Benemérita Universidad Autónoma de Puebla

Facultad de Ciencias Físico Matemáticas

Development of online software tools for the TOTEM-CMS Data Acquisition System

Tesis presentada al

Colegio de Física

como requisito parcial para la obtención del grado de

Licenciada en Física Aplicada

por

Nadia Mariana Leal Reyes

Asesorada por

María Isabel Pedraza Morales
Diego Figueiredo

Puebla Pue.
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To my loved ones. You have always been cheering me up along the way, through the good and bad times. You may never know how much a simple action or word on your part meant to me. I'm grateful for having you in my life.

To Diego Figueiredo, my supervisor in the CERN Summer Student Programme and this thesis. Thank you for being so patient, always willing to answer questions as basic as they were, helping me overcome the obstacles, and sharing all your tips and knowledge. Thank you for sharing the passion you feel about what you do. You have greatly inspired and motivated me along the way.

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Lastly, to myself and whoever might read this. I just want you to remember that life goes on and so do you. Everyday you will get stronger and heal. I'm proud of you.

Abstract

The TOTal cross-section, Elastic scattering, and diffraction dissociation Measurement (TOTEM) is one of the Large Hadron Collider (LHC) experiments. TOTEM is symmetrically installed in the LHC sectors 45 and 56 beamlines having a total extension of about 400 m and being located around the CMS interaction point (IP5). TOTEM originally consisted of a set of movable detectors named Roman Pots (RPs) utilized for tagging scattered protons and two charged particle telescopes, known as T1 and T2, installed to measure showers produced by hadronized particles from dissociated protons. In Run 3, TOTEM collaboration will complete its physics program in a special fill, where the inelastic component of the proton-proton interaction will be measured. For this purpose, a new telescope (referred to as new T2) has been built and is in the commissioning phase. The TOTEM DAQ has been totally integrated with the CMS environment, this system controls the vertical Si-Strips, meantime the new T2 detectors will be attached to the same DAQ. The CMS DAQ online environment relies on software tools for communication to configure the detector Finite State Machines (FSM).These FSMs, such as halt, configure, start or stop are defining transitions to prepare the detectors for the read-out. The communication between central DAQ (CMS) and its subsystems is linked with a scalable software framework called XDAQ within an exchange of SOAP commands. In this work, the development of a new online software utility, written in an object-oriented programming language, which controls the new T2 detectors through a slow control optical link is presented.

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Chapter 1

Introduction

The TOTal cross-section, Elastic scattering, and diffraction dissociation Measurement (TOTEM) is one of the Large Hadron Collider (LHC) experiments. TOTEM Physics program included the measurement of the total elastic and inelastic protons cross-sections and diffractive physics processes. Originally, TOTEM was designed to operate at low pile-up, or special fills, during LHC Run 1 and Run 2.

TOTEM is symmetrically installed in the LHC sectors 45 and 56 beam lines, where movable detectors named Roman Pots can approach up to $1.5mm$ to the LHC beam spot. The RPs are installed around 200m from the Compact Muon Solenoid (CMS) experiment per sector. In the CMS detector, two charged particle telescopes, known as T1 and T2 were installed to measure showers produced by hadronized particles from dissociated protons.

Given the nominal high luminosity fills of the LHC Run 3, the CMS and TOTEM collaboration firstly joined efforts in special runs and data acquisition integration, still in Run 2, which gradually ended in an agreement of a new collaboration. This new collaboration named Precision Proton Spectrometer (PPS) proposed a physics program that extended CMS acceptances for tagging scattered protons and measuring central exclusive processes, as well to build new horizontal RPs units to accommodate 3D pixels sensors and cylindrical (and boxed) RPs units with diamond timing detectors. These upgrades increased the sensibility for tagging protons at high pile-up runs. Thus, while the first are more robust for radiation, the second are used for background suppression and vertex identification.

PPS experiment inherited TOTEM know-how, manpower, as well as its technology to operate close to the beam and under non-uniform radiation flux. Moreover, not only the Si-Strips detectors from TOTEM are used by PPS, but also their Data Acquisition (DAQ) system has been upgraded to comply with CMS requirements: data throughput, trigger rate, and others.

The TOTEM DAQ has been integrated with the CMS environment. This system controls the vertical Si-Strips and the new T2 detectors will be attached to the very same DAQ. Modern DAQ systems are integrated not only at the hardware level but also at the communication levels, which are controlled by the software. The CMS DAQ system relies on software tools for communication to configure the detector Finite State Machines (FSM). These FSMs are well-defined transitions to prepare the detectors for the read-out. The communication between central DAQ (CMS) and its subsystems is linked with a scalable software framework called XDAQ.

1.1 Problem statement

In Run 3, TOTEM collaboration will complete its Physics program in a special fill planned for September (2022), where the inelastic component of the proton-proton interaction will be measured taking into account the proton dissociative component.

TOTEM's Telescope 2 (T2) surrounded the beam pipe at 13.5m from the CMS interaction point (IP5). Since the beam pipe was upgraded, the T2 detector needed upgrades to fit the new pipe at CMS. For this purpose, a new telescope (referred to as new T2 or nT2) has been built and is in the commissioning phase to be ready for Run 3.

The aim of this project is the development of a new online software utility, able to control a new design mezzanine for the TOTEM experiment (new T2), through a slow control optical link [41]. The slow control is vastly used within the CMS collaboration since the beginning of Run 1, relying on the CCU25 radiation hardness communication ASIC that distributes a token ring for all the front-end boards that can be electrically chained in the same optical link.

1.2 Thesis Contributions

This work presents the development of a new online software utility, written in an object-oriented programming language, that controls the new T2 detectors. This tool integrates the communications between the PPS/TOTEM DAQ, applying automatically changes to the FSM and configuring them by a hardware level software that relies on an optical link library. The software tool is running in a Virtual Machine (VM) located within the CERN network and is accessible by an internet browser.

Chapter 2

Experimental Apparatus and Upgrades

2.1 Conseil Européen pour la Recherche Nucléaire

The Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research) more known for its acronym CERN, is a prestigious research centre established in 1954. With high-energy particle physics as its main area of research, it has large and complex particle accelerator facilities to perform breakthrough science. CERN's accelerator complex is shown in figure 2.1 where the different stages of the proton bunches being accelerated are described. Starting from the Linear Accelerator (LINAC 2) and going through the Proton Synchrotron Booster (PSB), the Proton Synchrotron (PS) and the Super Proton Synchrotron (SPS) until they are fed into the Large Hadron Collider, where they reach their maximal energy and are collided.

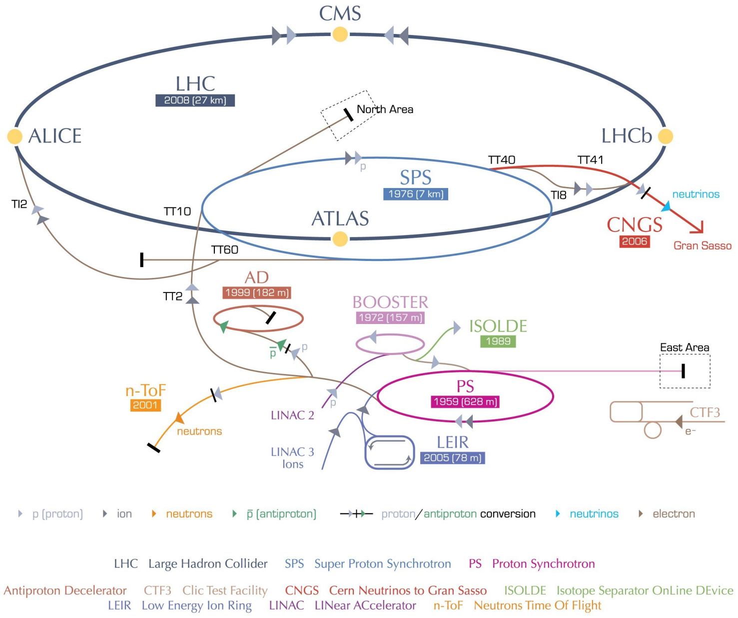


Figure 2.1: Scheme of CERN's accelerator facility. The figure is taken from Ref. [35]

2.2 Large Hadron Collider

The Large Hadron Collider (LHC) is the main accelerator at CERN and the most powerful particle accelerator till this day. LHC is a 27-kilometre long ring, composed of superconducting magnets. The beams inside the LHC, composed of protons or heavy ions, are accelerated in opposite directions in two separate vacuum tubes by applying opposite magnetic fields. The beams collide at four locations, where they share the same beam pipe and four particle detectors are installed: A Toroidal LHC ApparatuS (ATLAS), Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE) and Large Hadron Collider beauty (LHCb).

Preparing for run 3 and foreseeing the plan and necessities for High Luminosity LHC (HL-LHC) era in a few years, major upgrades have been performed to the LHC and to the four main detectors. A timeline for the plans and upgrades is shown in figure 2.2 .

Figure 2.2: LHC/HL-LHC Plan of upgrades. The figure is taken from Ref. [56]

2.3 The TOTal cross-section, Elastic scattering, and diffraction dissociation Measurement

The TOTal cross section, Elastic scattering and diffraction dissociation Measurement (TOTEM) [21] is one of the Large Hadron Collider (LHC) experiments. It has an extension of about 440 m and is located around the CMS interaction point (IP5). It was previously made of a set of different detectors that include two types of charged particle trackers (telescopes), known as T1 and T2, which were installed symmetrically in the CMS forward zone on either side of the IP5 at about 10.5 m and 13.5 m respectively. The third type of technology corresponds to the Roman Pots (RP) detectors, which were positioned symmetrically at about 200 m from the IP5. Figure 2.3 shows a scheme of the position of the TOTEM detectors with respect to CMS in the IP5.

