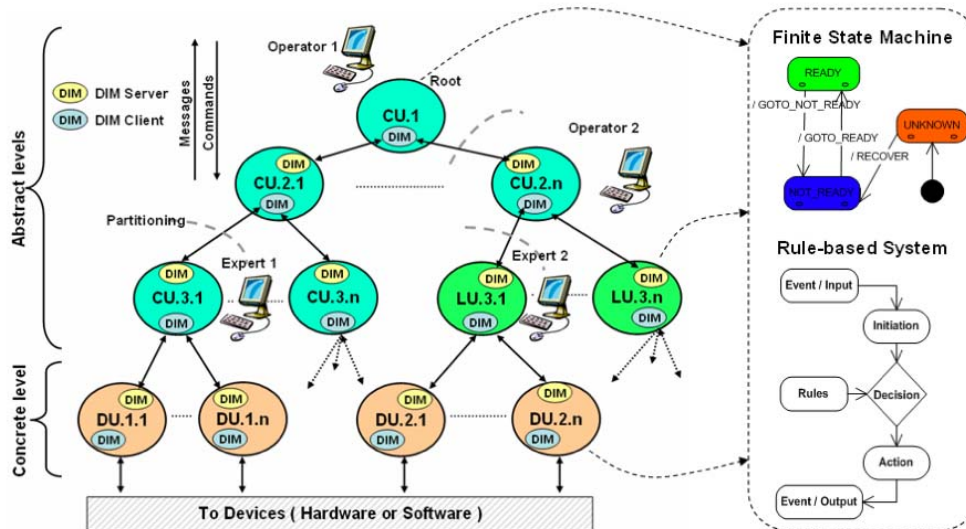


Fig. 3.3: The FSM general concept

The programming language is object oriented and it foresees 3 main object types: Device Units (DUs), Logical Units (LUs) and Control Units (CUs). All of them are fundamental building blocks of the whole hierarchical control system. The CU and LU shape and control the sub-tree below them, while the DU is connected to a device (power supply, PLC, etc.). The hierarchy can have as many levels as required in order to provide the sub-detectors with the number of abstraction layers they need.

A great advantage that characterizes such a hierarchy is its partitioning capability because it allows its components to work in an independent way. Parts of the system, usually sub-trees, can be separately and simultaneously controlled and monitored. This feature is very important, especially during the installation and commissioning stages, when sections of the control system might not be available yet but sub-detectors need to control the installed equipment. It is also valuable during debugging operations, tests or the calibration of sub-detectors. Further details concerning the implementation and the philosophy according to which such general tools were developed can be found at reference [14].

3.3 The PVSSII package

PVSS is software used to develop a SCADA (Supervisory Control and Data Acquisition) system chosen by JCOP. Generally a SCADA system is defined as a computer system that monitors and controls processes. The controlled process can be industrial (manufacturing, production), linked to infrastructures (water treatment/distribution, electrical power, large communication systems) or facility-based (airports, buildings, ships, space stations).

The CERN programmers use a software called PVSS II, which is the German abbreviation for "Prozessvisualisierung und Steuerungssystem" that means process visualization and control system II [2].

PVSS is a software package especially conceived for engineering automation, in fact it is mainly used to operate and supervise technical installations. One of its main advantages is that it not only visualizes the status of a process in progress but it also allows to send commands to the process in order to control the related equipment.

PVSS is successfully used to connect to hardware or software devices to get the data they produce and to monitor their behaviour so as to initialize, configure and operate the devices themselves.

This software is also characterized by other basic functions which include alerting the operators when a crucial state takes places, when limits are exceeded or when danger points are reached. In such cases the data are archived to be afterwards displayed and analysed. Operators can use these functions by means of a mouse, a keyboard or other standard computer input tools and the response to their actions is immediately displayed on the screen. PVSS provides the following features:

- Device description and access
- Alarm Generation & Handling
- Alarm display, filtering, summarizing
- Archiving, trending, logging
- Access Control
- Drivers

This software platform is characterized by a highly distributed architecture. A single application is made of processes called Managers which communicate with one another

through a PVSS-specific protocol over TCP/IP. When a Manager wants to access some data it receives them directly from the process image of the Event Manager without having to communicate with a controller. This is made possible by an option that consents to select a threshold in order to determine when the drivers can send data to the Event Manager.

In particular, when a significant change is detected one out of four options can be chosen: data, time, data and time, data or time threshold. Therefore, in stable conditions, i.e. when the process variables are not changing, there is essentially no data traffic.

Fig. 3.4 shows a typical PVSS application: it is a simple configuration which consists of a Database manager (DB), an Event Manager (EV), User Interface managers (UIs), an Application Programming Interface manager (API), a Ctrl manager (Ctrl) and some Drivers (D).

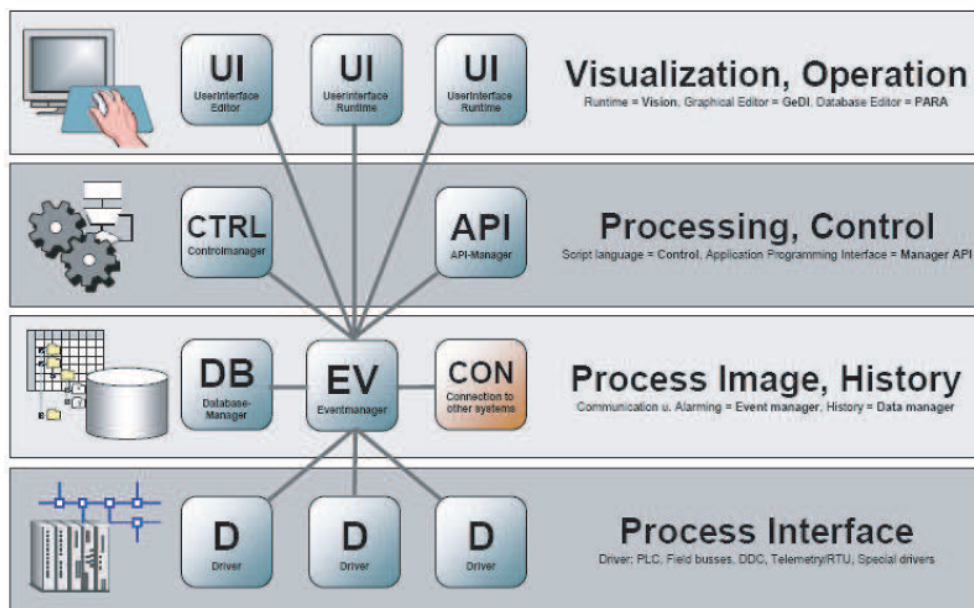


Fig. 3.4: An example of the PVSS system which shows the main manager types

The lowest level of the PVSS system displays the drivers. The ones provided by this software can be OPC, Profibus, CANbus, Modbus, TCP/IP and Applicom. Drivers serve as interfaces to the devices to be controlled, in fact they read online states, measured values or counter readings received from such devices, they send back commands and set point values to the controllers. A great advantage of PVSS is that it was conceived to provide a link between external software developed in different language (i.e. C++). Moreover it also allows to implement a custom programming and through standard protocols (i.e.: Distributed Information Management– DIM) it can process the data received by such programming and make them available for further use or analysis.

The second layer hosts Communication and Memory. The Event Manager handles any communication. It receives the data from the Drivers (D) and forwards them to the Database Manager to be stored in a database. The EV retains the “process image” in its memory and it also distributes the data to all the Managers that have subscribed them.

Moreover, it also manages alerts and it can make several calculation functions in an autonomous way.

The third level displays the Ctrl Managers which are scripts that handle data as "background" processes. The API Manager allows users to write their own programs in C++ using a PVSS API to access the records stored in the database.

The User Interface, which occupies the top level, is the real interface with the users. The UI displays values, sends commands and tracks the kind of warnings that are included in the list of alerts. Usually trends and reports can be displayed in it.

The way the relevant values and fields are shown is up to the software developers according to the kind of process that has to be monitored.

PVSS can be expanded for very large applications but in that case one system would not be enough and a PVSS Distributed System, a confederation of communicating systems, should be used.

Fig. 3.5 shows a distributed system: the systems are equipped with Distribution Managers (Dist) that are connected with one another. This way hundreds of systems can be interconnected.

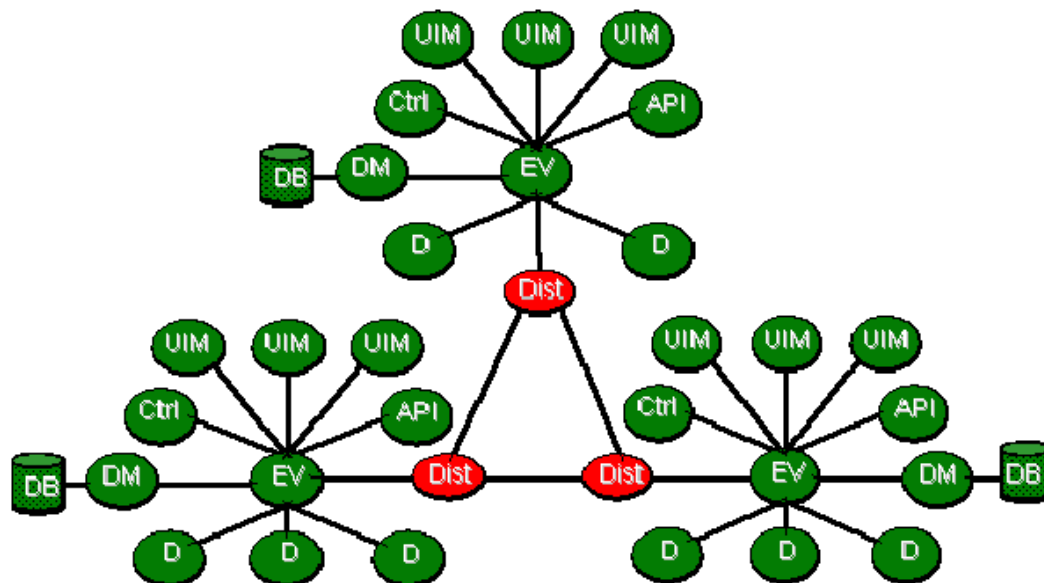


Fig. 3.5: An example of distributed system

With this software users can design their own user interface panels in a "drag and drop" fashion. The Graphic Editor allows to plan the static part of a panel by positioning buttons, tables, plots, etc. Then actions can be assigned to each device and triggered when requested, i.e. on initialization, user click or double click, text input, etc.

Moreover, PVSS foresees the possibility to create a single reference panel that can be used several times. Any changes made in this panel are inherited by all its instances.

In a PVSS database data are structured as Data Points (DPs) of a preset Data Point Type (DPT). The software allows devices to be shaped using these DPTs.

A Data Point Type is a classification that identifies one of various kinds of data; it describes the data structure of a device and information related to a particular instance of

such device is contained in a Data Point. The structure of a DTP can be defined by users and it can be as complex as required and hierarchical if needed.

A DPT is formed by elements called Data Point Elements (DPEs) which can be user-defined too. Once a user has selected the data point type to be used, he/she can create them in order to hold the records of each device (actuator, module, temperature sensor, humidity sensor etc.). This structure allows to store in the DB data concerning a device and to implement the alarm system per single datum defining the threshold that will trigger a warning or alarm message for operators.

Data Point Types and Data Points can be modified either using the Graphical Parameterization tool (PARA) or the ctrl scripts. The first allows users to choose the structure of the database, mark out what data should be archived and select which information coming from a device should generate alarms.

3.4 Joint COntrols Project (JCOP)

A working group called JCOP [15] was set up at CERN at the end of 1997 in order to mark out projects common to the four LHC experiments, especially regarding Detector Control Systems. Therefore, in order to provide them with a common DCS, a project team was formed with the purpose of defining, selecting and developing the framework and the components of the control system to be used.

Since the experiments have similar needs, the Joint COntrols Project meant to provide a more efficient use of resources, especially trying to reduce duplication of controls by centrally developing and supporting the control systems.

JCOP defines the Framework as:

“An integrated set of guidelines and software tools used by detector developers to realize their specific control system application. The Framework will include, as far as possible all templates, standard elements and functions required to achieve a homogeneous control system and to reduce the development effort as much as possible for the developers”. Hence, JCOP can be regarded as an Open Source project that developers can use to optimize their control system.

The four LHC experiments number 50 different sub-detectors in all, several of which are managed by multiple teams working in parallel. To prevent useless waste of energy and money the hardware of all the detectors was standardize as much as possible and a bigger effort was made for similar ones (i.e.: most detectors were equipped with power supplies produced by the same company, CAEN – Italy). For this reason the JCOP group decided to develop some dedicated interface tools to monitor and control the CAEN modules.

Sub-detector experts can draw from the general ALICE framework to implement the control applications that are more suitable for their detectors such as high voltage control, front-end electronics control, etc. Around 140 applications were integrated for the ALICE control system.

Figure 3.6 shows the standard components that are used to implement user applications.

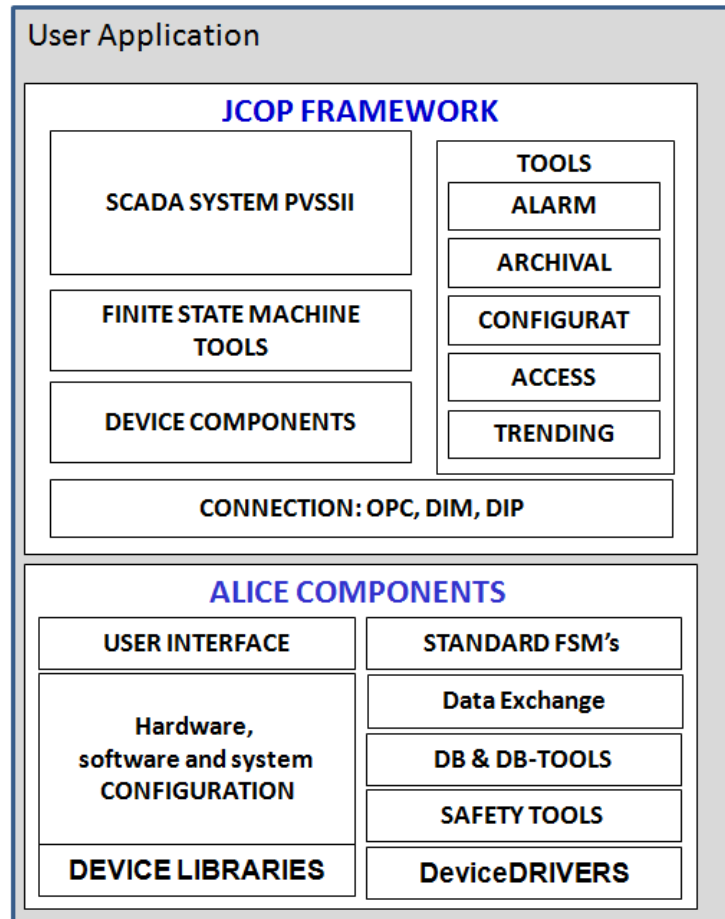


Fig. 3.6: The JCOP framework applications

JCOP took on products such as PLCs, fieldbus or SCADA tools because all of them had been successfully used in existing High Energy Physics (HEP) laboratories. PLCs are very useful to perform autonomous and secure local process control.

The fieldbus is regarded as an ideal solution in a geographically scattered environment. Using a standard bus is favourable because it is easy to handle since it does not require to write and maintain any drivers. The software communications have to be written when the fieldbus is connected to a SCADA system or to a PLC component.

OLE (Object Linking and Embedding) is an emerging non-proprietary software standard for Process Control (OPC) used to interface components from different vendors (see Fig 3.7).

This software offers many advantages: firstly, it connects and keeps together independent layers of a system and at the same time it permits to change single layers without interrupting the whole system. Secondly it allows to include in the overall DCS the components that were developed separately.

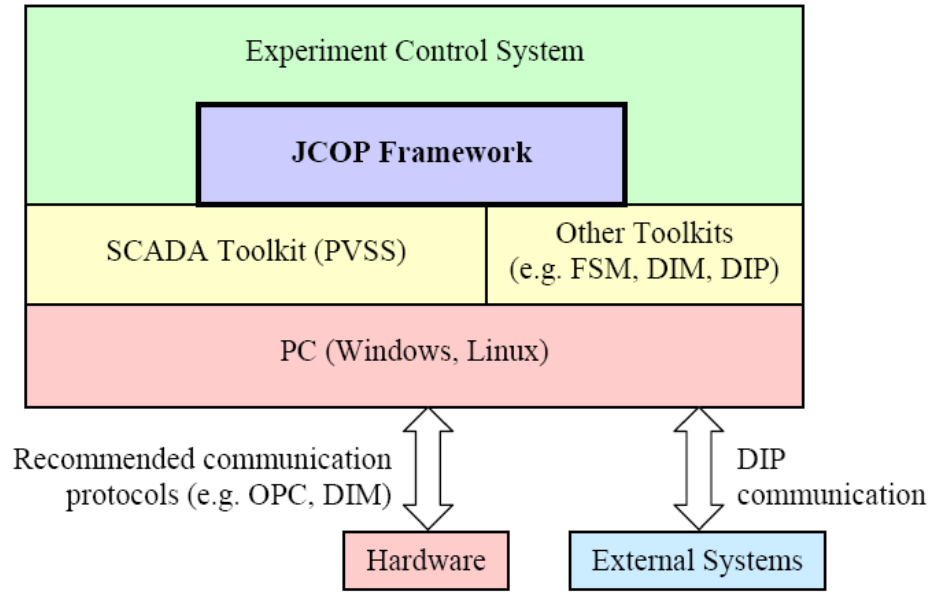


Fig. 3.7: The JCOP FW structure in a typical experiment control system

In spite of all the benefits offered by OPC, at the beginning it was developed as a platform-dependent protocol running on Windows. Therefore, the Data Interchange Protocol (DIP) was chosen to supplement OPC for the exchange of information between the DCS and external systems (e.g. LHC machine, Data acquisition, CERN Technical Services).