The T2 detector needed upgrades to fit the new Beam Pipe at CMS. Therefore, the new T2 was designed and is under commissioning to be ready for Run 3, starting this year. For this run T1 will not be used, only T2 and the RPs. More details will be given in the following sections. Later in this section the complete description of the new T2 detector can be found and in section 2.4.2 details on the CMS beam pipe upgrade are given.

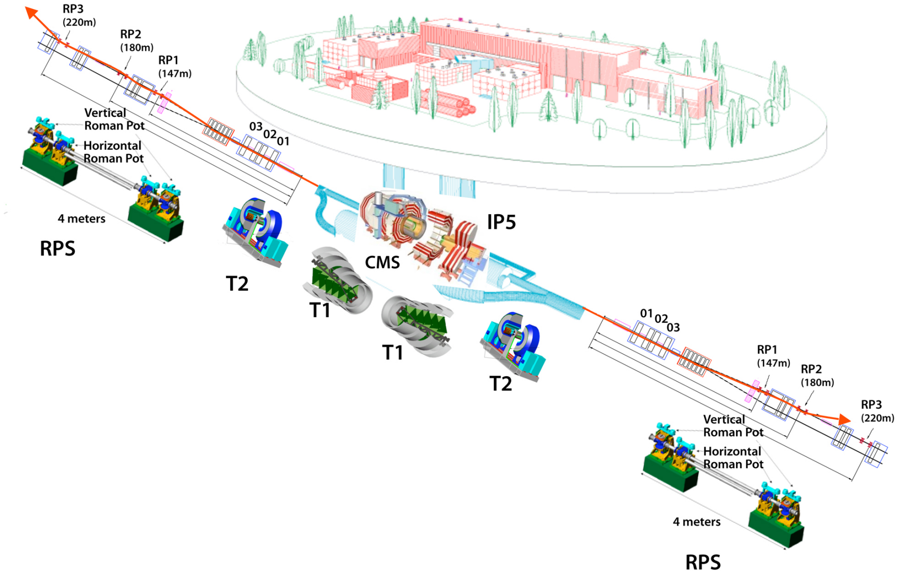


Figure 2.3: Schematic diagram of TOTEM's detectors. The figure is taken from Ref. [59].

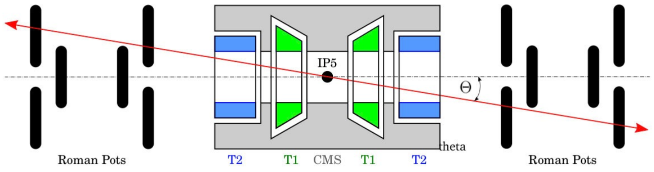
2.3.1 Physics Motivation

TOTEM is dedicated to the measurements of the total proton-proton cross-section and the study of elastic and diffractive proton-proton scattering at the Large Hadron Collider.

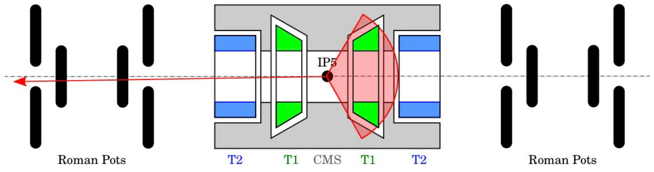
The inelastic events make the most contributions to the total cross section (σ_{TOT}), about 70%. However, the CMS detector only has a coverage of $|\eta| < 4.7$, which is why a complementary inelastic detector like the new T2 with an $\eta = 5.3 - 6.5$ range is really important as it will allow detection of about 90% of the inelastic events.

Interesting results have already been published: "Luminosity-independent measurements of total, elastic and inelastic cross-sections at $\sqrt{s} = 7$ TeV" [8], "Evidence for non-exponential elastic proton–proton differential cross-section at low |t| and $\sqrt{s} = 8$ TeV by TOTEM" [6], and "First measurement of elastic, inelastic and total cross-section at $\sqrt{s} = 13$ TeV by TOTEM and overview of cross-section data at LHC energies" [7]. However, there is still so much left to do in this area and future measurements are expected to be even more precise.

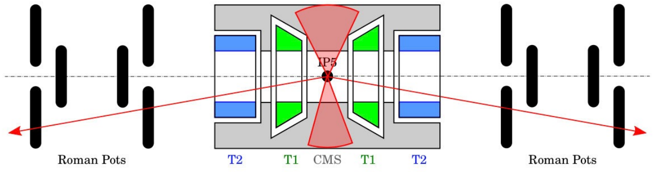
For the studies on elastic and diffractive physics, the TOTEM experiment is also important. Different scenarios are shown in Figure 2.4 and will be briefly described. In the first case (2.4 (a)), an elastic scattering occurs, leaving the protons intact and scattering in small angles, the protons can be identified by the Roman Pots. In the case of single diffraction (2.4 (b)), one proton can survive the collision and other particles are created, then the Roman Pots identify the remaining proton, and T2 detector (along with the CMS detector) identify the new particles. Lastly, in the case of central diffraction (2.4 (c)), both protons survive the collision but other particles are created as well, the protons are tagged by the Roman Pots and the rest of the particles by CMS.



(a) Elastic scattering.



(b) Single diffraction.



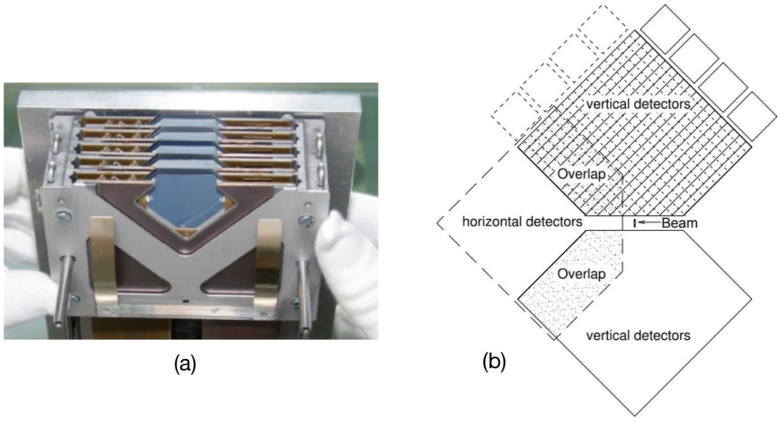
(c) Central diffraction

Figure 2.4: Schematic diagram of three types of measurement scenarios conducted by TOTEM. The figure is taken from Ref. [32].

2.3.2 Roman Pots

TOTEM's Roman Pots (RPs) are installed in the LHC sectors 45 and 56 beamlines, they are movable detectors able to approach up to $1.5mm$ to the LHC beam spot. The RPs are installed around 200m from the Compact Muon Solenoid (CMS) interaction point (IP5). The RPs are made with a special alloy vessel, able to avoid the beam radio-frequencies (RF) interferences and can house different type of detectors. TOTEM's RPs house the silicon microstrips (Si-Strips) tracking sensors. At the closest position of the beam, at the low boundary of the vessel, the RPs have a very thin window which must handle the secondary vacuum in respect to the LHC. Finally, the tracking measurements are translated in the momentum loss of the protons (ξ).

The Si-Strips detectors are conformed by 10 planes of edgeless silicon strip sensors, each plane is made up by 512 strips and have a pitch of 66 μm. Five of the planes are oriented at a $+45°$ angle and the other five at $-45°$ thus forming five "double-planes" as they are placed orthogonally back-to-back, a diagram showing this configuration can be observed in Fig. 2.5 along with a picture of the strip detector package.



(a) (b)

Figure 2.5: (a) Photograph of a strip detector package. The photograph is taken from Ref. [40]. (b) Scheme showing the overlap among the Roman Pot detectors. The vertical detectors correspond to the silicon strip detectors and the top detector shows the $+45°$ angle and $-45°$ angle orientations. The figure is taken from Ref. [48].

Further details on the strip detectors and their efficiencies can be found in refs. [40] [45] [26]

2.3.3 New T2

Previously, TOTEM's Telescope 2 (T2) was located at 13.5m from the CMS IP5, covered the region $5.3 < \eta < 6.5$ and used Gas Electron Multiplier (GEM) technology.

As previously mentioned, the T2 detector is part of the TOTEM experiment and upgrades were needed in order to fit the new CMS beam pipe. The design and technology employed for the new T2 telescope, which will be used from Run 3 operations on, is different from the previous one and is described in the following lines.

Detector Description

The new T2 detector had to be updated in order to fit with the new Beam Pipe at CMS, its position within the CMS forward zone is surrounding the pipe, therefore a completely new detector was created.

The new detector set will be located symmetrically in the forward zone at about 15 m from the CMS interaction point, as shown in Fig. 2.6, where the beam pipe diameter is 78 mm beam, with a length of 200 mm. Like the previous version, the new T2 detector will perform measurements in the pseudorapidity range $\eta = 5.3 - 6.5$ and will be divided in two T2 quarters, which are the basic units.

An important condition to analyze is the radiation the detector will receive. According to the calculations and simulations for the radiation environment in the new T2 region, the expected

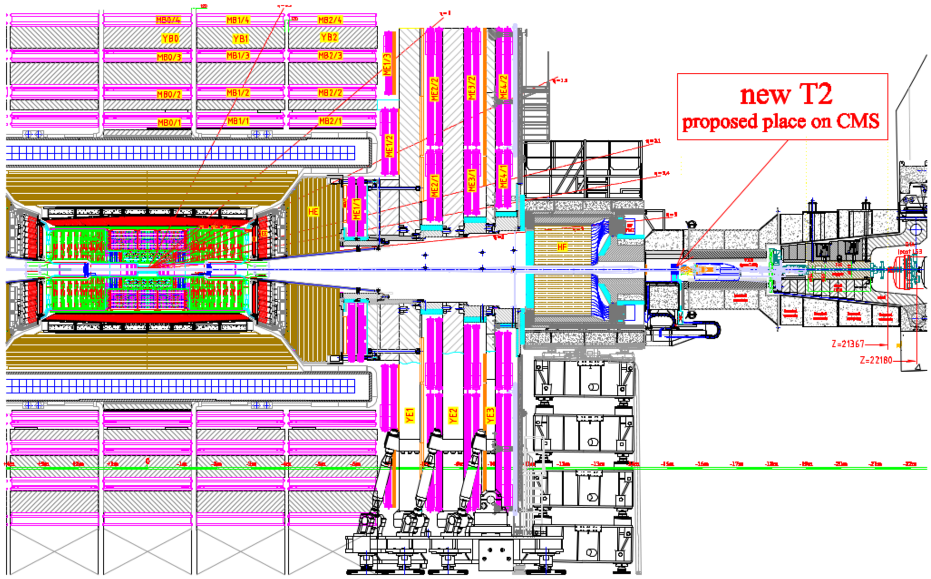


Figure 2.6: Longitudinal section scheme showing the proposed new T2 detector location in the the CMS experiment. The figure is taken from Ref. [60].

radiation dose that could be absorbed during the data-taking at low luminosity is considerably small and is not significant for the detector performance.

Scintillators

As previously mentioned, each new T2 Telescope is made up of two quarters and each of them are made up of four planes of segmented 2cm thick plastic scintillator, which is expected to be supplied by Protvino or Bicron [36]. A plane is conformed by eight segments or counters and in order to ensure hermiticity they overlap by 10 mm.

The light from the scintillator is collected by a green wavelength shifter (WLS) and is later sent through clear optical fibers (1 mm diameter) to the SiPm which will read it. The SiPm is located in a less irradiated region along with the frontend electronics. The frontend electronics will be described in the section 3.1, but basically the SiPM are sitting in a mezzanine PCB board which is connected to the frontend board called Digitizer Board.

Installation

The detector is located in the CMS forward zone, it will be around the beam pipe and at about z=15m its diameter is 78 mm. The new T2 will be installed on the Centauro And STrange Object Research (CASTOR) [58] table, which will act as its support.

One of the most important aspects for the new detector is a fast installation and dis-installation, in order to do so the new T2 with the layout previously explained was designed. Being a light detector, about 10 kg, on sliding rails it is possible to meet the requirements as there is no need for cranes to complete this process (as shown in Fig. 2.8).

Further details on the new T2 detector and its systems can be found in the Upgrade of the TOTEM T2 Telescope Technical Design Report [60].

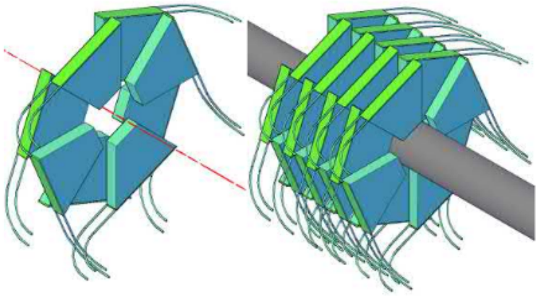


Figure 2.7: Scheme of the new T2 single plane of scintillators (left) and the set of scintillators around the beam pipe (right). The figure is taken from Ref. [60].

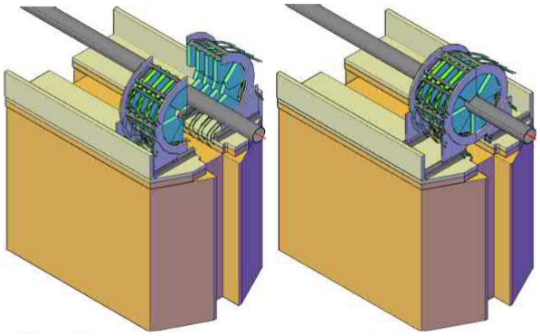


Figure 2.8: Scheme of the new T2 detector in its open and closed positions. The figure is taken from Ref. [60].

2.3.4 Data Acquisition System

TOTEM's trigger [32] possess a tree structure which can be divided in two, the detector and the counting room sides. In the detector side are included all the electronic systems which are installed along the detectors or in in a region close to them. On another hand, the counting room side is in a CMS Underground Service Cavern (USC-S2) which is where the filtered data from the detectors is received and assessed. Figure 2.9 shows the structure of TOTEM's trigger, signaling the main components and how the data flows throughout the system.

The main elements that make up TOTEM's trigger (Figure 2.9) are described as follows:

- The **Very Forward Atlas and TOTEM (VFAT)** chips receive the signals from the detectors, which is then discriminated and digitized.
- The **Coincidence Chip (CC)** was designed and is used for the trigger system designed for the RPs and T2 detectors to inspect, as suggested by its name, the coincidence of signals generated in the constituent planes of each of the detectors. If a certain number of coincident active areas in the planes are found then the signal is transmitted.
- The **Giga Optical Hybrid (GOH)** is a radiation hard module and is employed to serialize (translate the data to a format in which it can be stored) and transmit the data through an optical link to the USC.

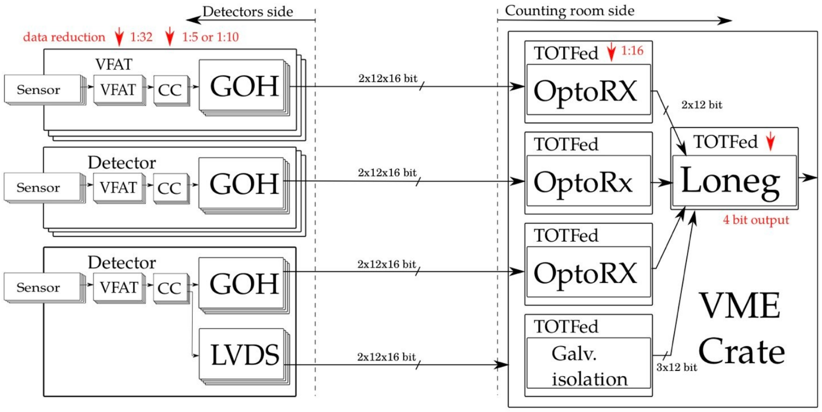


Figure 2.9: Scheme showing the structure of the TOTEM trigger. The figure is taken from Ref. [32].

- The **OptoRX** is a mezzanine that receives the optical data from the GOH modules.
- The **Level ONe triggEr Generator (LONEG)** is the final TOTEM trigger stage. It receives and processes the information from the OptoRX mezzanines (through the TOTFed) to generate the TOTEM L1 trigger.

The LONEG software is linked to the CMS L1 trigger. It is capable of exchanging information and performing an offline merging in desired scenarios. For the generation of the L1 signal for CMS, only the information from the TOTEM components is used. In addition, a L1 Special Algorithm (L1SA) is generated through a combination of the TOTEM and CMS data. In this case, only the events that meet the requirements for the common physics interests of both experiments make the selection cut. Furthermore, the TOTEM L1 trigger is generated by combining the signals from the TOTEM detectors, the L1SA and the CMS L1.

Having the TOTEM trigger integrated with the CMS trigger allows to make decisions based on the information collected by both detectors, as well as to unify the data.

The TOTEM DAQ has been totally integrated with the CMS environment. This system controls the vertical Si-Strips, which are still used for the PPS alignment runs and also accommodates the timing detectors readout. The new T2 detectors will be attached to the very same DAQ.

The CMS DAQ system relies on software tools for communication to configure the detector Finite State Machines (FSM). These FSMs are states, such as halt, configure, start or stop that have their transitions well defined to prepare the detectors for the read-out. The communication between central DAQ (CMS) and its subsystems is linked with a scalable software framework called XDAQ within an exchange of SOAP commands.

new T2 DAQ and Trigger

A software tool has been developed for the control and configuration of the detector based on a CMS online C++ framework. This development will be described in chapter 3 and 4. Moreover, the TOTEM trigger [32] interconnects the information acquired by the RPs and the T2. The new detector will follow the former system with an update on its firmware. Figure 2.10 shows a the block diagram of the detectors data flow.

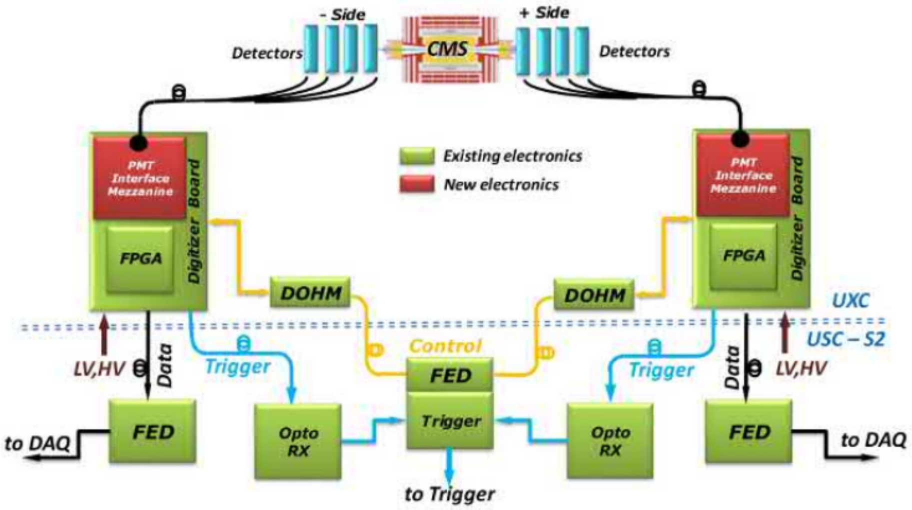


Figure 2.10: Scheme showing the electronic chain that the two new T2 quarters follow. The figure is taken from Ref. [60] .