Being based on the Distributed Information Management (DIM) protocol, DIP is a suitable way to exchange data among heterogeneous systems that run on different platforms. This protocol will be discussed further in chapter 4.

The JCOP project was faced with a critical choice concerning the supervisory and control software. In 1997/1998 the Experimental Physics and Industrial Control System (EPICS) was widely deployed at CERN. EPICS [16] consists of a triple venture: an architecture meant to build scalable control systems; a collection of codes and documentation including a software toolkit; collaboration with major scientific laboratories and industries.

However, the evaluation suggested that EPICS was not the most suitable choice for the LHC experiments and the CERN controls board decided to opt for a SCADA system. One of the reasons was the fact that SCADA suppliers release a major version and one or two additional minor ones every year. Since such products evolve very quickly it was deemed more useful to rely on up-to-date technology. Therefore, in 1999, the four LHC experiments chose the SCADA tool PVSS-II to build their back-end control systems. The following step was the creation of a software framework based on the just chosen SCADA system. Such framework is one of the sub-projects managed by the JCOP with the aim of providing a common set of software components, tools and guidelines that had to be generally used by the experiments to build their own control systems.

The JCOP group provides online assistance and up-to-date information regarding their applications, they take care of upgrading the components and even organize monthly courses for aspiring programmers.

3.5 The DCS integration in the Experiment Control System (ECS)

Every detector is defined by its own characteristics and to be controlled in an efficient and safe way it must be equipped with all the required features. Moreover, all detectors must be controlled by a centralized control system that should be as standard as possible in order to prevent human errors as much as possible.

The DCS of each detector is integrated in the central system through the FSM of the central DCS since the top node of the FSM of any of them is directly connected to it (fig. 3.8). Therefore the top node of the central FSM becomes the top node of the FSM of all detectors. As a consequence, DCS operators can send predetermined commands to all detectors during any accelerator phases and preliminary stages to data taking (*Go Ready*, *Calibrating*, ecc...).

In its turn, the central DCS is a subsystem of the Experiment Control System (ECS) which consists of independent ‘online systems’ that control different kinds of operations regarding such domains as: Data Acquisition (DAQ), Trigger system (TRG), and High-Level Trigger (HLT).

The main tasks of the ALICE Trigger, DAQ and HLT are to pick out interesting physics events, to allow access to them in order to execute high-level trigger algorithms and to archive such data for permanent storage and later analysis [2].

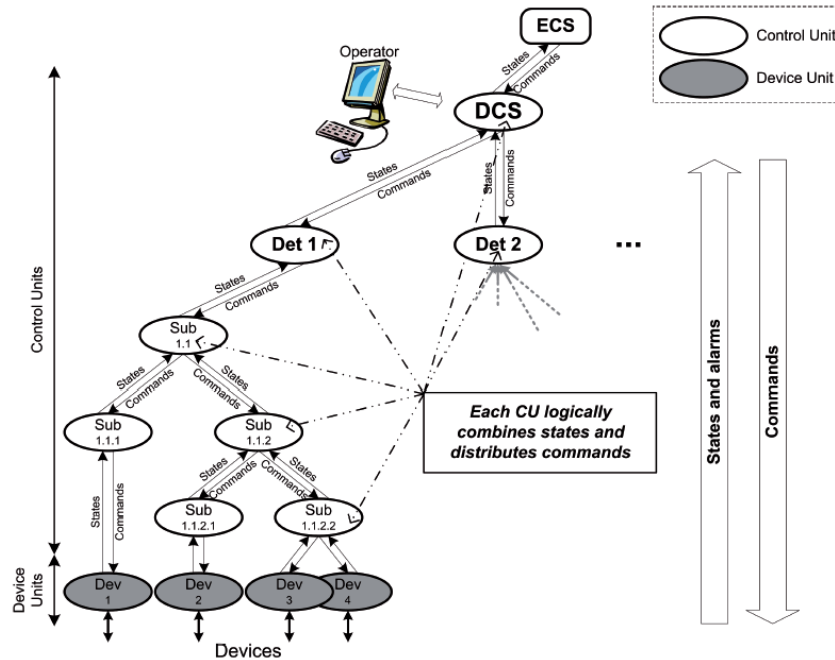


Fig. 3.8: The ECS-DCS FSM connection

Even if these systems are independent from one another they can interact with the particle detectors and allow partitioning, which is the capability to operate groups of detectors in a simultaneous way. The standard setup wants the detectors to be generally working together in order to collect physical data, while during commissioning they are debugged and tested separately. The possibility of operating detectors one by one is called ‘standalone mode’

and it is absolutely vital during adjustment and testing phases. It is also required when data are being taken to carry out calibration procedures on one or more detectors. Therefore it is regarded as an essential capability that will be very useful for the whole life cycle of research in the ALICE experiment.

The operations managed by the ‘online systems’ are coordinated by the the ECS. It allows independent, simultaneous activities on part of the experiment by different operators and it organizes the functions of the ‘online systems’ for all the detectors and within every partition.

The ‘online systems’ supply status information to the ECS components which send commands back to them through the FSM.

The interfaces between the ECS and these systems are equipped with access control mechanisms which handle the rights granted to the ECS: the ‘online systems’ can be controlled by the ECS or operated as independent systems. In the second case they provide status information to the ECS but do not receive commands from it.

The ECS and DCS were designed to shorten the downtime of the experiment and therefore to improve its running efficiency. In addition, they maximize the number of operational channels at any time and they determine and store all the parameters required to analyse the physical data in a very efficient way.

3.6 The SPD control system overview

The Detector Control System (DCS) of SPD was conceived to manage the exchange of information among its subsystems.

SPD is a complex detector that needs to be closely monitored since its performance depends on the real-time control of more than 5000 parameters such as temperatures, voltages, currents electronics configurations, cooling pressures, etc.). This is actually possible only by making use of automated control devices and user-friendly interfaces that can be easily operated.

The following is a brief description of the main characteristics of the DCS of SPD. Further details can be found in the bibliographic reference. [17].

The DCS was designed so that its components can be handled as independent parts. PVSS is meant to supervise the flow of information among the subsystems and prevent them from modifying or interfering with operations by any of them.

The highest level of this DCS is represented by the FSM since it controls the whole system and every subsystem refers to it. The block diagram in figure 3.9 shows the connections between the hardware and software components.

The DCS consists of 4 sub-control systems: Power Supply (PS) control, Interlock control, Cooling Control and the Front-End driver (FED) control. These systems communicate directly with the hardware via Ethernet (TCP/IP, OPC protocol). The FED exchanges data with the off-detector electronics (20 routers) via a VME bus.

Since PVSS is not meant for high speed control applications it would not be suitable for the SPD electronics control.

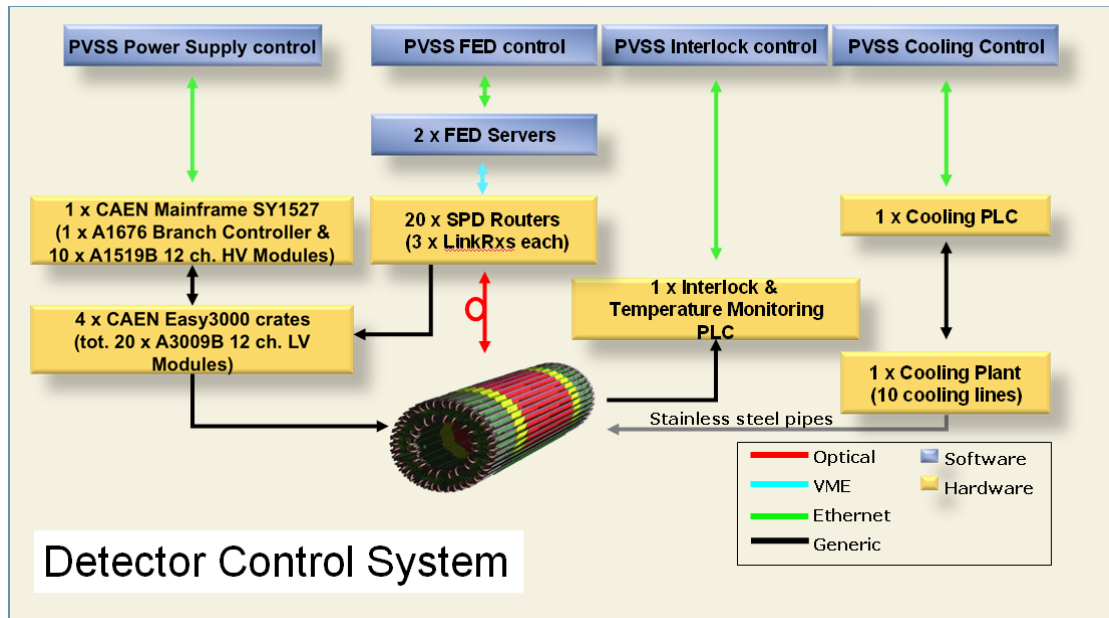


Fig. 3.9: The SPD control system block scheme

The hardware interlock system reacts very fast and if necessary it can switch off the power supply of a half sector or the whole detector. Every time a temperature value overgoes a set threshold a DPs alarm is triggered. Communication with the DIP and the temperatures read-out is supervised by a background script which switches off automatically the relevant HSs in case of high temperature or faulty communication. The software interlock system is the link that connects the control script running in the background with the Low Voltage (LV) crates.

Even if this system reacts more slowly, it can act directly on single half staves, as is the case when one gets Hot.

Part of the job I carried out during my doctorate concerned the implementation of panels for operators and experts. Some of them display online the working parameters of SPD and allow users to save these data in text files for offline analysis.

The first task I applied myself to as soon as I started to work for the DCS group was the implementation of a panel for experts to set the temperature alarm threshold for the HSs read by the DSS system (fig. 3.10). The check boxes on the left side of the panel allow to select the alarm threshold that can be set for one or more half staves (DP selected). On the right the panel provides the check boxes to configure the temperature values for standard working, warnings or alarms (Fatal). This panel is also equipped with instructions for users.

Since PVSS is intended for slow control applications it is ill-suited to directly control the fast front-end electronics.

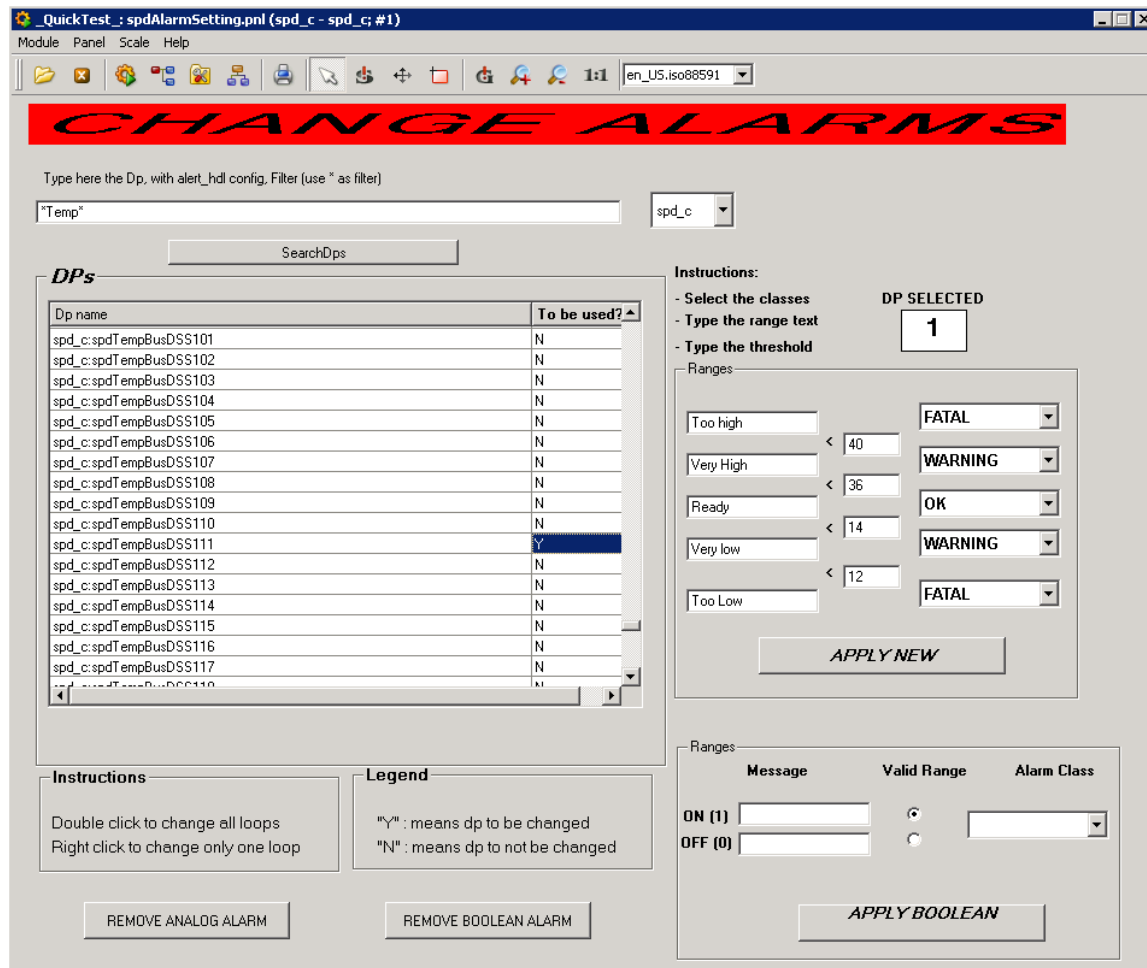


Fig. 3.10: The expert panel to set the DSS alarms

The FED was built in order to interface PVSS with the SPD electronics. It manages two Front-end device servers (C++ based) [17], it receives macroinstructions and it autonomously operates the front-end/off-detector electronics. It is equipped with an Oracle database interface that controls the whole configuration of SPD. This device reads and stores the required parameters in the Configuration Oracle Database (CDB).

The cooling plant is connected to a PLC that is directly operated by the Technical support Cooling Ventilation department (TS-CV). This group manages all the cooling plants of the LHC experiments.

PVSS allows to supervise and modify some working parameters (liquid and gas pressure) even if direct operations on PLC are not authorized.

Thanks to some background scripts it is possible to monitor the operations that are being carried out in order to make sure that the detector works properly and to prevent any errors that may damage its hardware or software components.

The DCS of SPD was split into 4 different PVSSII projects that run in 4 computers: 3 working nodes and 1 operator node. These projects make up a distributed system and they communicate with each other through an Ethernet (TCP/IP) protocol.

The working nodes were installed in 3 Windows XP machines that can be operated only by expert users because they control the detector. The operator node where all users can login hosts the user interface and it is equipped with a Windows server 2003.

The FSM supervises the control logic units and PVSS serves as an interface between them and the hardware components.

Further details about the hardware and software architecture of the DCS of SPD and its configurations can be found in the bibliography [17].

The Finite State Machine of SPD (fig. 3.11) connects the defined logical states of the detector components and sends via PVSS sequences of operations addressed to the hardware called macroinstructions (i.e.: Go Off, Go Ready, etc). The FSM can be regarded as synchronized equipment that controls the whole system and all of the subsystems (sectors, Front-end electronics, cooling...) refer to it.

Details concerning the FSM states and commands can be looked up in [17].

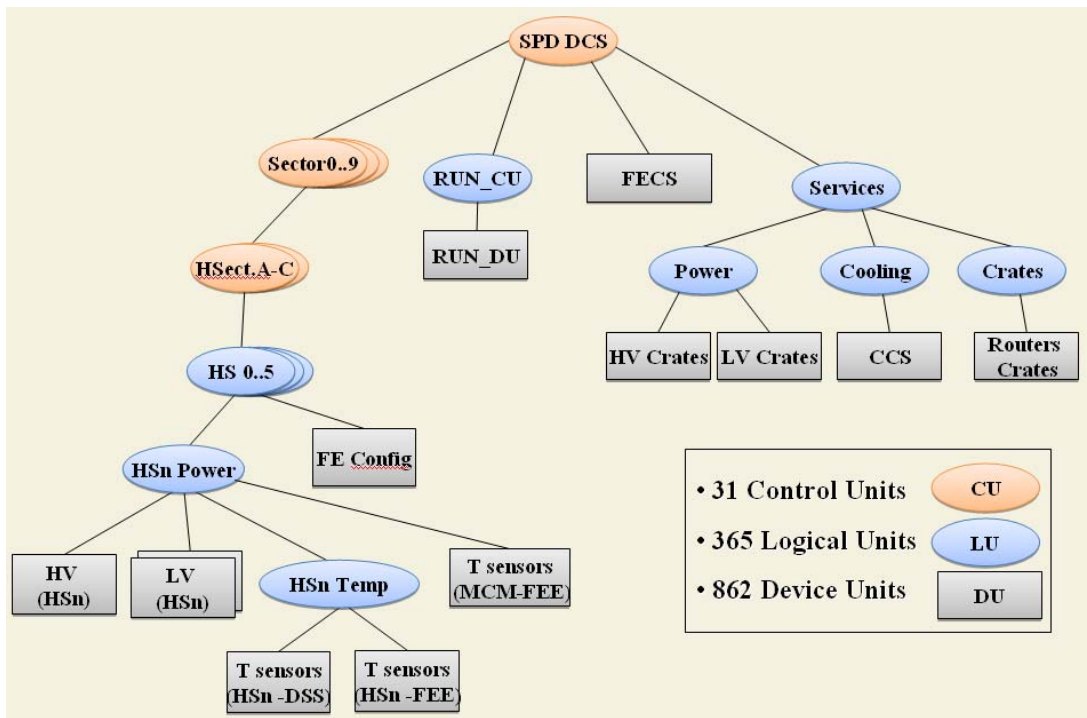


Fig. 3.11: the SPD FSM hierarchy structure is a typical example

The DU represents the hardware system. It consists of 862 units that forward information concerning their state to 31 control units by means of 365 local units. Signals are transmitted from the bottom to the top and any action that is carried out depends on the kind of signal received.

The top node communicates with the ALICE control system and processes all information. Some background scripts (running), connected to the control units, check the system stability all the time and they allow or forbid to carry out the actions required by the commands sent by operators. In case a DU changes its state, the local units send the information to the upper nodes and the control units modify their state accordingly.

The CUs allow to control only the parts of the detector involved in the situation in order to avoid affecting the detector general state.

The User Interface (UI) is the graphic tool (Fig. 3.12) that allows operators to supervise and operate the detector in a watchful way. A lot of the work I carried out to develop this control system concerned in the implementation of some of the panels that form the UI.

Simplified panels, as expected by the ALICE UI framework, were made to supervise and control the detector.

Through this interface operators can gain access to several panels that allow to manage single parts of the detector such as the front-end electronics, power supply and the cooling plant. Each part is schematized in dedicated panels that include the working parameters and the actual states codified by colours as shown in table 3.1 (Green= Ready state, Red = Error State...).

Green	ready status
Grey	excluded part or dead
Blue	Off , StandBy
Yellow	temporary state (moving up or down)
Red	error state
Orange	warning state

Tab. 3.1: Colour convention

The ALICE UI framework was implemented to make integration easier for all the sub-detectors by placing general use tools at their disposal (buttons to open the alarms panel, information about the state of the LHC, etc...). The management of every subsystem was free to decide how to configure one's own user interface according to the requirements of each detector.

Figure 3.12 shows that the Ui of SPD consists of a central part that depicts the detector in the colour that matches its actual FSM status (Ready, Off, Error...). The panel is also equipped with buttons that open other specific panels, for ex. to monitor temperatures; the hierarchical structure on the left allows to display the data concerning single sectors, half sectors or services (power supply, cooling, etc...).

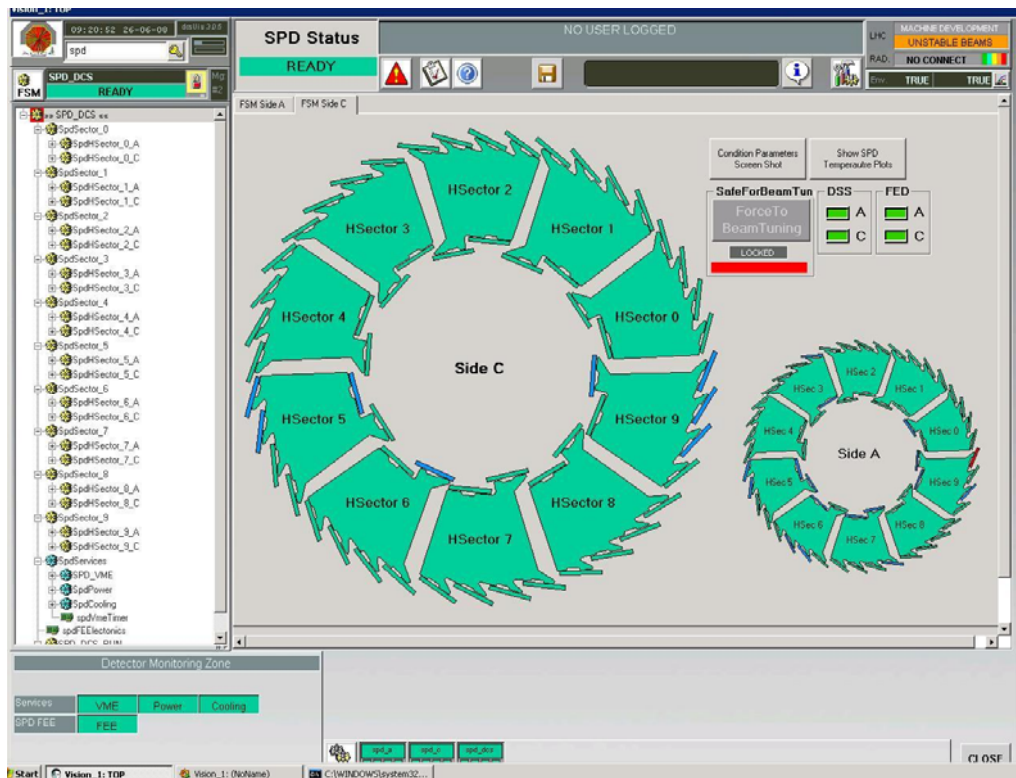


Fig. 3.12: the User interface

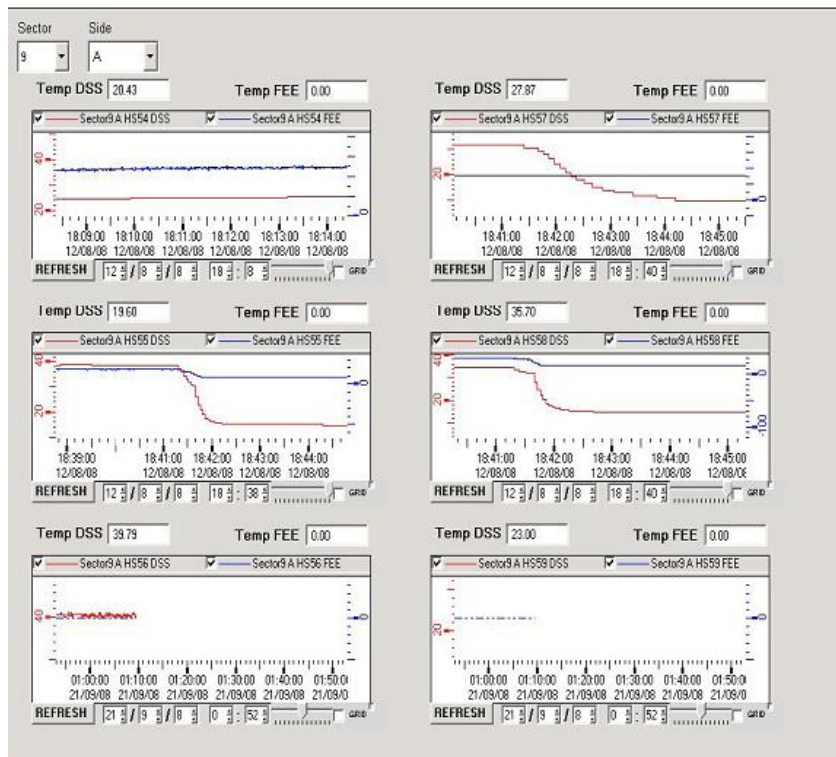


Fig. 3.12: temperature trend panel

The values regarding temperatures, voltages and currents of the HSs and the main operating parameters of the cooling plant are stored in a special database. They can easily be displayed in plots and tables or saved in text files for offline analysis.

Figure 3.12 respectively displays the temperature trends of the half staves sector by sector, while figure 3.13 shows the panel that allows to control the cooling plant. This kind of panels are usually marked by pictures that represent the part of the system it refers to (sector, routers, Hs, power supply, etc...)

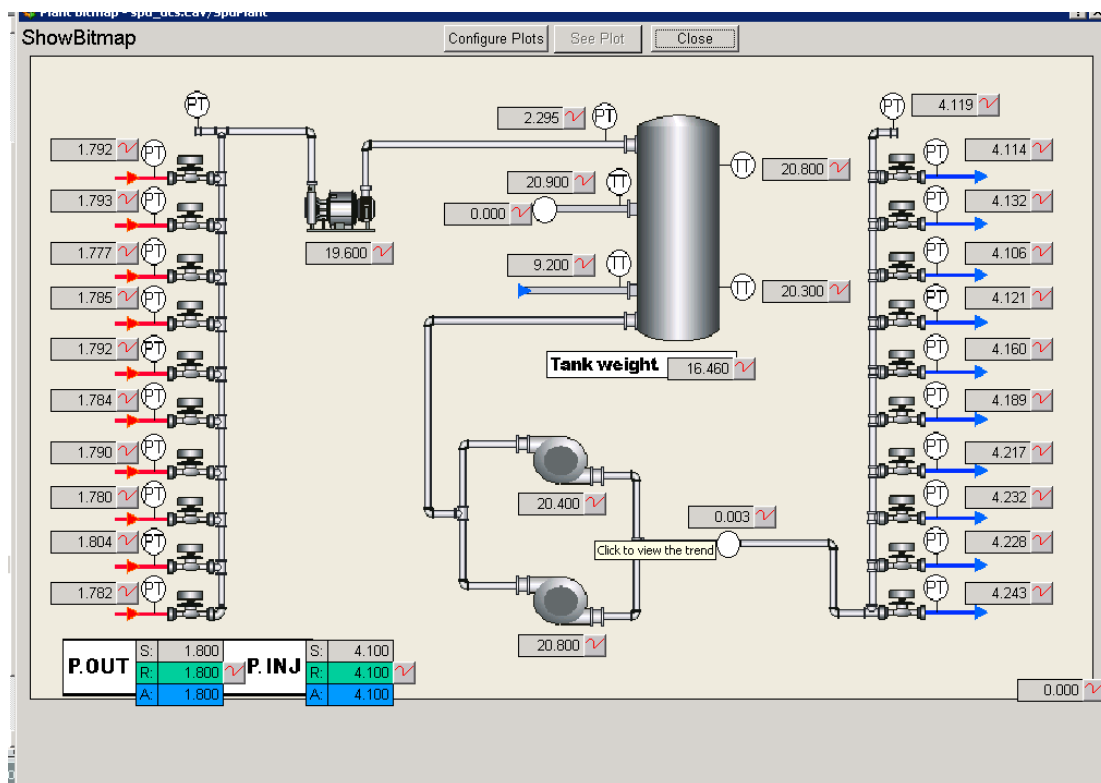


Fig. 3.13: Cooling plant panel

3.6.1 Cooling pressure and temperatures readout

As already mentioned in chapter 2, during the summer of 2009 I participated in the installation of a system that monitors the thermodynamical conditions of the cooling fluid as close as possible to the heat load region. I shared in laying out the hardware that included 20 temperature and 20 pressure sensors. The latter have been installed in line with minor modification in the cooling pipes. Instead, the temperature sensors were installed in contact with the external part of the pipes. This procedure required particular care to maximize the thermal contact between the pipes and the sensors. I dealt with the implementation of the sensor read-out system based on an electronic board called Embedded Local Monitor Board (ELMB). This board results from the cooperation started in 2001 between CERN, the National Institute for Nuclear and High energy physics of the Netherlands (NIKHEF) and the Petersburg National Physics Institute in Russia (PNPI).

It's a plug-on board equipped with standard analog and digital input/output facilities. It is installed on a standardized motherboard and it can directly read out front-end electronics

through a commercial Kvaser PCI CAN card interface. The firmware it is provided with includes the instructions required to drive the input/output functions and the communication over CANbus by means of a higher level protocol CANopen. Users can take advantage of its "plug and play" feature.

This kind of board is usually equipped with 64 analog input channels (16bit, multiplexed) up to 16 digital inputs and outputs.

Further details about its software and hardware architecture can be found in [18].

For the correct operation of the read-out system, it is important to set the right match between the CANbus messages and the OPC item as defined in its configuration file called "OPCCanServer.cfg". Then the DPs have to be configured in the address config with the same names as those defined in the OPC config file. The OPC is the major way of communication between hardware and software, through the CANbus and PVSS. The OPC establishes the communication between the OPC server and the OPC client, therefore PVSS does not need to know the CAN protocol.

The ELMB is provided with adaptors that can directly supply the microvolt variation given from the detected temperature difference. Through a standard conversion formula it is possible to find out the equivalent value in centigrade degrees.

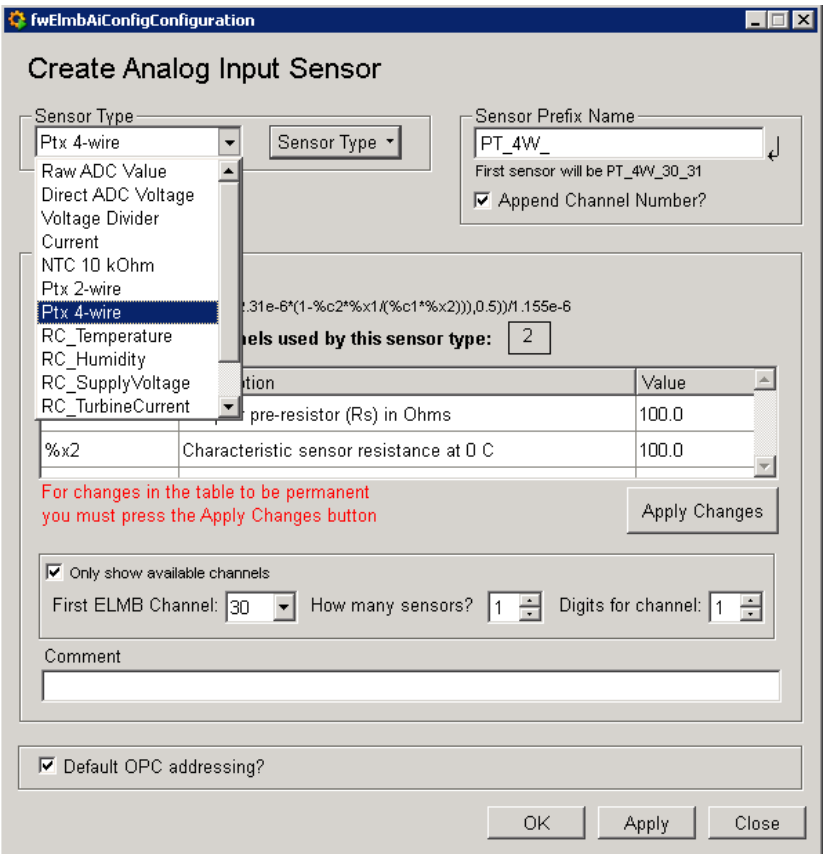


Fig. 3.14: Fw panel to configure the analog input from the ELMB

After creating a model sensor in compliance with our requirements and resolving on the number of sensors to be generated accordingly, I gave each of them the corresponding

ELMB channel number. At the end of this operation the Dps, where the data received from the ELMB are written, were automatically generated. (fig. 3.15). These data points allowed to implement the final UI panel used to display the temperature and pressure values in PP4 (side C) and PP1 (side A). Afterwards the panel was finished by adding the flow rate reading received by the cooling plant PLC.

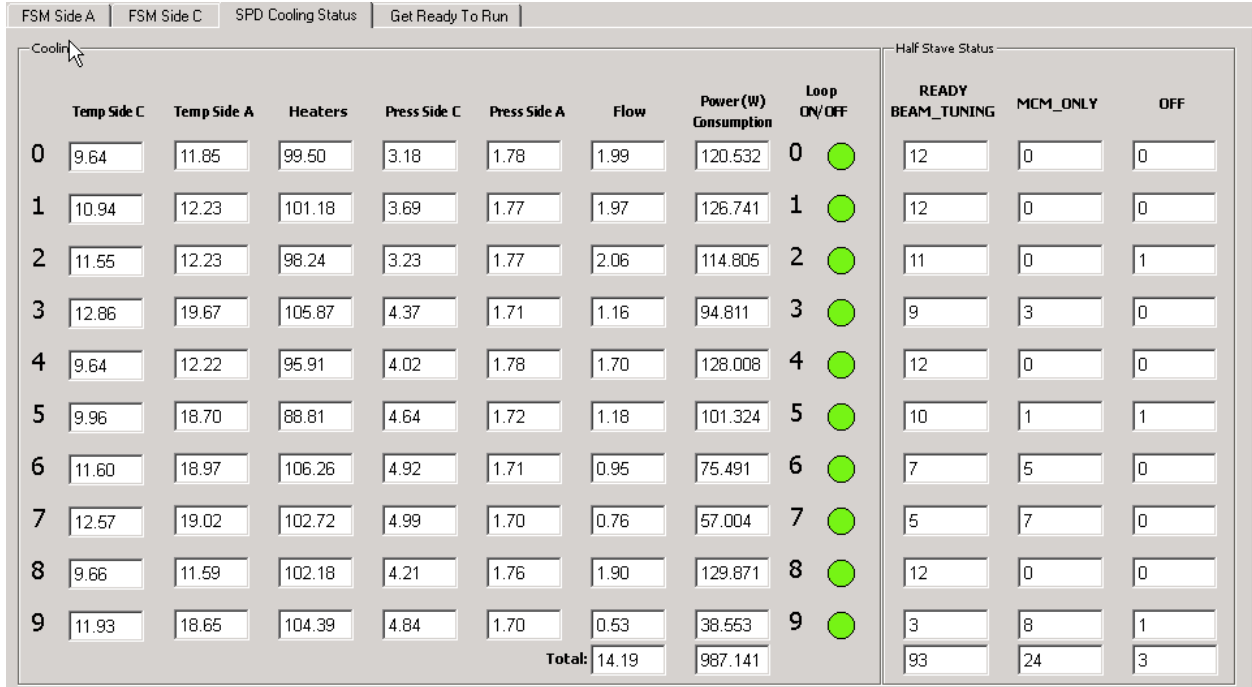


Fig. 3.15: Temperatures, pressures and flows readout panel

3.6.2 PVSS – Configuration Database Connection and improvements

One of my contributions consisted in realizing part of the direct connection between PVSS and an Oracle database, named Configuration Database (CDB) where the system configurations are stored.

Even if the ALICE DCS group provides for the infrastructure and the CDB maintenance, every detector can freely manage its own database.

The Configuration Database (CDB), where the configurations of SPD are stored, consists of several versions that contain 52,800 Digital to Analog converters (DACs) values each.

This database is an optimized structure that generates new configuration versions without any need to duplicate the data. Any time the DACs values are changed the DB creates a configuration with a new version number that is retrieved by the FED through the rearrangement of the pointers (fig. 3.16).