2.4 Compact Muon Solenoid

The Compact Muon Solenoid (CMS)[3] is a general-purpose detector designed to probe physics spanning energy ranges up to several TeV. The main body of the detector is a multi-layer cylinder 21 m long and 15 m in diameter, with a total weight of 14,000 tons. Figure 2.11 shows a general overview of the design of the detector.

2.4.1 Detector description

CMS consists of a silicon tracker, an electromagnetic calorimeter (ECAL), a hadron calorimeter (HCAL), a superconducting solenoid and a muon spectrometer.

The components are described as follows:

- **Tracker** [31]. Composed of pixel and strip detectors, it reconstructs the trajectories of charged particles.
- **ECAL** [53]. Calorimeter made of lead tungstate crystals that is able to provide track measurements of electrons and photons.
- **HCAL** [54]. Set of sampling calorimeters designed to measure the energy of the hadrons.
- **Superconducting Solenoid** [55]. Has an internal diameter of 6m and is 13 m long, provides a 4T magnetic field
- **Muon Spectrometer** [33]. Constituted of Drift Tubes (DTs), Resistive Plate Chambers (RPCs), Cathode Strip Chambers (CSCs) and the more recently added Gas Electron Multiplier (GEM) detectors, that are able to measure muon tracks.

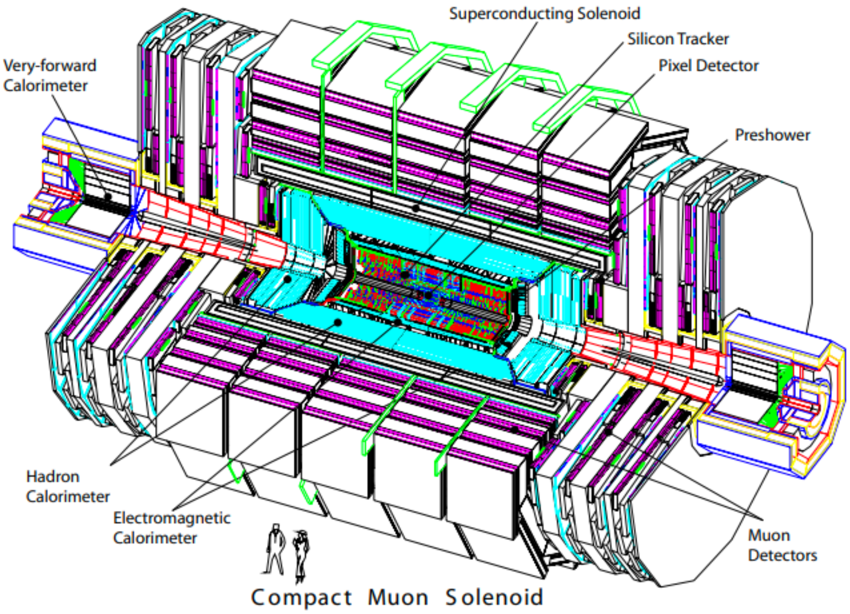


Figure 2.11: Overview of the Compact Muon Solenoid's detector structure. Its most relevant components are highlighted and a comparison of average people with respect to the detector for a better comprehension of the size of the experiment are shown. The figure is taken from Ref. [3].

As previously mentioned, the Precision Proton Spectrometer (PPS) collaboration was created by CMS and TOTEM, proposing a physics program that extended CMS acceptances for tagging scattered protons and measuring central exclusive processes. Hence, PPS is a sub-system of the CMS experiment and will be later described in this section.

Given the technologies previously described, the CMS experiment is able to identify different particles and their tracks successfully. Fig. 2.12 shows a diagram of where the muons, electrons, charged hadrons, neutral hadrons, and photons are tagged and have their tracks reconstructed on the different components of the CMS detector.

An overview of the CMS coordinate system is given in Appendix A

2.4.2 Upgrades

During the Long Shutdown 2 (LS2), that had been going on since 2019 and finished at the beginning of 2022, there have been various improvements done to the detectors that make up the CMS experiment following the requirements for Run 3. The main upgrades to the CMS systems will be discussed in this section.

Hadron Calorimeter

The Hadron Calorimeter is made up of a Barrel (HB), endcap (HE), Outer (HO), and Forward (HF) sections. The main upgrade performed on the HB, HE and HO was the replacement of the hybrid photodiodes (HPDs) with new silicon photomultipliers (SiPMs). The SiPMs have higher photon detection efficiency and gain, as well as recovery time of about 10 ns. Regarding the forward calorimeter, the photomultiplier tubes (PMTs) were upgraded to models that possess thinner optical windows and multi-anode outputs [47].

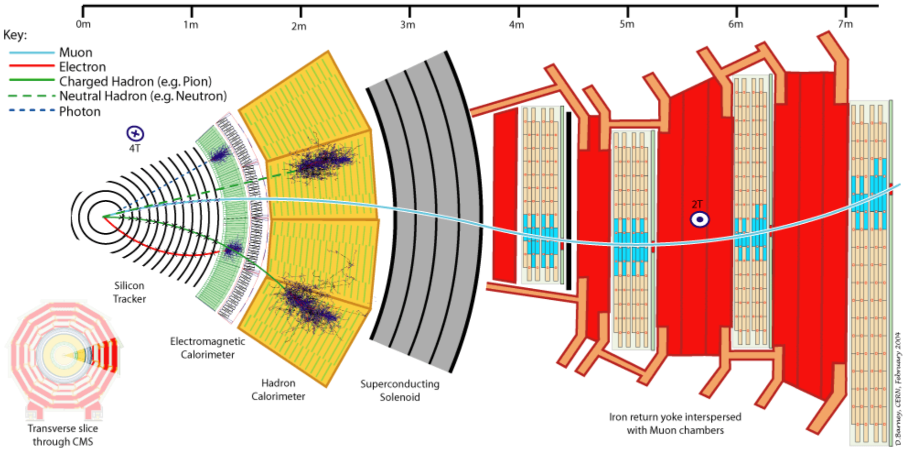


Figure 2.12: CMS cross-sectional distribution The figure is taken from Ref.

In order to read data from the new detectors, the front-end electronics were upgraded, where a high precision timing readout was included. The back-end electronics were upgraded as well, and are now based on commercial FPGAs, to process the readout of the front-end.

Electromagnetic Calorimeter

The electromagnetic calorimeter (ECAL) consists of lead tungstate crystals that absorb about 98% of the energy and make the tracking of electrons and photons possible. The detector is divided into a Barrel (EB), Endcaps (EE), and preshower (ES). The ECAL Detector Control System (DCS) software is responsible for the supervision of the interaction between the subsystems. During the LS2, migration of software was performed and upgrades [30] were implemented. In particular, the WinCC OA and JCOP control framework, the OPC UA, the control system, and the notification system were updated and are ready for Run 3 data-taking period.

Muon system

CMS muon spectrometer is made of different technologies, Drift Tubes (DTs), Resistive Plate Chambers (RPCs), Cathode Strip Chambers (CSCs) and more recently GEM detectors were added.

Double-layer triple-Gas Electron Multiplier (GEM) detectors [1], were installed in GE1/1 station in the innermost ring of the first muon station in the endcap, in the η region: $1.6 < |\eta| < 2.1$. This station is aimed to improve the momentum resolution, as the muon direction will be measured by hit positions obtained from the GEM GE1/1 and CSC ME1/1 chambers that are located in the same η.

Pixel Detector

The pixel detector is located in the innermost section of CMS experiment [3] and was mainly upgraded as part of the Phase-1 upgrade during the Long Shutdown 1 (LS1) [24]. The detector is composed of 1856 segmented silicon sensor modules, 1184 in the barrel pixel detector (BPIX) and 672 modules in the forward disks (FPIX) [2].

The barrel pixel detector is divided in four barrel layers, where the innermost (L1) is the layer that receives the highest radiation [38]. During the Long Shutdown 2, a new L1 layer was installed in order to extend the detector's lifetime and performance.

On the other hand, the pixel detector uses DC-DC converters to provide the necessary current to the modules [2] and some challenges have presented since 2017. To address the problems, during the LS2 all converters were replaced with the latest version of the FEAST ASIC[15].

CMS beam pipe

A new beam pipe[5] was designed and installed during LS2 on the Interaction Point 5, being the biggest upgrade performed to the system. The central chamber of the cylindrical section has an aperture of 43.4 m and it is extended from 1.6 m to 3.1 m from both sides, in order to ensure compatibility with the expected Phase-2 tracker.

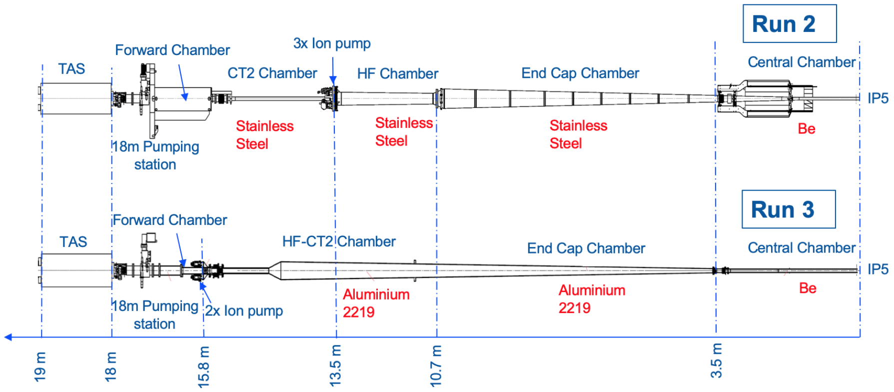


Figure 2.13: CMS vacuum chamber distribution schemes for run 2 and run 3. The figure is taken from Ref. [5]

Near beam and Forward Systems

The Beam Radiation, Instrumentation and Luminosity (BRIL) group installed the Beam Condition Monitor Fast (BCM1F), the Beam Condition Monitor for Losses (BCM1L) and the Pixel Luminosity Telescope (PLT) [52]. These instruments make up the BRIL sub-system and its purpose is to measure the luminosity and beam conditions.

2.4.3 Data Acquisition System

The proton-proton collisions at the Large Hadron Collider happen every 25 ns with an average bunch crossing rate of 40MHz. However, not all the events are recorded. Only a small amount of them that contribute to the CMS physics interests are selected and the data acquisition rate is greatly reduced. In order to select the most relevant and interesting events CMS conducts a process through its two-level trigger system.

Level 1 Trigger

The level 1 (L1) trigger [51] is made up by sophisticated hardware that conducts the first selection from the raw data taken. This level has only 4 μs, its latency is fixed, to decide if an event is accepted or not. Given this tight processing time it is not possible to do full reconstructions. However, candidate objects with low resolution are reconstructed from the calorimeters (electrons, photons, jets, τ leptons and missing transverse energy candidates) and the muon system (muon candidates). The outputs of both systems are then transferred and interlinked in the global trigger where the final selection at this level is made, with an event rate up to 100kHz, based on the trigger menu that takes the kinematics into consideration.

High Level Trigger

The high level trigger (HLT) [17] is the second level of the system and is executed by a software computing farm which hosts thousands of cores, about 32000, that reduce the trigger rate to about 1kHz. The HLT receives the event selection from the L1 and is able to conduct a more sophisticated reconstruction, it is asynchronous (unlike L1T) and similar to the offline reconstruction.

Although before the HLT is able to receive the data, it first has to go through the event building system that is made up of Readout Units (RU) and Builder Units (BU). These units are dedicated to collect the data from the FEDs, build it completely for each collision and finally send it into the HLT where further selections and processing are made through its Filter Units (FU).

After all the selections are made, the events are stored in the Tier-0 tapes at CERN were they can be reconstructed and studied.

A more detailed description on the CMS trigger system can be found in Ref. [23]. The upgrades implemented for run 3 and the forthcoming changes scheduled for this system are described in Refs. [22] [57]

Detector readout

Each subsystem utilizes its own custom hardware to obtain the readout of their corresponding detectors once the L1 trigger has completed the selection of events. A description on the readout system for the new T2 detector will be presented in the next sections.

Online software framework

The communication between central DAQ (CMS) and its subsystems is linked with a scalable online software framework called XDAQ. XDAQ[19] is a middleware, software that enables a bridge of communication between two or more applications or services in a distributed network. It was designed and developed at CERN to serve as a platform for the development of distributed data acquisition systems. XDAQ has all the data-flow applications, as well as the subsystem readouts, implemented in its framework.

2.4.4 Precision Proton Spectrometer

The Precision Proton Spectrometer (PPS)[4] is a sub-system of the Compact Muon Solenoid (CMS) experiment, which has been designed for measuring scattered protons. Historically, PPS was originated as a joint project between CMS[3] and TOTal Elastic and diffractive cross section Measurement (TOTEM)[10] Collaborations.

PPS is made of set of mechanical near-beam movable units, which house tracking[39] or timing[12] detectors sealed under a secondary vacuum in respect to the LHC primary vacuum. In the literature, this type of detectors are known as Roman-Pots (RPs). PPS RP detectors are symmetrically installed in stations along the LHC beam pipe at about 200m from the CMS Interaction Point (IP5), as shown in Figure 2.14.

Detector description and upgrades

As previously mentioned, PPS is made of a set of mechanical near-beam movable units known as Roman-Pots (RPs) which are sealed under a secondary vacuum, in order to avoid any possible contamination in the primary vacuum. Two units, near and far, make up a Roman Pot station.

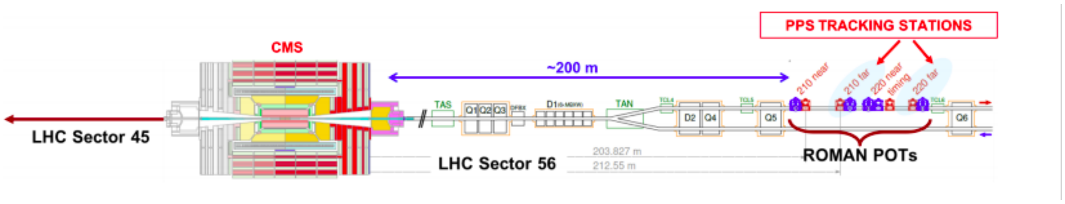


Figure 2.14: Schematic diagram of one of the LHC sectors where PPS is installed. The timing station is placed between two tracking stations. The figure is taken from Ref.[12].

A Roman Pot unit is formed by three RPs: top vertical, bottom vertical and horizontal. A photograph of the unit with its elements signaled is shown in Fig. 2.15

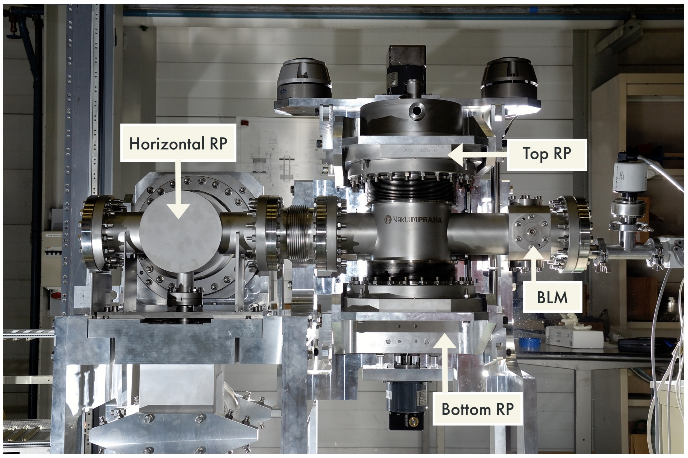


Figure 2.15: Photograph of the Roman Pot unit [13] before installation, the three RPs are signaled as well as the Beam Loss Monitor (BLM).

The Roman Pots host different types of detectors. In LHC's Run 2, PPS operated for the first time commissioned with different technologies for tracking (CMS 3D pixels and micro-strips) used for proton kinematics measurements, and timing (artificial single-crystal diamonds - scCVD and Ultra Fast Silicon Detectors - UFSD), for pile-up rejection.

Tracking system

The PPS tracking system is the one responsible of measuring the interested protons' position and direction.

PPS intended to start its operations in 2017 but they ended up starting a year early in 2016. At the start of operations, given that the pixel sensors were not available at the time, TOTEM's Si-Strips detectors were used. However, the Si-Strips could not endure very well the radiation they were exposed to and were not able to identify multiple tracks, which is particularly important when there are high pile-up conditions. Nonetheless, as previously mentioned this technology is still used in the vertical RPs that only operate during the alignment or during special low luminosity runs.

▷ 3D Pixels

Throughout the years the strips on the horizontal detectors were replaced by 3D pixel sensors in the horizontal RPs, as these RPs are the ones used in high luminosity runs, and is the technology that will continue to be used in Run 3. Fig. 2.16 shows the changes to the system from the first installation to the latest upgrade performed to this system.

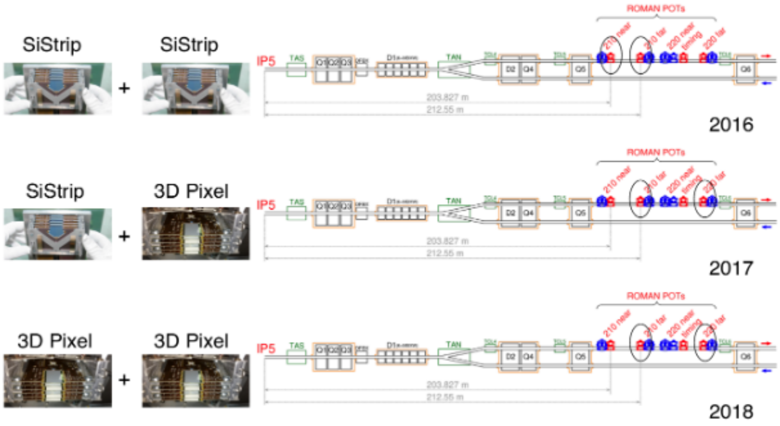


Figure 2.16: Scheme showing the upgrade to the horizontal tracking detectors from 2016 to 2018 and the different technologies used (3D Pixels and Silicon Strips). The figure is taken from Ref. [18].