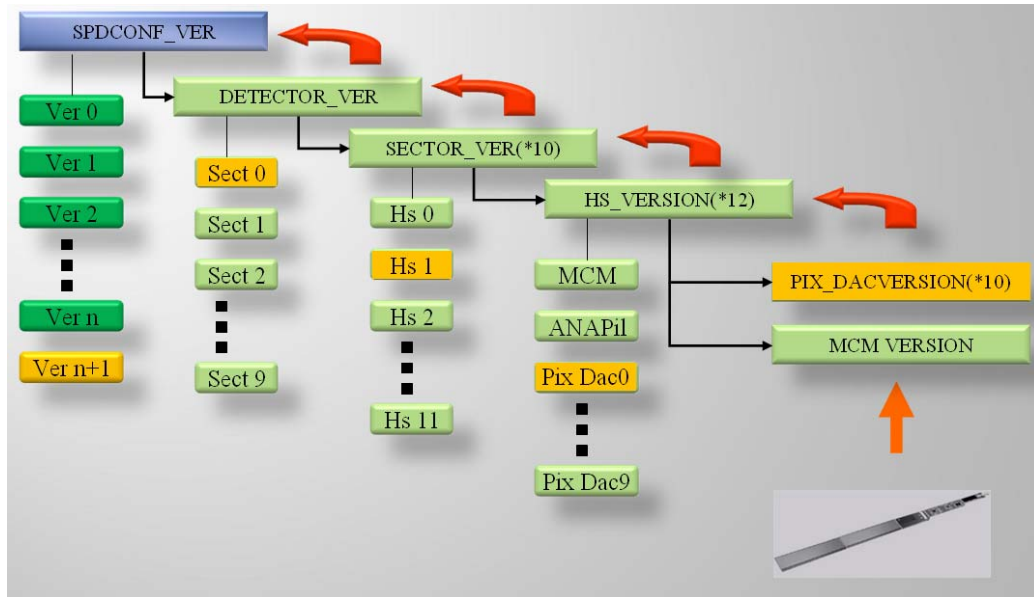


Fig. 3.16: saving a configuration mechanism

The working configurations saved in the CDB can be controlled in a very efficient way thanks to the direct connection that was implemented between PVSS and the CDB (fig. 3.17). Some library functions, used in the framework of PVSS and adjusted to the CDB structure, allow to raise preset queries to the SPD CDB and to display their results in the UI panels. Thus, it is possible to gain direct access to all the stored configurations.

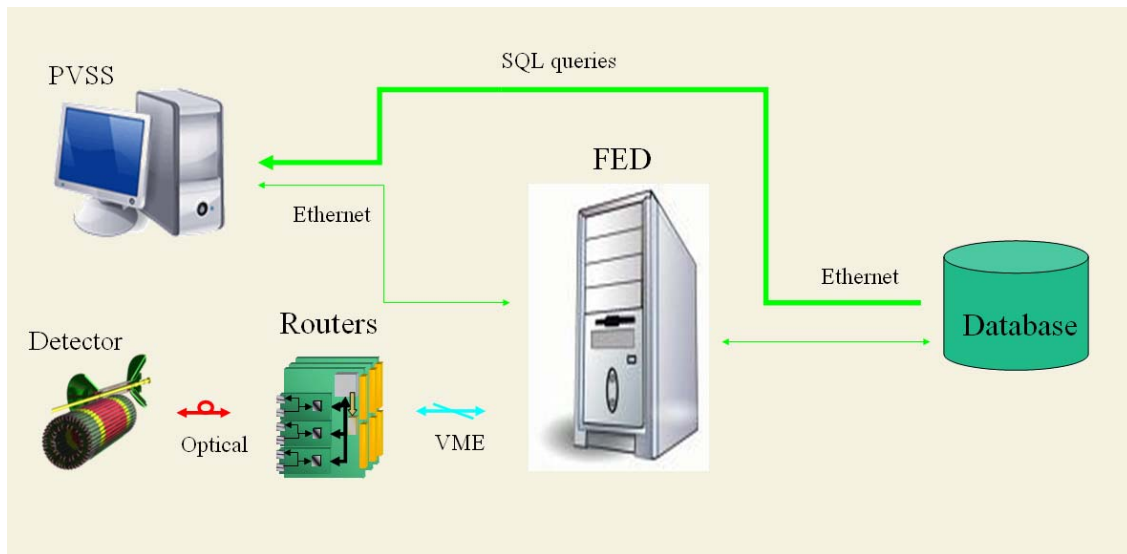


Fig. 3.17: PVSS - DB connection scheme

More panels were implemented in order to compare the configurations of a half stave or the ones of different staves (fig. 3.18) to check the way it worked during a slot.

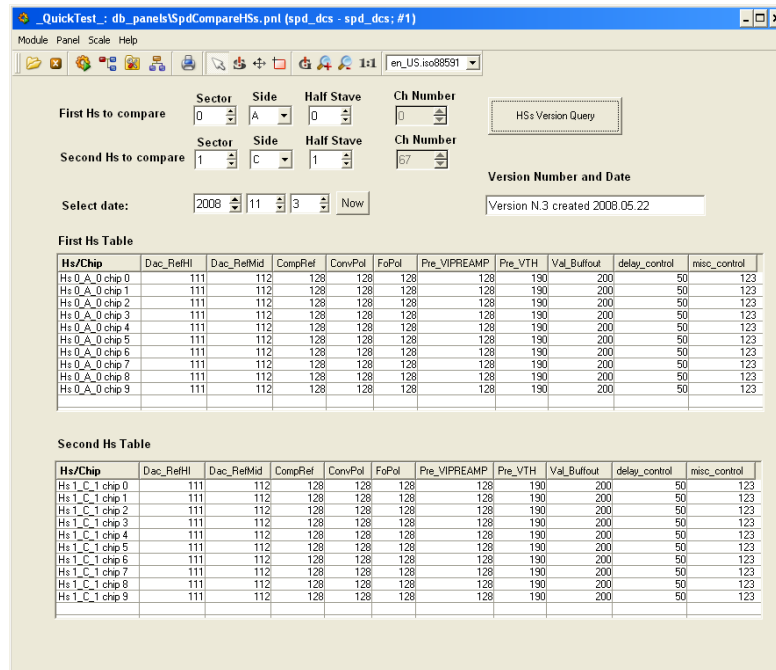


Fig. 3.18: panels for experts used to compare the configuration parameters of different HSs

The following is a further example of a panel I implemented. It is used to analyse the evolution in time of the configuration parameters of single HSs (fig. 3.19). The panel displays the configuration values, the number of the CDB version in which they were saved and the date of creation of each configuration.

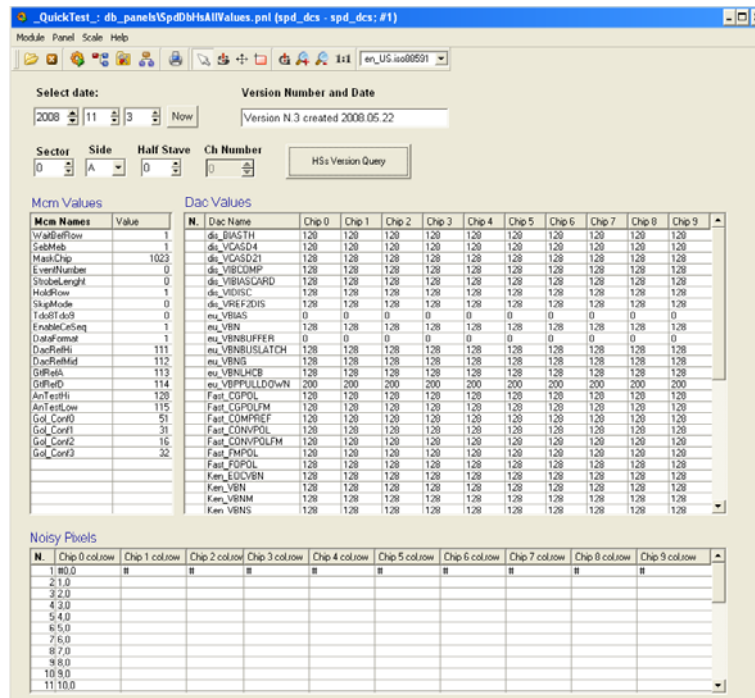


Fig. 3.19: panel for experts used to analyze the configuration parameters of the HSs

Such tools are very important to experts since they allow to monitor the performance of SPD as time goes by. Actually the CDB contains more than 200 configurations and each of them was created to optimize the performance of this detector compatibly with the required running and with conditions of the beams (beam intensity, number of colliding bunches...).

Recently we have developed a hardware system (Error Handler) that allows to detect the errors coming from the detector (i.e.: optical connection status, data format errors, front-end and back-end errors, wrong trigger sequences, etc.) [19] even when it is taking data.

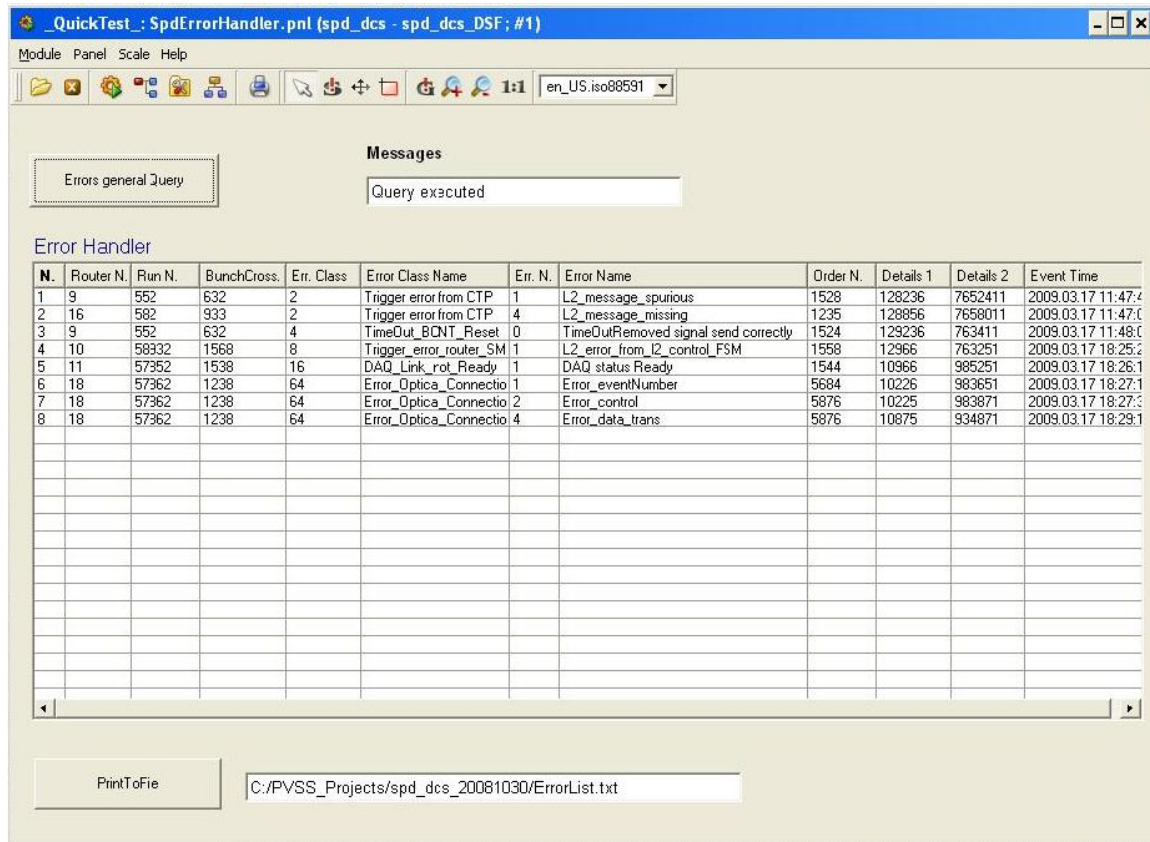


Fig. 3.20: the Error Handler panel

The routers transmit the errors to the FED which pools them together online and stores them in a dedicated table in the DB. As soon as the FED receives such data from the routers, it generates a signal and PVSS sends it to the operator (fig. 3.20). Therefore thanks to the direct connection between the database and PVSS operators receive information concerning errors without interfering in data taking operations.

This implementation made the storing procedure more user-friendly. Besides, the panels containing the predefined queries are very useful because they allow operators to get real-time information about the detector state and therefore they can supervise it more closely and efficiently.

Thanks to the experience I gained working in the DCS group of SPD during more than a year at CERN, the ACC group asked me to join them in July 2009.

Therefore, while still working for SPD, I participated in the finalization and operating of the control system that manages the data exchange between the ALICE experiment and the LHC control system. I actually implemented and developed some important parts of the ALICE-LHC Interface project that will be explained in the following chapter.

Chapter 4

The LHC Exchange Interface Project

This chapter focuses on the LHC Interface Project. The first part deals with its general characteristics and main tasks, while the second one describes the work I carried out and the tools I implemented for this system.

4.1 Main parameters exchanged between LHC and experiments

The LHC Exchange Interface (LHC_EI) project was conceived to provide an interface between the accelerator and the ALICE control systems.

The ALICE experiment and the LHC exchange information through an interchange protocol called DIP (Data Interchange Protocol) by means of dedicated servers. The kind and amount of the exchanged data comply with the official requirements [21], [22].

Hardware links were implemented so as to transfer critical signals, such as the injection permits in a more efficient way.

These control systems exchange a large quantity of information with one another in real time in order to optimize the performance of the experiments. This way the accelerator, the experiments and all the subsystems connected to them can be safely operated.

The data swap between the LHC and the experiments (fig. 4.1) is used to synchronize several operations during different working stages, like the injection phase which is very important to attain the scientific achievement they are aiming at.

These data also supply LHC operators with feedback about the experiments allowing to react quickly to any fault and fix it at the soonest.

The data coming from the accelerator and the experiments are characterized by an absolute UTC timestamp that is taken from a GPS module in the CERN Control Centre (CCC).

Besides, a brief summary of the LHC status is displayed on TV screens and accessible via web thanks to the implementation of a page called VISTAR.

The following are the most important data that LHC notifies to the ALICE experiment:

- total beam and individual bunch intensities
- average 2-dimensional beam size
- average bunch length
- luminosity at the interaction points
- average beam loss
- average horizontal and vertical beam positions

ALICE in its turn sends the same data measured by the detectors in order to check non-stop the state of the beam and of the collisions. These operations allow to optimize the beam conditions so as to obtain the required luminosity and a background below the preset values.

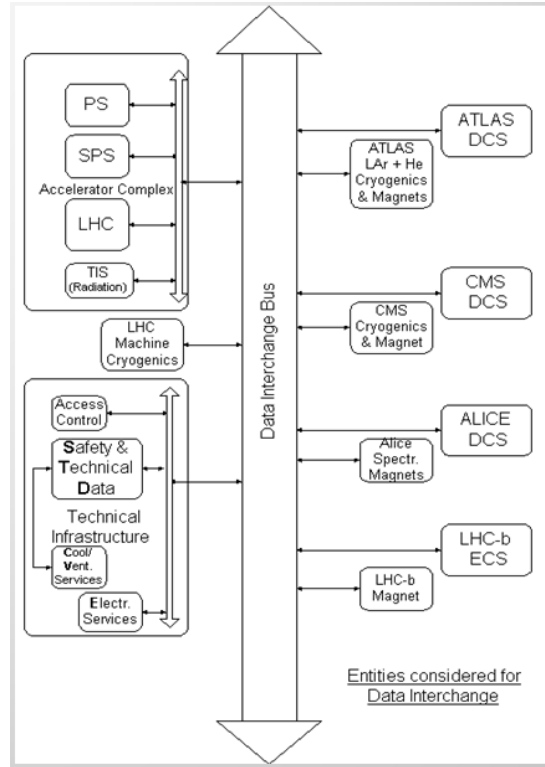


Fig. 4.1: Entities considered for data exchange at the LHC

Past experience with other accelerators taught that it is often difficult to foresee the background induced by the machine because of the great number of factors that affect its behaviour.

Therefore it is extremely important for the ALICE experiment to rely on trustworthy background values in order to operate the detectors in a safe and efficient way. Such values have to be transmitted to the LHC control room too.

These data actually have to be monitored, especially during the stages that come just before the stable beam which is the condition that allows the experiments to start taking data and put all the sub-detectors in a ready state.

Further beam detection systems, called BPTX were installed upstream and downstream ALICE, about 145m away from the interaction point; they detect the beam intensity by means of electromagnetic induction. The two BPTX provide time reference signals that are used to monitor the LHC clock phase with regard to the position of the bunches of particles.

During normal operation the LHC can work in preset modes according to a regular sequence. Such operating modes are sent to ALICE via DIP and in most cases they are used to synchronize the experiment with the LHC. As a matter of fact some detectors are turned to ready during the adjust stage, while others only after the beam is in a stable condition according to the characteristics of each detector. Some of them are more sensitive to beam losses and they can be operative only when the beam is declared stable.

The injection phase, when beams are introduced into the LHC ring, is very delicate and potentially dangerous for the electronic equipment. Through a series of electronic signals, called Injection Permits and Beam Permit, the experiments send the LHC the permission to

start the injection. For this reason it is preceded by a step called Injection Handshake during which the accelerator and the experiments carry out a sequence of preset actions to synchronize and get ready for it. In this particular situation the experiments can operate single detectors, usually to switch off high voltages in the most sensitive ones. Injections cannot take place in ALICE until the whole experiment has been moved to such a state (SAFE) that allows to change the condition of the injection permits from False to True. Only when such permits are True the beams can be injected. This change is made by sending some signals to an electronic board called TELL1 which represents one of the hardware links between ALICE and the LHC. When the injection permits are enabled the LHC can inject the beams. The same kind of operation is foreseen before the adjust and the beam dump phases.

LHC is equipped with a protection system called Beam Interlock System (BIS) whose task it to make sure that the accelerator operates only in controlled beam conditions. If only one of the beams becomes unstable, thus potentially dangerous for the machine and the experiments, the interlock system promptly reacts by activating the beam dump operation (fig 4.2).

This system consists of several sensors distributed along the LHC ring and inside the experiments. Each sensor measures some of the beam characteristics and when necessary it sends a signal to the BIS in order to dump it.

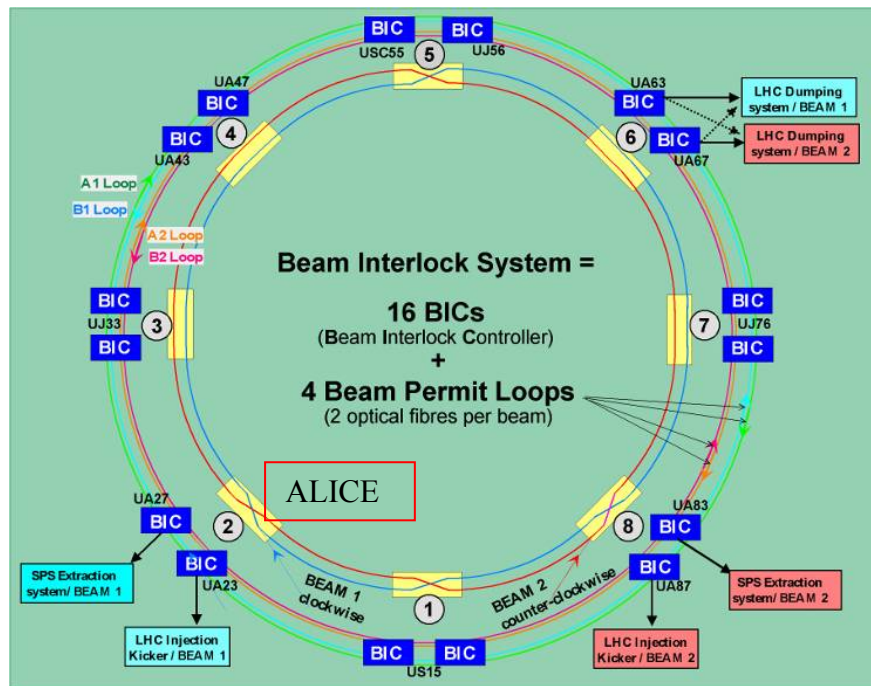


Fig. 4.2: Beam Interlock system schema

Injections can take place and beams can circulate only when all the users send a consent signal. If one of these signal changes the beams (also during the circulation phase) are dumped by magnetic switches in less than 300 ms. In this case the beams are actually pulled out of their circular trajectory and diverted through two bypass galleries at the end

of which they are caught by an absorber. The latter consists of a cylindrical graphite block, 7 m long and with a diameter of 70 cm, inserted in a cement block that weights 750 tons.

The ALICE DCS is connected to the BIS by hardware units named Beam Interlock User Interfaces provided by the AB/CO group; they are installed in the user rack.

This system is so flexible that it can evolve according to the experience built up during the operation of the LHC and ALICE. The beam dumping device and the hardware and software structure that manages it will be discussed at paragraph 4.2.1.

One of the most important tasks of this DCS project is to monitor the quality of the collisions in the ALICE experiment. In order to reach such aim the tools that will be described at paragraph 4.2.3 were implemented (panels, trends...). This is one of the jobs I did during the period I spent working for the ACC group.

The implementation and setting at work of parts of the LHC interface control system were carried out while the LHC was operational and ALICE was taking data. In 2010 the modifications and improvements on the LHC_EI project were made on the working system and the new features were tested during technical stops. Therefore every intervention had to be carefully aimed since it was carried out in real time but most of all because it had to be made while bearing in mind the whole structure of the system and of the sub-systems connected to it in order to avoid to make modifications that could affect the system itself or parts of it.

4.2 The interface between ALICE and LHC

As explained in the previous chapter, the DCS, a subsystem of the ECS, is one of the basic nodes in the experiment control system. Figure 4.3 shows the DCS as a block diagram: the subsystems can exchange data with the central DCS which also interchanges information with CTP, HLT and external infrastructures such as the Offline system.

The distributed system mentioned in chapter 3 allows to exchange information between the central DCS and the DCS of the detectors.

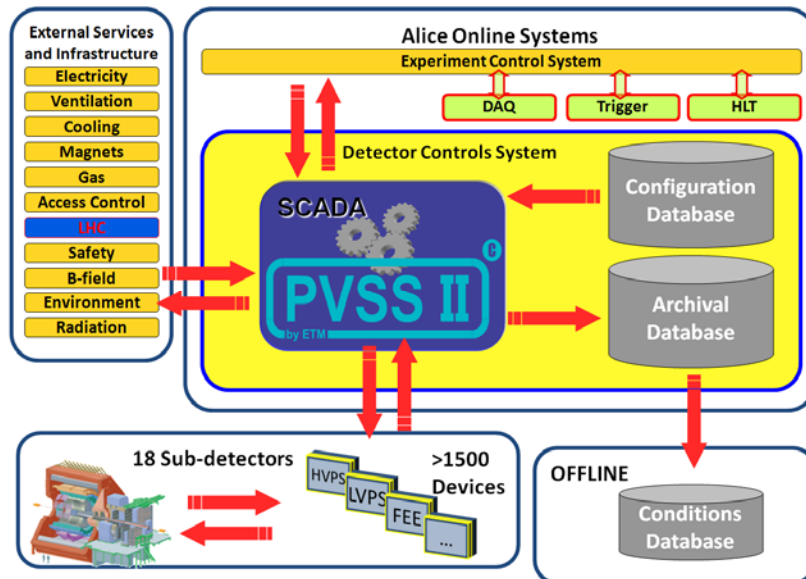


Fig. 4.3: ALICE DCS block scheme

Many working parameters are stored in an Oracle DB (OCDB); some of them are just put aside while others, like the running configurations of single detectors, are saved in dedicated databases (as explained for SPD in chapter 3, par. 3.5.4). This was done so that the different configurations could always be available according to the actual need.

A substantial amount of data is exchanged with the infrastructures in the experimental area, such as the power supply system, the ventilation general service, the safety system or the control of the magnets.

The LHC Exchange Interface (LHC_EI) is the PVSS project that provides the communication with the accelerator. Its implementation began in 2006 with the aid of only a worker node called *lhc_exchange* and afterwards more nodes were added to it in order to meet the requirements about the flow and data processing. At present it includes 6 PCs: 5 worker nodes and an operator node. The general outline of this project is shown in figure 4.4: the 5 PVSS projects manage the data flow to/from the LHC control via DIP protocol.

LHC_EI can be regarded as a collector of information coming from the subsystems connected to it; it is also a data processor since it dispatches them to other systems after smoothing value and time about the data contents and their broadcasting frequency (i.e.: calculate the average).

The LHC and the detectors of the ALICE experiment are both providers and users of the data exchange project. The main difference concerns the transfer protocol since for the LHC it is via DIP while communication with the detectors is via the PVSS distributed system.

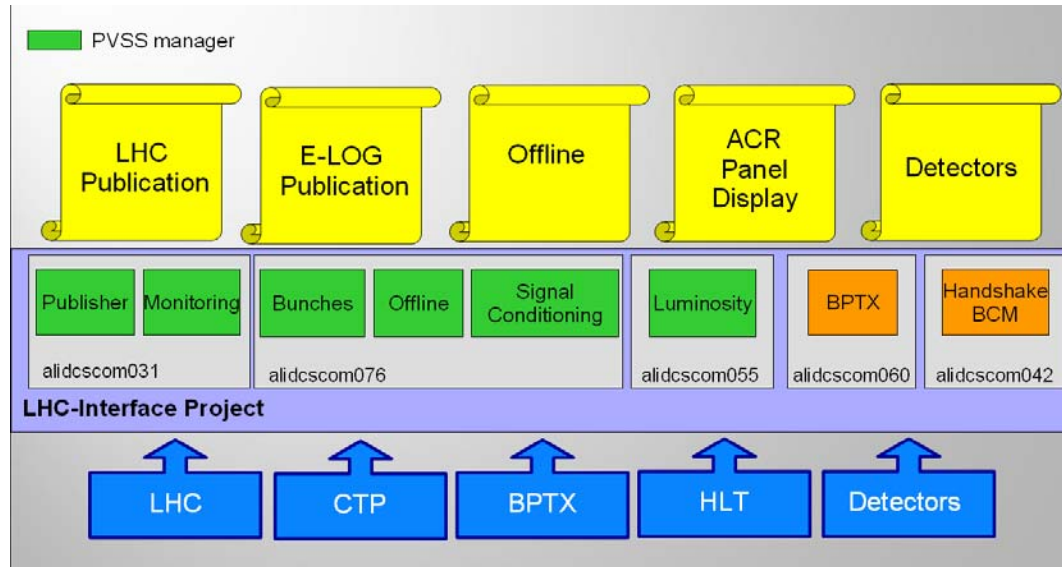


Fig. 4.4: LHC_EI project architecture

LHC_EI receives data from CTP and HLT via the Distributed Information Management (DIM) which is a communication system conceived for distributed/mixed environments. It provides a network transparent inter-process communication layer based on a client/server paradigm [23].

A DIM Name Server (DNS) was set up to allow transparency (i.e. a client does not need to know where a server is running) and easy recovery from crashes or migration to other servers.

When data are transferred via DIM, the provider publishes them in a chosen server; to access the sever clients need to know its name as well as the name of the published data, referred to as “services”.

The server name keeps an updated directory of the servers and services that are available in a system. Figure 4.5 shows how DIM components (Servers, Clients and the Name Server) interact.

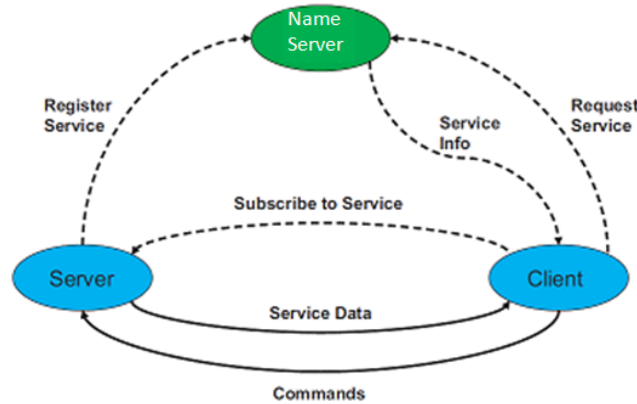


Fig. 4.5: DIM communication: interaction among components

The DIP protocol was implemented at CERN in order to provide a medium suitable to the exchange of data between the LHC and the experiments and vice versa.

The following is the definition of the DIP protocol that is published in the related web page “DIP is a system which allows relatively small amounts of real-time data to be exchanged between very loosely coupled heterogeneous systems. These systems do not need very low latency. The data is assumed to be mostly summarized data rather than low-level parameters from the individual systems, i.e. cooling plant status rather than the opening level of a particular valve.”

One of the tasks I applied myself to during the time I worked for ACC is the subscription and the publication via DIP of the exchanged data.

At the end of any physics run the Offline system receives files containing data, such as beam intensities and luminosity, from the exchange server (FXS) [2]. Besides, a program called Shuttle runs after every data-taking run in order to collect all the data from the FXSs and the DCS archive; it processes them, if necessary, otherwise it simply stores them in the OCDB [2]. These data are used for first pass reconstruction.

As time went by the LHC_EI project was no longer used only to exchange information because it had become strategic for the ALICE experiment and it is now the link among several of its components. Moreover, the data volume coming from the LHC control system has considerably increased, therefore, it was unthinkable to manage all of it with one computer only. That’s why the original project was split into 5 and *lhc_exchange* was joined by *lhc_instrumentation*, *lhc_monitoring*, *lhc_bunchserver* and *lhc_luminosity* (see table 4.1).

PC number	Project name	Main managers
Alidcscom031	lhc_monitoring	Publisher, monitoring
Alidcscom042	lhc_exchange	BCM, Handshake
Alidcscom055	lhc_luminosity	Luminosity
Alidcscom060	lhc_instrumentation	BPTX
Alidcscom076	lhc_bunchserver	Bunches, signal conditioning and Offline files

Tab. 4.1: Projects name and main managers

The PVSS projects were intentionally conceived to distribute the data processing load in a balanced way and to optimize as much as possible the data source layout as well as their final destination.

The main data processing function is handled by some control managers which continuously copy the data between the source and the recipient; they sometimes carry out arithmetical operations so as to correct some values or they work out the average in order to transmit reliable information to the recipient (LHC, Offline...) as soon as possible.

4.2.1 The handshake and BCM

One of the main and most delicate steps in the communication between ALICE and the LHC is called Handshake. This procedure is very important while beams are being injected. It is common to all the experiments therefore no beam can be injected in the ring until the injection handshake status is READY in the 4 experiments.

The handshake management system was implemented in the *lhc_exchange* project (alidcscom042) and it includes hardware and software components. The hardware consists of a direct link between ALICE and the accelerator which is represented by the electronic board TELL1. This board manages a series of signals among which three special ones respectively called Beam Permit, Injection permit Beam1 and Injection permit Beam2.

The Beam Permit is a signal that is directly connected to the ALICE experiment safety system and at the same time to the accelerator interlock system.

ALICE is also equipped with a Beam Conditions Monitor (BCM) that is meant to deal with potential harmful beam conditions, especially hadronic showers generated by misaligned beams or components failure during particle injection in the LHC. The BCM is the link between the ALICE experiment control system and the beam interlock controller of the LHC.

In 2006 it was thought suitable to install a BCM system based on the same principle as the one already set up in LHCb [24]. This system uses a synthetic diamond as detecting material. Further details concerning the working principle can be found in the bibliography [24].

The sensors consist of diamond pads ($1 \text{ cm}^2 \times 0.5 \text{ mm}$ pCVD) arranged on both sides of the interaction point close to the beam pipe. One group of 4 diamonds is installed at respectively $z \approx +4.5 \text{ m}$ (BCM A) on side A. The BCM C system includes 8 sensors located between the Small Angle Absorber 3 (SAA3) and the wall that divides the LHC tunnel from the area of the ALICE experiment at $z = -19 \text{ m}$.

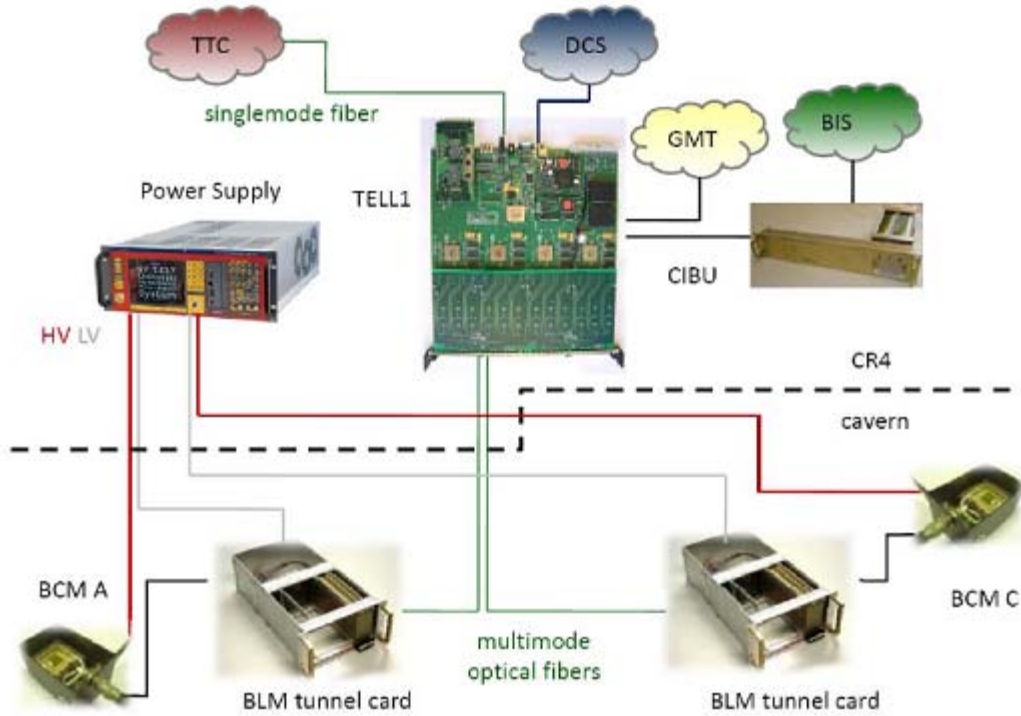


Fig. 4.6 Schematic overview of the BCM readout chain

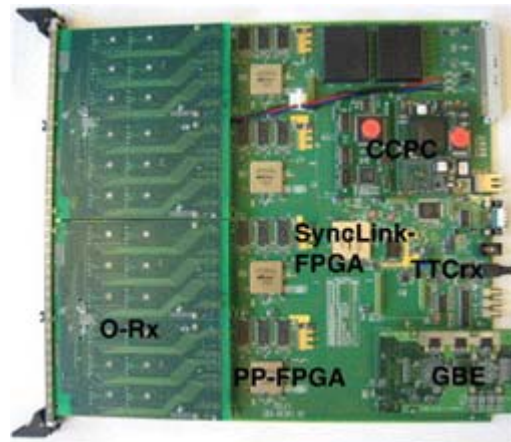


Fig. 4.7 the Tell1 board

The readout chain of the BCM is shown in fig. 4.6: the front-end cards of the LHC Beam Loss Monitors acquire the currents from the diamond sensors; these monitors are a few meters away from the BCM stations. The digitized signals are sent to the back-end electronics, located in one of the counting rooms, via optical links. It was believed suitable to use the LHCb TELL1 data acquisition board (fig. 4.7) as back-end electronics also for the ALICE BCM. LHCb uses this board to read out the information received from the front-end electronics of its sub-detectors [25], [26].

The board is controlled and supervised by the ALICE detector control system (DCS). The User Permit signal is supplied to the beam interlock system by means of a CIBU interface module (fig 4.8).