The tracking reconstruction is performed using the hits identified in at least three of the six planes that make up the detector package. For Run 2, the 3D pixel sensors used were built into a 230μm thick wafer, columns with 200μm depth and a diameter of 10μm [40]. They had a pixel size of 100 x 150 μm^2 and there were two configurations, one and two readout columns.

The 3D pixel sensors where chosen as the main technology for tracking due to their radiation hardness and the prospect to minimize the insensitive edge area by implementing slim edges [42]. In the present detector the slim edges are 200μm and could be reduced to $\sim$ 50μm. A further detailed description of the 3D Pixel detectors can be found in refs. [46, 44].

The radiation is non-uniform in PPS and although it presented a reduction of the detection capability in a small area most of the detector worked correctly and had a high average efficiency [25].

In Run 2 the main issue was due to the radiation exposure of the PSI46 electronic chip, the problem was mitigated by vertically moving the detectors inside the Roman Pots. To address this issue, for Run 3 new 3D pixel sensors equipped with read out chip PROC600 [50] will be installed in all the tracking stations, along with a system of motors that allow the pixel detectors to be vertically moved remotely [20]. The readout and control of the PPS 3D pixels are based on the CMS Phase-1 Pixels, which relies on μTCA electronics.

Further details on the proton reconstruction process performed with the PPS detector can be found in Ref. [27]

Timing system

For the timing system two detector technologies have been used for pile-up rejection: artificial single-crystal diamonds (scCVD) and Ultra Fast Silicon Detectors (UFSD). The pile-up rejection is important as the Precision Proton Spectrometer has to operate in a high luminosity environment with up to 60 pile-up interactions per bunch crossing. This system allows PPS to correlate the protons measured with the vertex CMS reconstructed.

▷ UFSD

The Ultra Fast Silicon Detectors (UFSD) [9] are $50\mu m$ thick, have an active surface of 12x6 mm^2 and are organized in 16 columns and 2 rows of pixels.
The UFSDs were expected to have a time resolution of $\sim$ 35 ps [16] and were used during Run 2 but given that radiation hardness is an issue this technology will not be used for Run 3, although more tests are in progress and possible solutions are being explored.

▷ Diamond detectors

The PPS diamond sensors are made of artificial single-crystal diamonds (scCVD) with a surface of of 4.5x4.5 mm^2 and a thickness of 500 µm, with a total active surface coverage $\sim 20x4.5mm^2$

For Run 2 a Single Diamond architecture (SD) was used and then a Double Diamond (DD) architecture was developed. DDs replaced some of the previous detectors in 2018, this architecture is shown in figure 2.17 and was expected to have a better performance [11].

Diamond detectors were used to collect data in 2016. In 2017 diamond detectors were used along with Ultra Fast Silicon Detectors (UFSDs), each timing station contains a set of four planes of detectors and during this year three of them consisted of diamonds and one of UFSDs. In 2018 diamond detectors were used and it has been confirmed that they will continue to be used for Run 3. These detectors possess radiation hardness and will be able to resist the determined conditions in PPS.

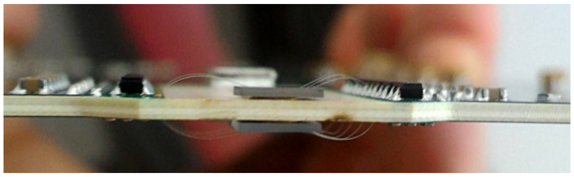


Figure 2.17: A picture of the DD sensor in a lateral view is presented, the diamond crystals are glued on both sides of the hybrid board which allows to double the signal. The figure is taken from Ref. [11]

Furthermore, in order to get a resolution a new hybrid board has been constructed and is being evaluated for its use in Run 3 [12]. Other upgrades include a remote LV control, a new discriminator, the implementation of a parallel independent readout, the installation of DD layers for each of the four planes in all stations, as well as the installation of a second timing Roman Pot in each sector.

Finally, the whole Precision Proton Spectrometer's readout is fully integrated with CMS for common data-taking. For such purposes, a set of software tools have been developed in order to control, configure and prepare the detector finite state machines (FSMs), based on a CMS online C++ framework, named XDAQ [14].

As mentioned before, PPS has been designed for measuring scattered protons. Protons can be scattered during the collisions but are contained inside the beam pipe and can be measured with technology located in the forward zone, the RP detectors which are symmetrically installed in stations along the LHC beam pipe.

Central Exclusive Production

The main physics interest in PPS is the study of the central exclusive production (CEP) processes ($pp \rightarrow p \oplus X \oplus p$). In this scenario the protons may remain intact, PPS is able to measure their kinematics, and the CMS detector can identify the X state in hard scattering events. These processes can be driven by colourless exchanges, a photon-photon interaction or double Pomeron. A diagram for these CEP processes is illustrated in fig 2.18

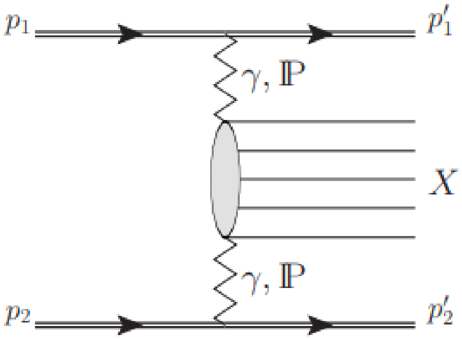


Figure 2.18: Diagram for the central exclusive production, $pp \rightarrow p \oplus X \oplus p$, which is characterized by large pseudorapidity gaps ($\oplus$). The figure is taken from Ref. [20]

Relevant results in this area of study using the Precision Proton Spectrometer have been published. In particular an analysis performed using the first set of PPS data, the “Observation of proton-tagged, central (semi)exclusive production of high-mass lepton pairs in pp collisions at 13 TeV with the CMS–TOTEM precision proton spectrometer” [49].

More recently, the "First search for exclusive diphoton production at high mass with tagged protons in proton-proton collisions at $\sqrt{s} = 13$ TeV" has also been published [61].

Moreover, the detectors that make up PPS use to good advantage their location at a very forward region due to its acceptance, and provide important insight on relevant physics topics such as:

- Measuring high masses exotic states produced via gamma-gamma interactions, due to the large suppression of quark-gluon (qg) and/or gluon-gluon (gg) cross-sections.
- Measuring Anomalous Quartic Gauge Couplings (AQGCs) in Beyond Standard Model (BSM) Physics.
- Measuring emerging intact protons from colourless exchanges with small momentum loss ($\xi = \triangle p/p$ between 2 and 10%) and providing data for forward physics processes.
- Monitoring the LHC beam optics and stability, as well as providing feedback for the LHC teams operations.

A detailed description on these and other equally interesting research topics can be found in Ref. [20]

Chapter 3

Electronics and Online System

The Finite State Machines (FSMs) of the CMS subsystems are controlled by a scalable software framework, which is able to broadcast states for all the CMS subsystems using SOAP commands [62]. The XDAQ tool enables connectivity and communication between different applications layers distributed in all the CMS data acquisition online network.

This thesis started from the project developed for the "CERN Summer Student Programme 2021" [34] and later evolved to the present work. The aim of this thesis was the development of a new online software utility, written in an object-oriented programming language which is able to control a new mezzanine (new T2's mezzanine) designed for the TOTEM frontend board through a slow control optical link [41].

Despite the new T2 being part of the TOTEM experiment, as described previously, the TOTEM DAQ is already fully integrated with the CMS environment. Thus, the new T2 detectors FSM transitions are controlled by the CMS DAQ. Finally, the new T2 data packet is sent out upstream to CMS DAQ infrastructure.

3.0.1 Slow Control

The slow control [41] has been used within the CMS collaboration since the beginning of Run 1, relying on the CCU25 as its main component, a radiation hardness communication ASIC, that distributes a token ring for all the front-end boards that can be electrically chained in the same optical link. TOTEM also did a customized slow-control system based on the same ASIC.

The slow control configures the system and distributes its commands. It also relies on the Front-End-Controller (FEC) boards which are located in the Underground Service Cavern (USC). These boards have optical fibers that convert the signals to electrical ones through a Digital Opto Hybrid module (DOHM). A ring can be conformed by various Communication and Control Units (CCUs).

3.1 Hardware

3.1.1 Digitizer Board

Part of the new T2 DAQ sub-system uses the CCU25 token ring to configure the field programmable gate arrays (FPGAs) soldered in a specific designed front-end board, named Digitizer Board, figure 3.1 shows a picture of the board developed and currently used. The Digitizer board is an interface card hosting a Microsemi SmartFusion2 M2S150-FC1152 FPGA which codes 32-bit word packets and delivers data upstream CMS DAQ with a 40 MHz clock synchronization.

The Field Programmable Gate Array (FPGA) is a semiconductor device, composed of configurable logic blocks (CLBs) arranged in a matrix, that can be reprogrammed after its manufacturing. The FPGAs utilized in the new T2 system are based on the SmartFusion2 ASIC and are able to link the input data with the output data section.

The I^{2}C lines of the FPGAs are distributing commands for the embedded devices, such as phase lock loop (QPLL) or Giga Optical Hybrids (GOH), while the JTAG lines are specifically used for the read-out ASICs communication. Finally, for the back-end side, the slow control ring is interfacing a Front-End Control (FEC) board based on the VME standards. Due to its adaptability allowing customized mezzanines hosting different read-out ASICs, the digitizer board has been used in PPS (and TOTEM) for different data-taking layouts.

Moreover, in the case of the New T2 detector the mezzanine developed is set to receive the light signals from the scintillator, which are then digitized and transferred to the counting room by the digitizer board through the Gigabit Optical Hybrids (GOH) or the Pixel Optical Hybrids (POH) links.

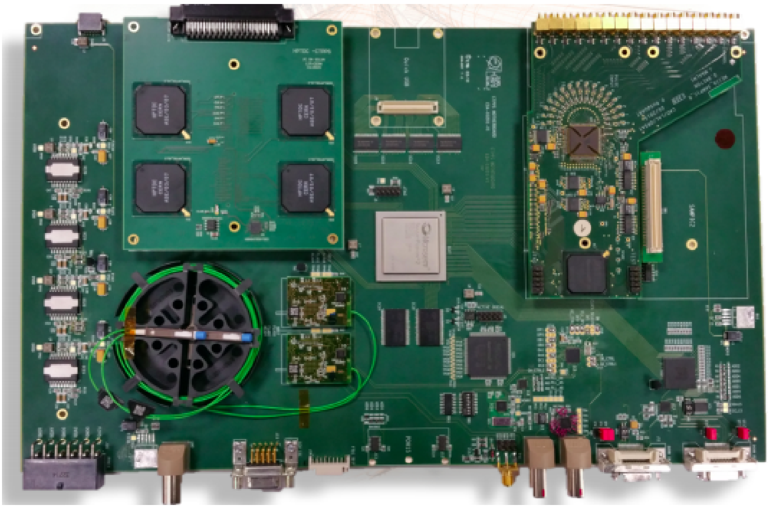


Figure 3.1: Digitizer board hosting a Microsemi SmartFusion2 FPGA in the center, two mezzanine slots and GOH connector, CCU25 ASIC, LHC clock and trigger inputs. The system features a remote FPGA firmware upgrade by optical links (Credit: G. Antchev).

In order to have a deep understanding of the elements and how they are related, a description of the basic blocks is presented.

QPLL. The Quartz crystal Phase Locked Loop (QPLL) is based on the PLL25 chip that administers clock and commands to every board component synchronously.

GOH. The Giga Optical Hybrid (GOH) is a module employed to serialize (translate the data to a format in which it can be stored) and transmit the data through an optical link to the USC.

JTAG lines. The Joint Test Action Group (JTAG) lines are used for the read-out ASICs communication.

3.2 Setup for Testing and Validation

In the scope of this project, Figure 3.2 is showing a scheme of the setup mounted at CERN for the new T2 mezzanine software development: a computer is interfacing the VME crate controller, where the FEC board is placed. From the FEC board mezzanine (i.e. ring 1 to 12) an optical link is connected to an optical to electrical converter (DOHM), which can interconnect in a control loop multiple front-end boards. The computer is interfacing the VME controller (Optical Link Bridge, V3718) by a PCI CONET board (A2818).

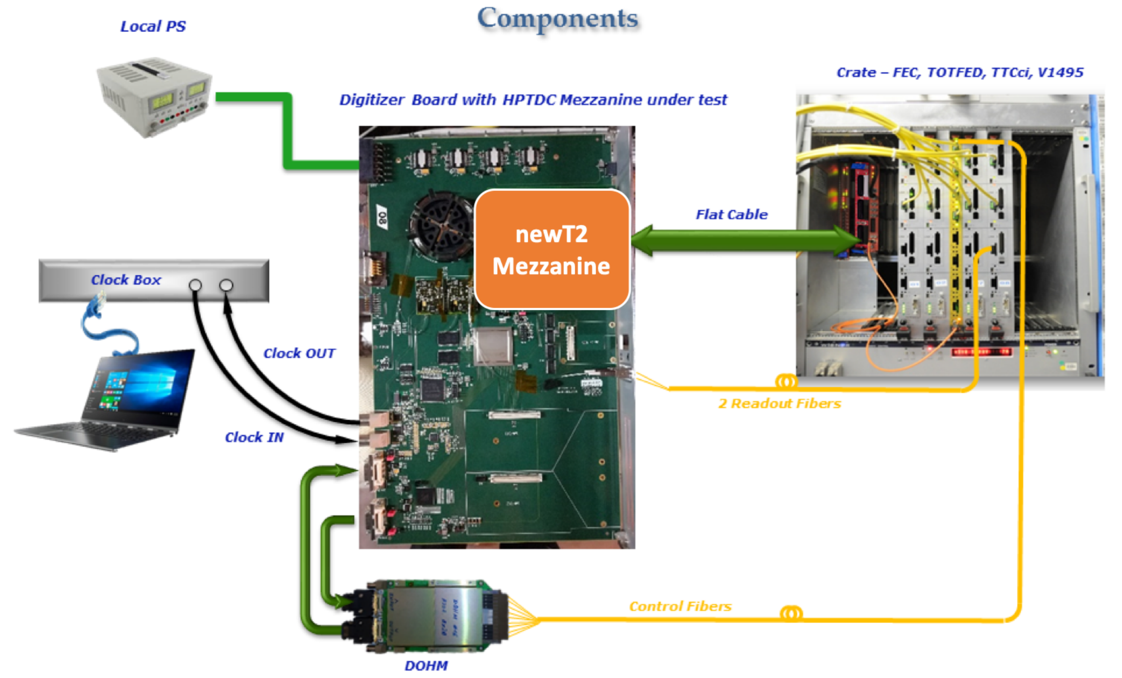


Figure 3.2: Scheme of the batch setup for the new T2 software development. The digitizer board is hosting the new T2 mezzanine. The digitizer board is controlled through the slow control (an optical link between the FEC VME backend and the DOHM). The commands are sent by a computer to the VME crate controller (Credit: G. Antchev).

A brief description of the components shown is presented:

DOHM. As previously mentioned, the Digital Opto Hybrid module (DOHM) is an optical to electrical converter able to interconnect in a control loop multiple front-end boards.

Local PS. Local Power Supply (Local PS).

FEC. The Front-End Controller (FEC) is a board located in the Underground Service Cavern (USC) that transmits the slow control instructions and fast commands.

TOTFED. The TOTEM Front EnD (TOTFED) board is a plug-in card. It has FPGA chips installed in its host board, some are destined for the optoRX mezzanines (Mains) and one is used as a "merger". It collects the frontend data and propagates it to the Level ONe trigger Generator (LONEG).

TTCci Timing, Trigger and Control CMS interface (TTCci) acts as a link between the trigger controller and TTC targets.

Moreover, a great accomplishment was made by the TOTEM collaboration by setting up the new T2 detector Readout Box in the radiation protected (RP) area in CMS, which is shown in Fig. 3.3. In this zone the system can always be powered up and stay non-attended given that the infrastructure against fire and other safety requirements are met. Work can be done remotely, providing flexibility for testing and debugging, and colleagues from outside CERN site are then able to collaborate in the hardware.

Figure 3.3: new T2 detector Readout Box.

3.3 Control Software

The design of the control software is based on two layers. The first layer is the interface library between the hardware and the back-end. This library has the methods to create the slow control objects as well as the methods for reading or writing in specific registers, when provided the CCU25 address and I^2C channels. Furthermore, in that layer the sequence algorithm for configuring specific embedded devices (readout ASICs, QPLL, GOH, etc.) are hard-coded. The second top layer is made to translate the CMS DAQ commands into FSM changes in the detector. In the same layer, there is a command-line used for debugging and testing the hardware library methods, as shown in Figure 3.4.

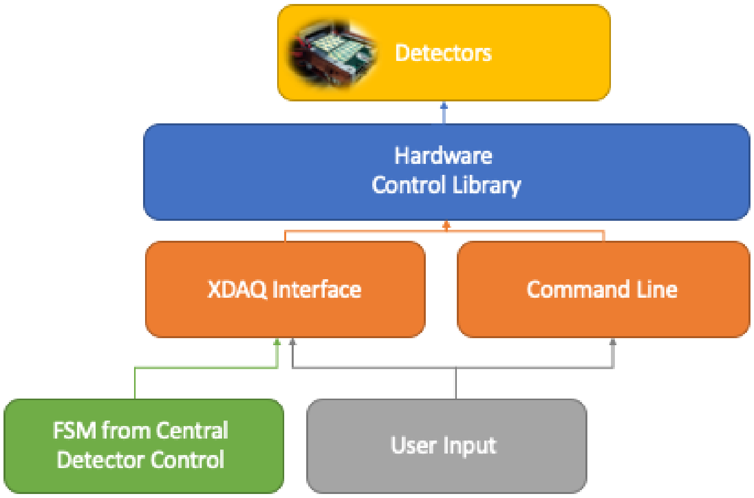


Figure 3.4: Scheme of the PPS control software: a user can send direct commands to the hardware using buttons (XDAQ) or thought command line. In addition, the software receives SOAP commands from the CMS DAQ shifter. Another layer of the software, is the interface between the computer and the detector (hardware library) using the slow control protocol.

3.4 Virtual Machine Configuration

The first approach for this project was based on the configuration of a virtual machine (VM), in which all the XDAQ dependencies libraries and packages were installed on Cent OS 7 unix system. The new T2 software[43] mimics a validated control software used during Run 2 operations. The configured VM has been accessible through a terminal, by a local CERN network connection[1].