The ALICE DCS can access the board through a Credit Card PC (CCPC) installed on it TELL1 and booted up from a dedicated server via LAN. The board is equipped with an optical receiver card 3(ORx), accepting up to 12 optical links, for communication with the front-end electronics. The BCM can use the inputs 0...5 (mapped according to the pre-processing FPGA PP0) of the ORx card. A dedicated BCM interface card (BCM-M) mounted on TELL1 assures the connection to the BIS. This BCM TELL1 board is housed in a 9U VME crate.

The injection permits allow or forbid the beams injection in the LHC ring according to the signal sent by the control system to the TELL1 board. These permits are managed by the so called Injection Handshake which is based on an FSM layout (fig. 4.9).

The implementation of the control system that handles the Handshake was part of the job I carried out within the development of this project. It is described in the following pages.



Fig. 4.8 CIBU modules for the user permits Beam (top), Injection 1 (middle) and Injection 2 (bottom). Two redundant lines (A, B), whose state is shown by LEDs, transmit the use permit flags to the CIBU. In this picture all permits are set to False.

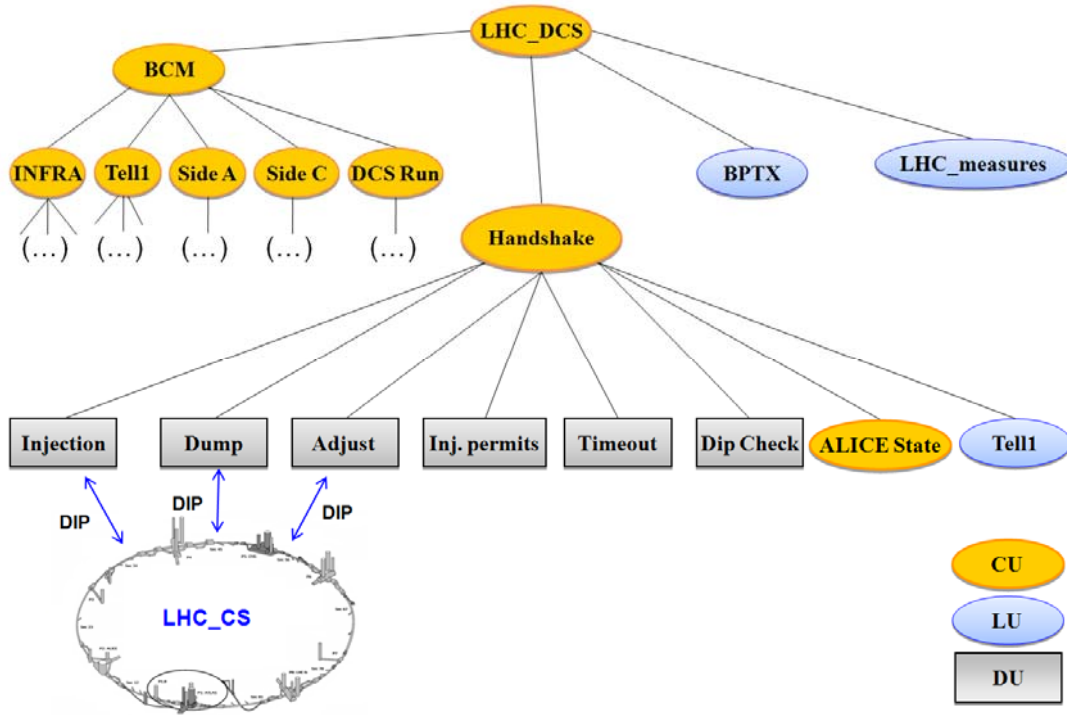


Fig. 4.9: LHC_EI FSM hierarchy

The FSM top node (LHC_DCS) is connected to two control units (BCM e Handshake) and two logical Units (BPTX e LHC Measures). Figure 4.9 witnesses the complexity of the FSM; I chose to illustrate only the part concerning the handshake.

The signals that activate the FSM handshake node are sent via DIP by the accelerator control system when, according to the LHC schedule, one of these stages has to start:

1. Injection
2. Adjust
3. Dump

Each stage must be agreed upon with the experiments because they may give rise to conditions that could be unsafe for them.

The sequence according to which commands are sent to and received from the control systems was decided by a working group made of accelerator experts and representatives of the experiments. This sequence is the same for any kind of handshake. Only the injection handshake is dependent on the injection permits while Dump and Adjust Handshakes are not because, in these cases, the beams are already circulating inside the accelerator.

When a new handshake has to start, an operator in the main control room sends a “Warning” string to our control system; the string is automatically written in a PVSS Dp that activates the DU concerning the enabled kind of handshake (fig. 4.9).

The following illustrates an injection handshake step by step.

Steps	LHC State	ALICE state	ALICE FSM State	DCS operator action	Injection permits
1	Warning	Veto	Inject Warning	Send “Inject Prepare”	
2	Warning	prepare	Inj_Warn_Conf	Move ALICE to SAFE state and then (if ALICE is SAFE) Send “Confirm inject”	
4	Warning	Ready	Inject ready	No Actions	
5	Ready	Ready	Inject ready confirmed	No Actions	
6	Standby	Veto	Standby	Close the handshake panel	

Tab. 4.2: Injection handshake – simplified operation sequence

The signal passes from the DU to the FSM top node which changes its status from STANDBY to INJECT_WARNING (fig. 4.10); the operator can now select the command INJECT_PREPARE from the FSM pull-down menu thus turning the status of the top node into Inj_Warn_Conf. At the same time the PVSS DP connected via DIP to the CCC is updated according to the new status “PREPARE”. The experiment sends a feedback to the LHC to confirm that a handshake has started correctly. The operator has around 5 minutes to move the experiment to a SAFE state for the injection. The full procedure is shown in table 4.2.

In order to complete this operation the operator has to send the command Go_Safe through the node FSM DCS SAFE, also called ALICE State. This is necessary to switch off high voltages in all the detectors that are sensitive to the beam loss. After that the command Confirm_Inject can be sent to the LHC which changes the ALICE state from PREPARE to READY, so as to confirm that the experiment is ready for the beam injection. Meanwhile a signal is sent to the TELL1 device unit to remove the Inhibit state from the injection permits that become TRUE. When the LHC sends the READY command to all the experiments, the FSM top node status becomes Inject Ready confirmed (fig. 4.11). At that moment the beam injection can start. Once the injection is finished and the beams are circulating, the handshake stage can be regarded as over only when the LHC operator transmits the STANDBY command. The latter is processed by the FSM which turns the top node status into STANDBY.

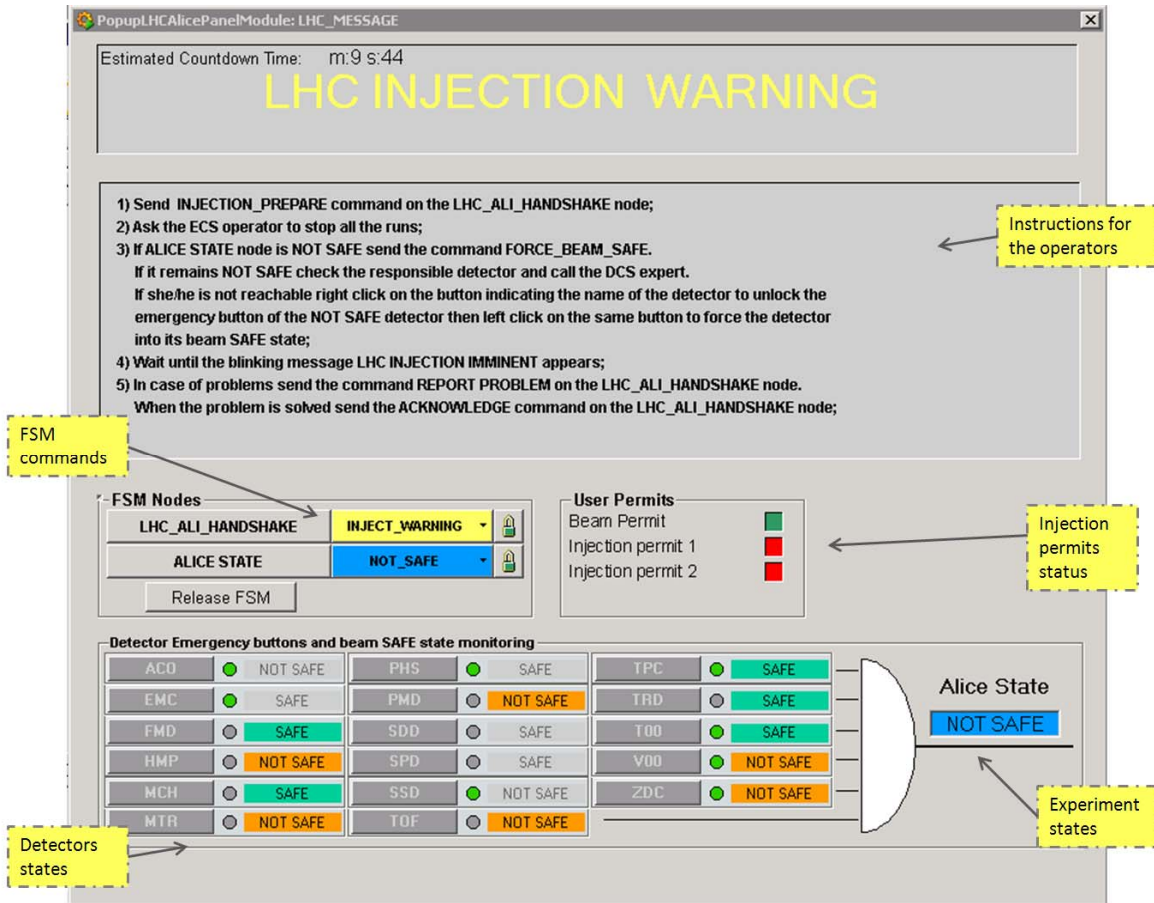


Fig. 4.10: Injection handshake panel: warning state

The above mentioned is the standard way of performing a handshake. The FSM also includes some states that are used when the standard sequence cannot be followed due to human errors (Handshake Error) or when it takes more than 5 minutes to move the experiment to a SAFE state. In this case the Timeout DU sends the command Problem Report to the LHC operator who becomes aware of the problem.

I attended to the updating of the handshake FSM layout as well as of the restyling of the operator interface panel. The top of this panel shows the message concerning the phase an ongoing handshake is in (fig. 4.10); in the middle the instructions for the operator are displayed step by step; under them the FSM nodes from which to send the commands can be found; the bottom is dedicated to the SAFE/NOT SAFE states of the detector which affect the general condition of the experiment. Operators can see the state of the injection and beam permits during the whole handshake phase.

The *lhcx* project is responsible for writing the Post Mortem (PM) file. This occurs any time the beam control is unexpectedly lost and it must be suddenly dumped. The PM file contains information concerning the event that caused the dump. It takes about 3 minutes to write it.

When dumping is not caused by the ALICE experiment only the injection permits are automatically inhibited. On the contrary, if the beam dump was triggered by the ALICE BCM sensors then the Beam permit is inhibited too.

The Post Mortem file is generated at the same time the beam is dumped, then it is stored in the PM database for subsequent analysis. After this file has been transmitted to the DB the operation for a new injection may take place.

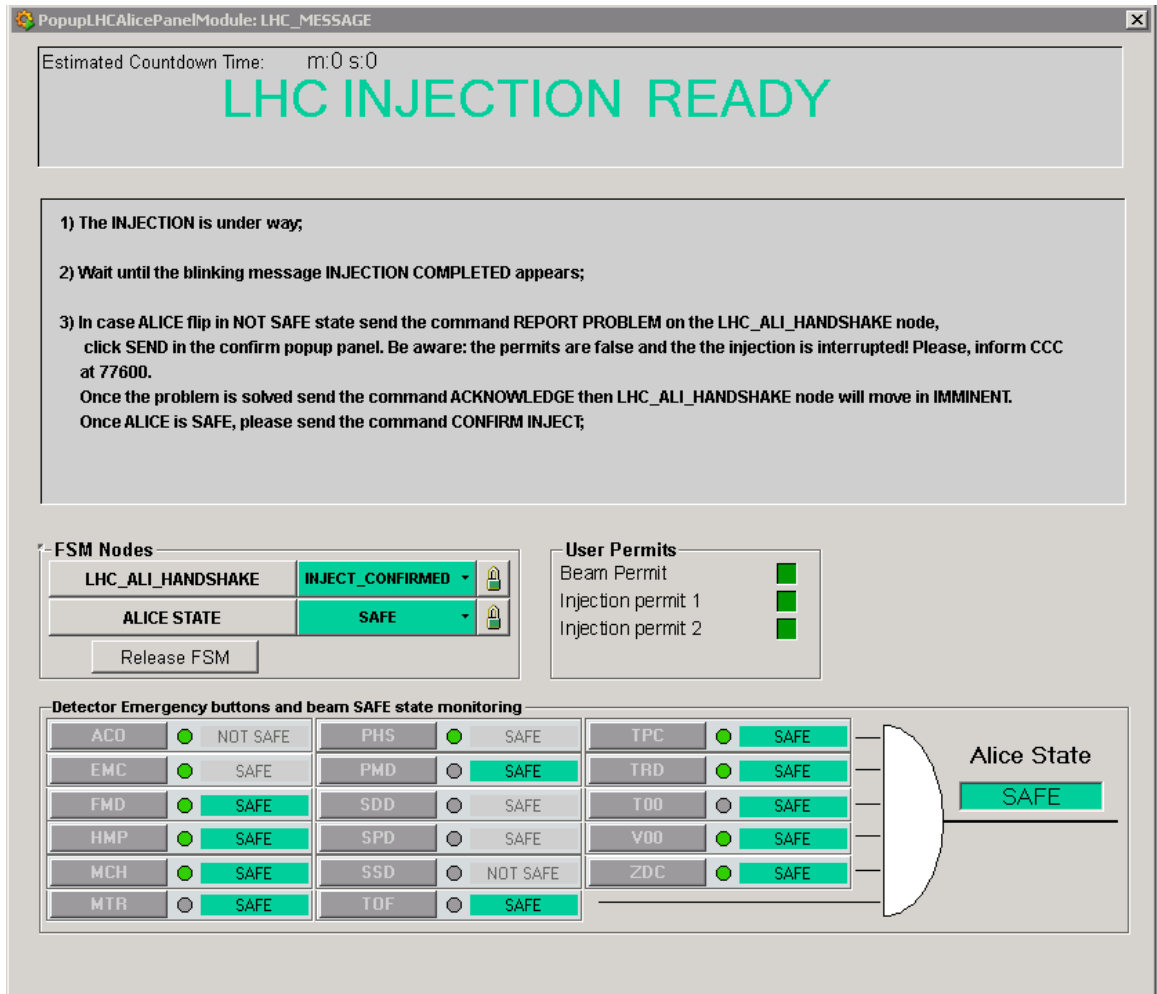


Fig. 4.11: Injection handshake confirmed phase

4.2.2 Data publication for LHC

The ALICE detectors can be regarded as sophisticated measuring instruments and their data can be used both for physics related purposes but also as analysis instruments to check the beams background, its centering or the rate of collisions according to the number of bunches circulating in the accelerator. Since several data are interesting either for the experiment and for the LHC they are transferred via DIP to both control systems. The information flow is output from ALICE through the DCS *lh_monitoring* (alidcscom031) project where a manager called “Publisher” processes the data coming from the detectors and copies them in DPs connected to LHC via DIP. Directions concerning the kind of data and the publishing rate were printed in an official document [23] and all of the experiments must comply with its requirements.

I implemented the output data processing for the ALICE experiment as well as their publication via DIP. Some of them are also displayed online both in the ALICE control room (fig. 4.12) and in the LHC VISTAR reference page (fig. 4.13) [27].

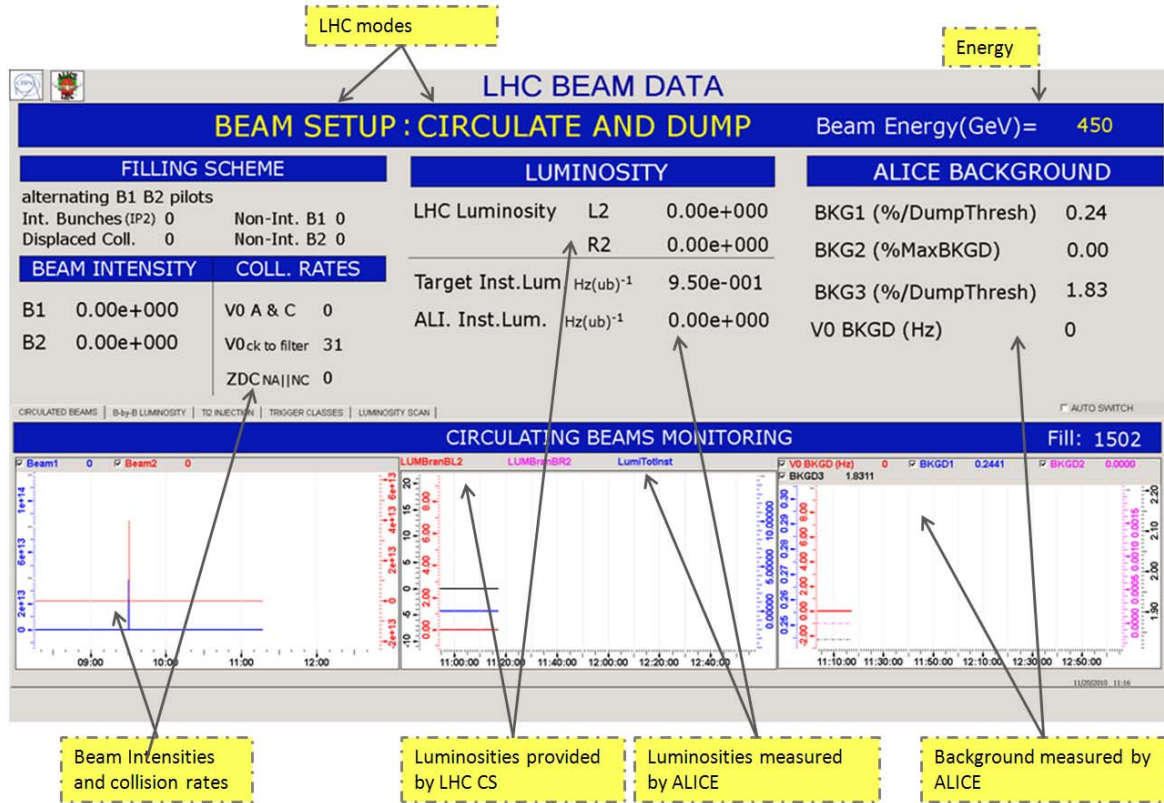


Fig. 4.12: Big Screen panel

This panel provides the operators in the ALICE control room with a prompt feedback about the state of the LHC beam (beam and machine mode, beam energy, data measured by ALICE). Luminosity (in the middle of the panel) is a very important parameter to be aware of the performance of the accelerator and of the ALICE detectors. In fact, it provides the number of particles crossing an area unit of measure (square centimetre) per second; this is strictly linked to the number of collisions per second inside the experiment. The collision rate displayed on the left side of the panel is measured by two dedicated detectors (V0 and ZDC.)

Any remarkable difference between the luminosity measured by LHC and the one detected by ALICE is evidence for something wrong. This would allow experts to react promptly and correct the working parameters of the detectors.

Background (right side of the panel) is also a very important value used to check the beam focus. As a matter of fact a well aligned beam generates a low background signal, on the contrary high background values mean that the beam is not perfectly controlled and therefore that the most sensitive detectors must be kept in a safe state (usually HV off). The background values are generated by the BCM sensors (BKG1 e BKG3) and by the detector V0 (BKG2). They are given as a percentage of a fixed safety threshold.

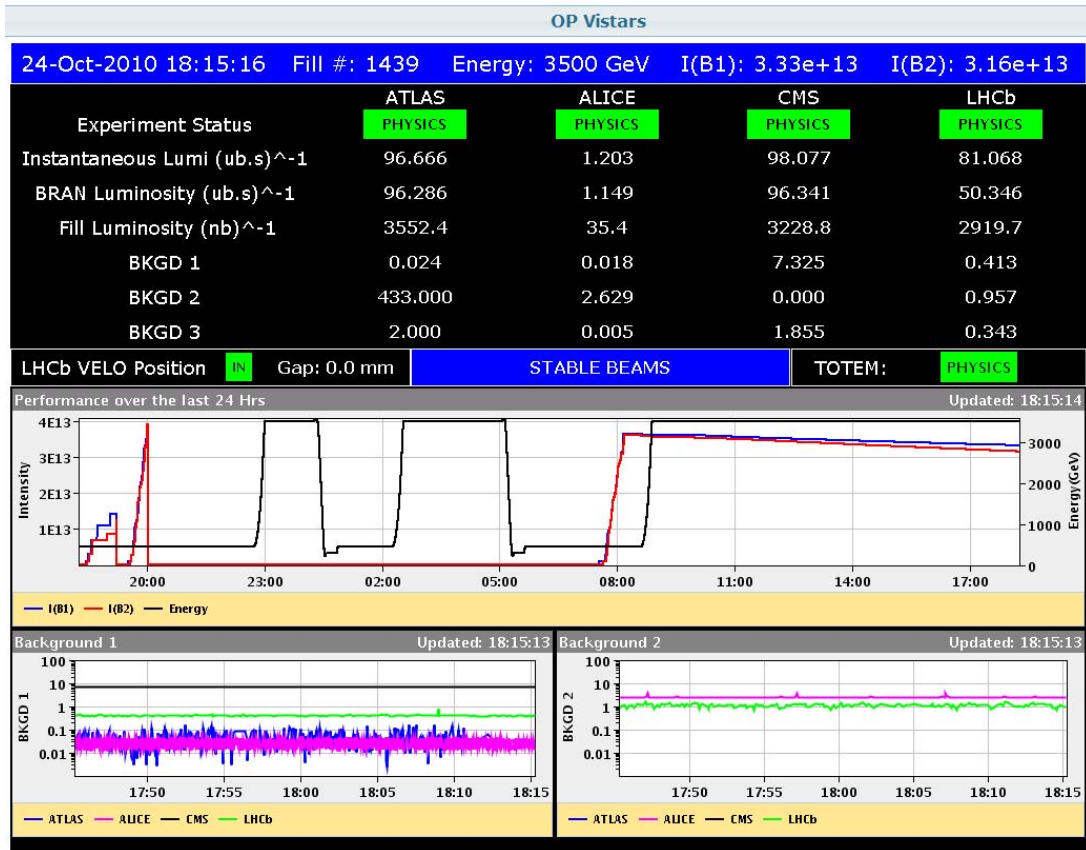


Fig. 4.13: VISTAR page: LHC_Operation

These pages display the most interesting information exchanged between the experiment and LHC, like beam intensity, luminosity measured by both systems, the experiment status (Standby, Calibration, Physics..).

The majority of these records concern ALICE and they are processed by the PVSS manager of the *lhc_monitoring* which is extremely important to the whole project.

Another chief manager is the one regarding the Signal Conditioning which calculates the average of some of the values measured by the LHC sensors such as luminosity. The average calculations are important to create files for the Offline system containing limited parameters as far as their number and values are concerned. Since these sensors are often extremely sensitive and not very trustworthy at low intensities, it was necessary to disregard values above or below certain thresholds.

4.2.3 *lhc_instrumentation*, *lhc_bunchserver* and *lhc_luminosity*: main functions

Most of the data managed by the LHC_EI is used to create the files for the Offline system. The manager that generates these files is called Offline Server and it works in the *lhc_bunchserver* PVSS project. Each time a data taking run starts, this manager records a preset series of data in some variables. This information is essential to reconstruct events offline with the related timestamp. Such data are organized into neat strings spaced by tabs.

At regular intervals these variables are transcribed into a text file that is finished as soon as the LHC_Measures logical unit (fig. 4.7) receives the End Of Run (EOR) signal from the ECS. Then a teleport device copies the just created file in the FXS where a program called SHUTTLE transfers it to the Offline database to be afterward used to reconstruct the run.

lhc_instrumentation is the PVSS project used to interface with the BPTX sensors which, as explained at paragraph 4.1, are crucial to measure some of the characteristics of the circulating beams such as bunch by bunch intensities, clock phase, etc.... Some of these data are saved in the files for the Offline system.

The most recent project of the LHC_EI is the *lhc_luminosity* which was conceived to create all the graphical interface concerning the display of luminosity. An important step is the luminosity scan which optimizes the luminosity value according to the experiment requests. During this phase the LHC experts move the beam along the x and y axes with reference to the beam pipe in order to increase or reduce the collision rate of the particles.

Several tools were implemented in the *lhc_luminosity* project to monitor this stage and part of my job concerned the creation of the graphical interfaces (fig. 4.14) that were later developed so as to make this step as performing as possible. These panels proved a very useful tool for operators since they display the operating state of LHC and ALICE. Scrollbars and trend views allow to show previous data and compare them with actual ones.

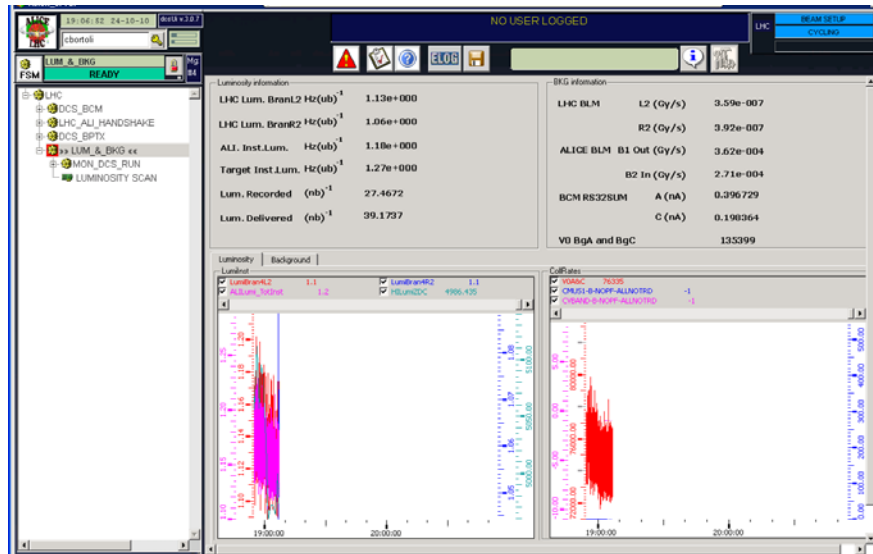


Fig. 4.14: Luminosity main panel

4.3 LHC Exchange Interface web page

Such a complex project, characterized by so many subsystems, needed an interface that could be easily accessed in order to get the most important information, like the name of an item published via DIP, the kind of smoothing applied to certain values or simply to look up the documentation that concerns the project itself. For this reason I was asked to implement a web page containing all the information and that could be accessed by all users.

The page, created with Microsoft FrontPage, is displayed in figure 4.15. The menu on the left allows to access the tables containing the 263 data currently exchanged with the LHC (fig. 4.16).



Fig. 4.15: LHC Exchange Interface web page

It is possible to know the following information for each datum: source, destination, archiving status, applied smoothing, name of the control manager that processes the datum and the naming with which it is received or published via DIP.

ALICE - DCS GLOBAL ITEM TABLE									
Ver. 1.8 Date: April 16, 2010									
ID	DESCRIPTION	L_LOG	OFFLINE	LHC PUB	ARCHIVE	FORMAT	SMOOTH	MANAGER	SOURCE
1	Array of flags of calibrated start-up/beam bunch by bunch turn					F 2564	80s	BunchServer	bits of set _lhc_bch_CTP_LuminosityPerBunchBeam_OutBunchIndex
2	Details on source, coincidence mode, etc.					S 1	80s	BunchServer	Constant = CTP_READY
3	ALICE adjust values VETO, PREPARE, READY, PROBLEM					S 1		Handshaker	
4	ALICE BeamDump values VETO, PREPARE, READY, PROBLEM					S 1		Handshaker	
5	ALICE injection values VETO, PREPARE, READY, PROBLEM					S 1		Handshaker	
6	Bunch intensities for Beam1, measured from BPTX					F 2564	1s	Orbitella	BPTX_A
7	Bunch intensities for Beam2, measured from BPTX					F 2564	1s	Orbitella	BPTX_C
8	Number of protons in the short gap of Beam 1					S 1		Orbitella	
9	Flag to indicate the ALICE sees a problem with particles in the s					S 1		Orbitella	
10	Number of protons in the short gap of Beam 2					S 1		Orbitella	
11	Flag to indicate the ALICE sees a problem with particles in the s					S 1		Orbitella	
12	Average over all bunch pairs that are supposed to collide at					F 1		Orbitella	
13	The RMS of the measurement of delay					F 1		Orbitella	
14	Time(BPTX1) - time(Orbita) + offset (ns)					F 1		Orbitella	
15	The RMS of the measurement of Phase of BPTX1					F 1		Orbitella	
16	Integer array of RF bucket numbers for all locations where the s					F 1		Orbitella	
17	Flag indicating if the observed bunch pattern is not as expected					S 1		Orbitella	
18	Time(BPTX2) - time(Orbita) + offset (ns)					F 1		Orbitella	
19	The RMS of the measurement of Phase of BPTX2					F 1		Orbitella	
20	Integer array of RF bucket numbers for all locations where the s					F 1		Orbitella	
21	Flag indicating if the observed bunch pattern is not as expected					S 1		Orbitella	
22	Primary background indicator, nominal range 1, 100					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 250
23	Description of data source of the BG01					S 1		PublisherServer	Constant = BG01_R102-BG01_R102
24	Secondary background indicator, nominal range 1, 100					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
25	Description of data source of the BG02					S 1		PublisherServer	Constant = BG02_R102-BG02_R102
26	Fraction of about thresholds, nominal range 1, 100					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 10
27	Description and mode of about threshold					S 1		PublisherServer	Constant = BG01_R102-BG01_R102_R102_R102_R102
28	State of equipment, values: OFF, CALIBRATION NOT READY					S 1		PublisherServer	Translated from _lhc_bch_bunchbeam01_R102 - _lhc_bch_bunch320
29	Accumulates only while stable beam flag is on. Summed over all					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
30	Accumulates when ALICE is taking data. Contribution to this in					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
31	Luminosity collision rate					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
32	Error in the acquisition of the luminosity collision rate					S 1		PublisherServer	Constant = 0
33	Integration time per acquisition in seconds					S 1		PublisherServer	Constant = 0
34	Description of the source of luminosity					S 1		PublisherServer	10 A and B in 1 km
35	Total instantaneous luminosity summed over all bunches					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
36	Total instantaneous luminosity summed over all bunches CTP1					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
37	Total instantaneous luminosity summed over all bunches CTP2					F 1		PublisherServer	lhc_exchange_bch_bunchbeam01_R102 - _lhc_bch_bunch320 - value / 100
38	Detail on source, coincidence mode, etc.					S 1		PublisherServer	10 A and C
39	Number of verified records					F 1		PublisherServer	Constant = 0

Fig. 4.16: example of table containing the data exchanged between ALICE and the LHC

Conclusions

This thesis deals with the results obtained during the three years of research doctorate I spent working for the ALICE experiment at CERN in Geneva.

I took care of the cooling and control systems of the Silicon Pixel Detector and of the optimization of the control system of the LHC_EI project which manages the flow of information between the experiment and the accelerator.

I cooperated in the commissioning of the cooling system of SPD which, as explained, is absolutely vital for the detector. SPD is one of the basic detectors of the ALICE experiment thanks to which it is possible to reconstruct accurately the vertex position of the interactions among particles. It is also equipped with a level 0 trigger.

I installed both the hardware and the software of a new system that monitors the performance of the cooling plant and which was also used to carry out several tests that provided better understanding of some of the problems that negatively affect the plant performance.

Moreover, during these three years I also dealt with the maintenance of the whole system.

I showed that the state of the SPD cooling is strongly affected by a pressure drop along the circuit, most probably due to partial clogging of the filters closest to the detector (PP3) and that any improvement that was made during the last years allowed to slow down its worsening.

A further series of tests has to be carried out in order to reproduce running conditions as close as possible to the real ones. To accomplish this task, we built a test bench endowed with a dummy sector that is provided with the same hydraulic equipment as a real sector of SPD. The only difference is that its carbon fibre supports do not house half-staves but heating elements powered by a common power supply. While building this test bench, we performed several tests using a thermosiphon plant based on a different working principle which can deliver C_4F_{10} at working conditions identical to the nominal ones. Thanks to such installation we could reproduce some of the behaviours we had observed on the real cooling system during the commissioning stage of SPD. The results, even if they are preliminary, provided important indications since they suggest the possibility that during the first running year the filter in PP3 became dirty since there was no $1\text{ }\mu\text{m}$ filter at the plant. Thus, as time went by, some particles may have come off the filter in PP3 and deposited all over the circuit any time the loop was opened again.

Further interventions have already been scheduled for 2011 and 2012 with the aim of trying to keep the cooling plant as performing as possible. With respect to this, a decisive intervention is being planned and arranged to be carried out during the long LHC shutdown in 2012-2013 when any part of the cooling lines will be accessible (filters in PP3 included).

As concerns the controls, I developed part of the Detector Control System (DCS) of SPD using a software SCADA (Supervisory Control and Data Acquisition). I realized several user interface panels for shifters and experts that made monitoring and supervising the detector much easier. I implemented both the hardware and the software read-out of pressure and temperature sensors for the cooling lines and I worked out a device that provides direct access between the control system and the detector Configuration Database (CDB) thanks to which many of the configuration operations of SPD were optimized and simplified.

My work also dealt with the implementation of the LHC Exchange Interface project (LHC_EI), particularly in the execution of the control system that is the link between the experiment and the collider. For the most part I worked on the optimization of some of the most delicate synchronization between ALICE and the LHC. I optimized the handshake phase working on the relevant FSM and on the interface panel which is used to send the commands to the LHC control system. This task was particularly important because it shortened the time required for the injection and beam dump phases thus allowing a remarkable increase in time dedicated to setting up the machine and data taking.

Therefore during the LHC start-up phase I was assigned the task of expert in charge of the beam injection operations in ALICE and of the data exchange with the accelerator. I realized also several analysis tools concerning the luminosity, intensity and background of the beams colliding inside ALICE. Besides I implemented several DIP subscriptions and publications of the ALICE and LHC parameters which were used by the experiment subsystems (CTP, HLT, Detectors, Offline...) in 2009 and 2010 to analyse the collisions.

This project still needs further development especially as far as the handshake mechanism is concerned because starting from next year more automatisms will be required in order to cut down human errors as much as possible.

Thanks to the work I carried out during my doctorate I could attain my aims and achieve good results that were used in scientific papers. SPD contributed very important data that provided stimulating information concerning the Standard Model physics that is a basic subject of research at CERN.

APPENDICE A

A.1 The ALICE detectors

The ALICE detector is composed of 18 elements: SPD (Silicon Pixel Detector), SDD (Silicon Drift Detector), SSD (Silicon Strip Detector), TPC (Time-Projection Chamber), TOF (Time-of-Flight), HMPID (High Momentum Particles Identificators Detectors), TRD (Transition Radiation), PHOS (Photon Spectrometer), EMCal (Electromagnetic Calorimeter), ZDC (Zero Degree Calorimeter), PMD (Photon Multiplicity Detector), FMD (Forward Multiplicity Detector), ACORDE (A Cosmic Ray Detector), T0, V0, Muon chambers, Muon Trigger and PIT (Pixel Trigger).

- The inner tracking system has three main aims: the secondary vertex reconstruction of hyperon and charm decays, particle identification and tracking of low momentum particles and the improvement of the momentum resolution [28]. All of them are carried out by six rolls of high-resolution detectors. The high density of particles require the four innermost layers, i.e. silicon pixel detector (SPD, see section 1.5) and silicon drift detectors (SDD), to be two-dimensional devices. The outer layers are at a distance of around 40 cm from the beam axis and are equipped with double-sided silicon micro-strip detectors (SSD). Four of the layers allow the inner tracking system to operate as a stand-alone, low pT particle spectrometer thanks to their analogue readout for independent particles identification via dE/dx in the non-relativistic region.

- The Time Projection Chamber is the foremost detector in the central barrel of the ALICE experiment. It has two main tasks: to track charged particle momentum measurements with more than the 90 % of efficiency and resolution higher than 2.5% for electrons with a momentum of about 4 GeV/c; to identify particles with dE/dx resolution higher than 10% and two-track separation in the region of $pT < 10$ GeV/c and a pseudorapidity of $|\eta| < 0.9$.

TPC is a cylindrical gas detector. Its active volume is between 90 to 250cm in radial direction and its length is 500cm along the beam axis. A high voltage (HV) electrode, placed in the middle of this detector, is aligned with the interaction point and so it divides the barrel into two symmetric drift volumes 250cm long. A very uniform electrostatic field is created by the HV electrode, which is made of an aluminized stretched Mylar foil, and two opposite axial potential degraders. The Mylar strips, wound around 18 inner and outer support rods, defines the potential of the drift region [29].

The design of TPC was especially conceived and optimized for high-quality double-track resolution. The use of $Ne/CO_2/N_2$ (90/10/5) particularly minimizes electron diffusion and reduces the space charge.

Two end plates of 18 azimuthal sectors at both ends of the detector house the 72 pad-readout chambers and feature 570.000 channels.

- The Photon Spectrometer measures photons at high resolution and detects light neutral mesons (π^0 and η) analyzing their decay into two photons. PHOS was conceived to investigate the pseudorapidity range $|\eta| = 0.12$ and an azimuthal field of 100 degrees. This detector is made of 5 identical modules which are composed of 3.584 detection channels each, for a total of 17.920 channels. . Every channel consists of a $2.2 \times 2.2 \times 18 \text{ cm}^3$ lead-tungsten crystal PbWO_4 (PWO), coupled to an Avalanche Photo-Diode (APD) and a low-noise preamplifier [30].
- The Electromagnetic Calorimeter is a Pb-scintillator sampling calorimeter characterized by cylindrical geometry. It improves Alice's jet quenching measurements, jet energy resolution and triggering on high energy jets. It also decreases considerably the measurement bias required from jet quenching studies and enhances the actual experiment capability to determine high momentum electrons and photons. Together with the ALICE experiment means and potential to track and detect particles from very low to very high p_t , the electromagnetic calorimeter allows a wide-ranging investigation of jet quenching. It is located near the ALICE magnet coil, about 4.5m from the beam line and opposite the PHOS. It covers a pseudorapidity range of $|\eta| < 0.7$. This calorimeter is divided into 12.672 projective towers, each covering $\delta\eta \times \delta\theta \sim 0.014 \times 0.014$. Its Readout fibres are coupled to an Avalanche Photodiode sensor (APD). EMCal provides triggers of level 0 and 1 for electrons, photons and jets [31].
- One of the main tasks of the ALICE experiment is to determine the mass of the emitted particles. Low energy particles can be identified from the loss of energy while high energy particles can be detected by measuring the time it takes a particle to fly from the collision point to the detector barrel which is 3.5 meters away. Such aim is achieved by making use of three detectors: HMPID (High Momentum Particle Identification Detector) [32][33], TOF (Time of Flight) [34][35] and TRD (Transition Radiation Detector)[36][37]. At very high energies, where the number of known particles is low, ALICE identifies particles using HMPID, a small detector of 14m^2 , which detects Cherenkov photons emitted by the particles in a dielectric medium. HMPID is also called RICH (Ring Imaging Cherenkov) because the pattern of the photons detected by its Cesium Iodide (CsI) photocathode is circular. HMPID consists of seven $1.5\text{m} \times 1.5\text{m}$ RICH proximity focusing counters installed at a distance of 4.7m from the interaction point in a space frame. Each module contains six $0.64\text{m} \times 0.4\text{m}$ CsI photocathodes (PCs) which cover a total active area of 11 m^2 . The HMPID detects kaons and pions in a range of $1 < p_T < 3\text{GeV}/c$ and protons and kaons in a range of $2 < p_T < 5\text{GeV}/c$. It was designed as a single-arm detector according to the yields of particles in pp and heavy-ion collisions and to the wide opening angle required for two-particle correlation measurements.

The Transition Radiation Detector (TRD) can identify electrons above 1 GeV/c. It also contributes to the trigger system (high-pT e^+e^- pairs) to reduce the collision rate to the readout event rate by increasing the statistics on rare signals such as J/ψ and Y' [36], [37].

TRD was installed between the Time Projection Chamber and the space frame. Its barrel has a radius range between 2.9 m and 3.7 m from the beam axis and a length of 7 m along the same axis, thus covering the central rapidity region of $|\eta| < 0.9$.

TRD is composed of 540 modules divided into 18 sectors and 6 layers. The detector takes up an area of 750 m² in the gas chambers with radiators for particle tracking and electron identification above 1 GeV/c.

Time of Flight (TOF) allows to separate kaons from pions up to 2.5 GeV/c and protons from kaons up to 4 GeV/c. This requires a global time resolution of ~ 100 ps.

It is composed of 18 supermodules which cover a 360° azimuth and a pseudorapidity range of $|\eta| < 1$ in a total area of ~ 150 m².

Every supermodule consists of 5 modules containing between 15 and 19 Multigap Resistive Plate Chambers (MRPC) strips. Each strip contains two stacks of resistive glass plates, divided by spacers of the same size. This structure creates a series of uniform gas gaps where voltage is applied to the external surfaces. The MRPC stack is made of 6 glasses forming 5 gaps with 250 μ m of width [36], [37].

- The pre-shower Photon Multiplicity Detector (PMD) was installed on the door of the L3 magnet 5.8 m away from the interaction point.

It is characterized by fine granularity and full azimuthal coverage in the pseudorapidity region $1.8 \leq |\eta| \leq 2.6$.

A Charged Particle Veto (CPV) installed in front of the converter rejects charged particles.

The design of the pre-shower converter and CPV are based on a honeycomb proportional chamber composed of $\sim 2 \times 10^5$ cells each taking up an area of 1 cm². The honeycomb wall forms a common cathode which is operated at high negative voltage. The anode wires read the signal at ground potential making use of GASSIPLEX front-end electronics.

PMD can take data together with the di-muon spectrometer as well as other high rate detectors [38].

FMD (Forward Multiplicity Detector) is made of 51.200 silicon strip channels distributed over 5 ring counters. It is composed of two silicon sensors which are divided into 20 (inner ring) and 40 sectors (outer ring) and they both cover a round angle.

The main task of this detector is to measure charged particle multiplicity in a pseudorapidity range of $-3.4 \leq |\eta| \leq -1.7$ and $1.7 \leq |\eta| \leq 5.0$, respectively. The read-out time of ~ 13 μ s allows FMD to contribute only to level 2 trigger in ALICE. However, together with the pixel detector system, it also provides charged particle multiplicity distributions for all collision types in a pseudorapidity range of $-3.4 \leq |\eta| \leq 5.0$ [39].

The T0 detector [39] consists of 2 groups of PMTs (Photo Multiplier Tube) equipped with Cherenkov radiators and located opposite the Interaction Point (IP).

The main task of this detector is to provide a signal for the level 0 trigger, especially for TRD and to supply a reference time for TOF.

T0 is characterized by a time resolution higher than 50ps and it covers two pseudorapidity ranges of $-3.3 \leq |\eta| \leq -2.9$ and $4.5 \leq |\eta| \leq 5.0$.

The V0 [39] is composed of 2 disks made of 8 segments of plastic scintillator tiles which are read out by optical fibres. It covers nearly the same pseudo-rapidity range as the FMD. The most important tasks of V0 are to provide a background rejection capability for the dimuon arm and to supply the online L0 centrality trigger for the ALICE experiment by setting a threshold on deposited energy.

The number of the colliding nucleons is related to the geometry of the collisions between lead ions. (fig. 1.7). It can be estimated by measuring the energy carried forward (0° with reference to the beam direction) by non-interacting (spectator) nucleons.

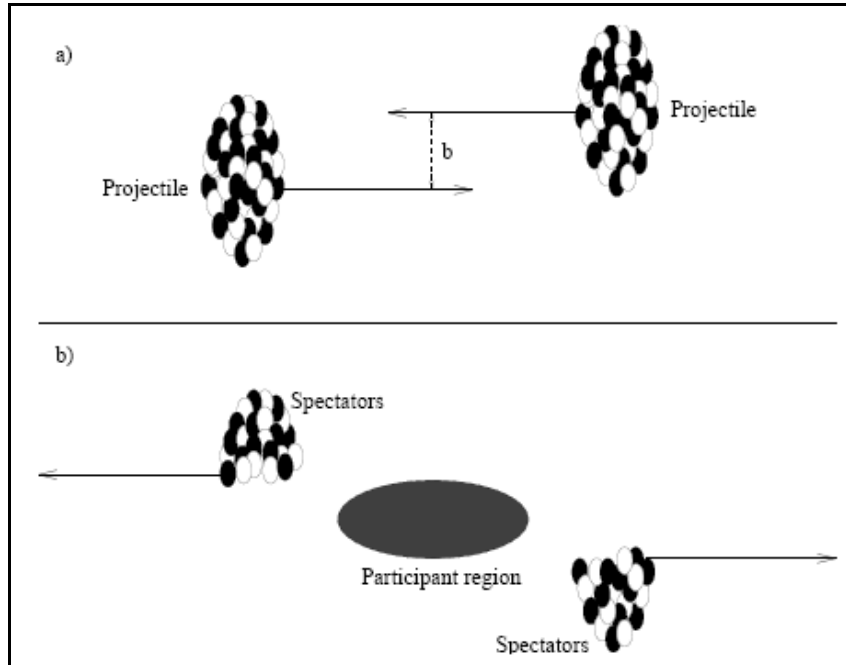


Fig. 1.7 Outline of a collision between two heavy nuclei.

a) two Lorentz contracted nuclei before the collision;

b) participant region and spectators after the collision;

In ALICE, spectator nucleons are detected by Zero-Degree Calorimeters (ZDC) [40].

Being ZDC also a position-sensitive detector it can provide estimates of the reaction plane in nuclear collisions. Moreover, the centrality information supplied by ZDC is also used for Level 1 trigger (L1).

In ALICE two sets of hadronic ZDCs are placed 116m away from each side of the Interaction Point and two small electromagnetic calorimeters (ZEM) are installed 7 m from the latter on both sides of the LHC beam pipe. Proton spectators are spatially separated from neutrons by the magnetic elements of the LHC beam line

opposite the muon arm Spectator. Therefore, each ZDC set is made of two different detectors: one for spectator neutrons (ZN) located between the beam pipes at 0° with reference to the LHC axis and one for spectator protons (ZP) placed on the outside of the outgoing beam pipe, on the side where positive particles are deflected. The ZN and ZP are mounted on lifting platforms in order to be lowered out of the horizontal beam plane (where radiation levels are highest) when they are not in use.

- The Muon Spectrometer detects muons in a pseudorapidity region $-4.0 < \eta < -2.5$. It is meant to detect muons in a polar angular range of 171° – 178° . This detector consists of the following elements: a passive front absorber that absorbs hadrons and photons (MCH) from the interaction vertex; a high-granularity tracking system which is composed of 10 detection planes; a large dipole magnet; a passive muon-filter wall; four planes of trigger chambers; an inner beam shield that protects the chambers from primary and secondary particles produced at large rapidity [2]. The Muon Spectrometer measures the complete spectrum of heavy-quark vector-mesons resonances (i.e. J/ψ , ψ' , Y , Y' and Y''), as well as the θ meson in the $\mu^+\mu^-$ decay channel.

This detector provides the possibility of measuring all the quarkonia species simultaneously thus allowing to compare directly their production rate as far as parameters such as transverse momentum and collision centrality are concerned. Moreover, it can also determine the unlike-sign dimuon continuum up to masses around $10 \text{ GeV}/c^2$.

The Muon Spectrometer will allow to study the creation of open (heavy) flavours since at the energies the LHC can reach the continuum is supposed to be dominated by muons originating from the semi-leptonic decay of open charm and open beauty. The heavy-flavour production in a range of $-2.5 < \eta < -1$ will be available by measuring $e^-\mu$ coincidences, where muons are detected by the muon spectrometer and electrons by the TRD.

The muon spectrometer will also take data during the Pb-Pb collisions in ALICE at luminosity $\mathcal{L} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$.

As regards intermediate-mass ion collisions (e.g. Ar-Ar), apart from a general ALICE run at low luminosity, $\mathcal{L} = 10^{27} \text{ cm}^{-2}\text{s}^{-1}$, a high-luminosity run at $\mathcal{L} = 10^{29} \text{ cm}^{-2}\text{s}^{-1}$ is also foreseen in order to enhance the Y' counting statistics. During the high-luminosity run, the muon spectrometer will take data together with some other ALICE detectors such as SPD, ZDC, PMD, T0, V0 and FMD which are the ones that can face the event rate. These detectors allow to determine the collisions centrality [2].

- ACORDE (A Cosmic Ray Detector) is the cosmic ray detector in the ALICE experiment. It is composed of an array of plastic scintillator counters placed on the upper side of the L3 magnet. It has the following two main tasks:

1. to provide a fast (Level-0) trigger signal, for the commissioning, calibration and alignment procedures of some tracking detectors in ALICE;

2. it also detects, together with TPC, TRD and TOF, single atmospheric muons and multi-muon events (called muon bundles) thus providing the possibility of studying high-energy cosmic rays in the energy region of the knee in the cosmic ray spectrum.

The ACORDE module is made of two overlapping scintillator counters, each characterized by an effective area of $190 \times 20 \text{ cm}^2$ and a thickness of 10mm. The end of each counter is equipped with two PMTs with optic guide and iron magnetic shielding.

Such a setup provides a uniform efficiency higher than 90% along the whole length of a test module [41].

Main Acronyms

ACC (Alice Control Coordination)
ACORDE (A Cosmic Ray Detector)
ACR (ALICE Control Room)
ALICE (A Large Ion Collider Experiment)
API (Application Programming Interface)
ASIC (Application-Specific Integrated Circuit)
ATLAS (A Toroidal LCH ApparatuS)
BCM (Beam Conditions Monitor)
BIS (Beam Interlock System)
BPTX (Beam Pick-up Timing eXperiment)
BKG (BackGround)
CAN (Controller Area Network)
CCC (CERN Control Centre)
CCPC (Credit Card PC)
CDB (Configuration Database)
CDH (Common Data Header)
CERN (European Organization for Nuclear Research)
CMS (Compact Muon Solenoid)
CTP (Central Trigger Processor)
Ctrl (Control manager)
CU (Control Unit)
D (Drivers)
DAQ (Data Acquisition)
DB (Database)
DCS (Detector Control System)
DIM (Distributed Information Management)
DIP (Data Interchange Protocol)
DNS (DIM Name Server)
DP (Data Points)

DPE (Data Point Element)
DPT (Data Point Type)
DSS (Detector Safety System)
DU (Device Unit)
ECS (Experiment Control System)
ELMB (Embedded Local Monitor Board)
EMCal (ElectroMagnetic Calorimeter)
EOR (End Of Run)
EPICS (Experimental Physics and Industrial Control System)
EV (Event manager)
FPGA (Field Programmable Gate Array)
FED (Front-End Device)
FMD (Forward Multiplicity Detector)
FSM (Finite-State Machine)
FXS (File eXchange Server)
GPS (Global Positioning System)
HLT (High-Level Trigger)
HMPID (High Momentum Particles Identificators Detectors)
HV(High Voltage)
INFN (Istituto Nazionale di Fisica Nucleare)
IP (Interaction Point)
ITS (Inner Tracking System)
JCOP (Joint COntrols Project)
LHC (Large Hadron Collider)
LHC_EI (LHC Exchange Interface)
LHCb (Large Hadron Collider beauty)
LINAC (Linear Accelerator)
LinkRx (Link Receivers)
LU (Logical Unit)
LV (Low Voltage)
MCH (Muon Chambers)

MTR (Muon Trigger)
OCDB (Oracle Database)
OLE (Object Linking and Embedding)
ON (Operator Nodes)
OPC (OLE for Process Control)
PARA (Graphical Parameterization)
PHOS (Photon Spectrometer)
PIT (Pixel Trigger)
PM (Post Mortem)
PMD (Photon Multiplicity Detector)
PMT (Photo Multiplier Tube)
PP (Patch Panel)
PS (Proton Synchrotron)
PVSS (Prozessvisualisierung und Steuerungssystem-Process Visualization and Control System)
QCD (Quantum Chromodynamics)
QED (Quantum Electrodynamics)
QGP (Quark Gluon Plasma)
RICH (Ring Imaging CHernkov)
RMS (root mean squared)
SAA3 (Small Angle Absorber 3)
SCADA (Supervisory Control and Data Acquisition)
SDD (Silicon Drift Detector)
SM (Standard Model)
SOR (Start of Run)
SPD (Silicon Pixel Detector)
SPS (Proton Synchrotron)
SSD (Silicon Strip Detector)
SUSY (Supersymmetry)
TOF (Time-of-Flight)
TPC (Time-Projection Chamber)

TRD (Transition Radiation)

TRG (Trigger system)

UI (User Interface)

URD (User Requirements Documents)

WN (Worker Nodes)

ZDC (Zero Degree Calorimeter)

ZEM (Zero degree Electromagnetic Calorimeter)

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