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[1] Secure Shell (SSH) connection to lxplus.cern.ch

Chapter 4

Control Software for new T2

The new T2 software has been made to control and configure the digitizer board frontend and its integrated circuits (ICs), thus to prepare the detector for data acquisition. The control software made receives FSM transitions from central DAQ (CMS) which automatically set the detector. The digitizer board, as mentioned before, has a FPGA in which the software communicates. All the instructions built at the firmware level are sent by the slow control library. Furthermore, the software is made of two layers: a layer for the hardware access and a top layer for the user interface. The aim of this project was the development of a new online software utility, able to control a new design mezzanine for the TOTEM experiment.

The main task performed for the project was focused on programming in C++ language and testing the software remotely with a setup mounted at CERN. In the first part of the project, it has been experienced some command line tools to get feedback from the hardware actions, and later on, the development of the top-layer software.

The application developed, as a first step of this project, allowed parsing the ccu, ring and slot addresses by the command line (see Fig. 4.7), as well as parsing them from a JavaScript Object Notation (JSON) file. The mentioned addresses are needed in order to perform any action in appropriate format, otherwise a message error will be showed thanks to the try and catch statements. These statements together allow to look out for errors while a piece of code is being executed and in case an error is found, the application will be stopped and a warning message will be displayed. The key point of programming hardware, it is to prevent that the software breaks on execution.

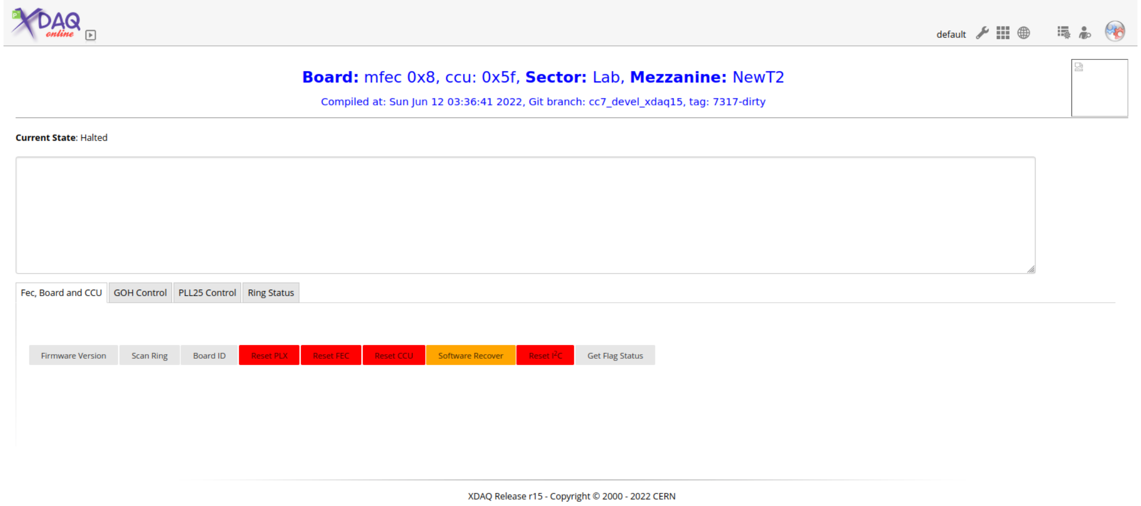
At first glance, this application uses high-level predefined hardware sequences for a given FSM action, i.e. configuring embedded digitizer board devices. Finally, features to retrieve feedback from the digitizer board were added.

The following options are available and can be performed through the command line as long as their requirements are met (the necessary parameters in each case are provided):

Option	**Action**
ScanRingDevice	Scans the ring devices and returns as an output the detected components.
CheckFPGA	Checks the registers.
SetBoardId	Tags a digitizer board with a fixed ID number. The desired Id number needs to be included in the input.
BoardId	Gets the board id.
Configure	Configures the Fec access.
StartRun	Starts the Data acquisition.
StopRun	Stops the Data acquisition.
PLLStatus	Gets the the digitizer board PLL status.
PLLReset	Resets PPL.
PLLPhaseInvert	Inverts the rising edge of the LHC clock.
writeReg	Writes to a specific register. An additional value parameter is needed as input.
readReg	Reads the register.
sendTrigger	Sends a L1A Trigger.
RingReconfigure	Reconfigures the ring (or the slow control).
CCUReset	Resets the CCU and generates a new token.
FecReset	Resets the Fec.
GOHReset	Resets GOH digitizer. PLL lock of GOH.
CheckPowerGOH	Checks the intensity of the GOH.
SetPowerGOL	Sets the GOL power. Additional parameters are needed as input for this option: first and second values.
GetPowerGOL	Reads the intensity of the GOL.
FullGOLProcedure	Additional parameters are needed as input for this option: first and second values.
GetFirmwareVersion	Gets the digitizer board firmware version.
GetFlagStatus	Gets flag status of the digitizer board.
GetGOHStatus	Gets the GOH status.
GetCounters	Gets the counters: trigger, event orbit, and bunch number.
GetConfig	Gets the full board configuration.
SetConfig	Sets the new t2 configuration from a configuration file.
ResetI2C	Releases all the I^2C bus devices communication on the board.

Once the command line was validated and tested, the same methods were migrated for the XDAQ control software. As mentioned before, the XDAQ framework is used for communication between central CMS DAQ and the subsystems partitions, or the subsystem's local DAQ.

The XDAQ software is loaded by an XML file containing a vector of the CCU chip, along with the ring and slot addresses, which can be selected one by one (or all at once) to perform different actions. Figure 4.1 is showing the new T2 XDAQ user interface which is accessible by an internet browser. Figures 4.2, 4.3, 4.4 and 4.5 show the tabs that were defined in the interface and the buttons available.



Board: mfec 0x8, ccu: 0x5f, **Sector:** Lab, **Mezzanine:** NewT2

Compiled at: Sun Jun 12 03:36:41 2022, Git branch: cc7_devel_xdaq15, tag: 7317-dirty

Current State: Halted

XDAQ Release r15 - Copyright © 2000 - 2022 CERN

Figure 4.1: new T2 XDAQ interface running in a VM located within CERN network. This application is accessible by an internet browser. In order to open it outside CERN network, a SSH tunnel is needed.

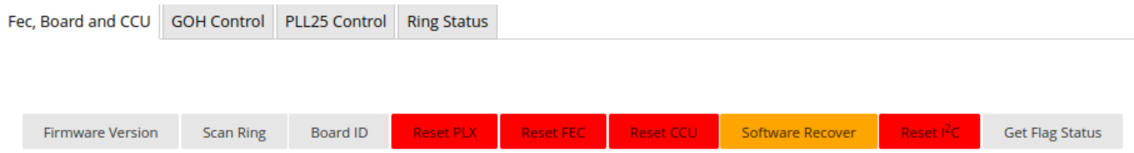
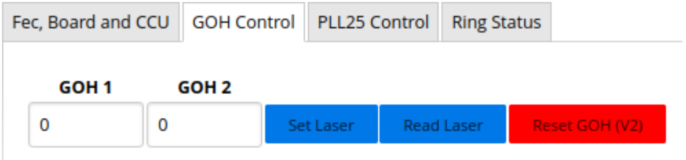


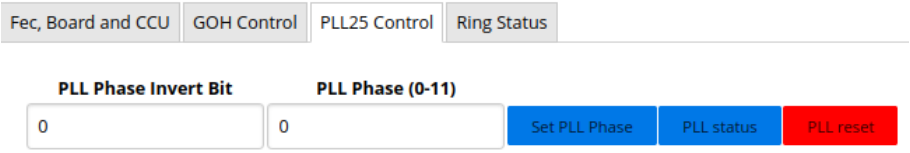
Figure 4.2: The Fec, Board and CCU tab (located inside the new T2 XDAQ interface) and its contents are shown.



GOH 1: 0

GOH 2: 0

Figure 4.3: The GOH Control tab (located inside the ew T2 XDAQ interface) and its contents are shown.

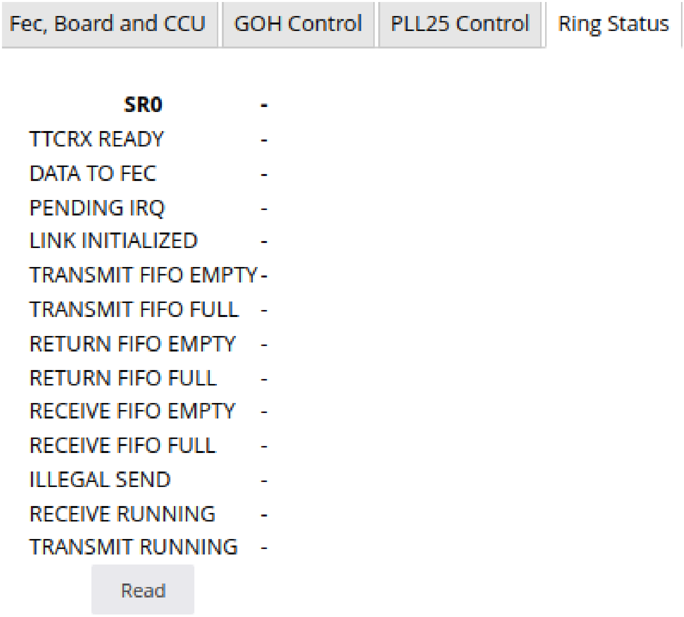


PLL Phase Invert Bit: 0

PLL Phase (0-11): 0

Figure 4.4: The PLL25 Control tab (located inside the new T2 XDAQ interface) and its contents are shown.

For running the interface from outside CERN it is first necessary to tunnel to CERN's Linux Public Login User Service (LXPLUS) and then from there tunnel again to the ttf43 machine. The



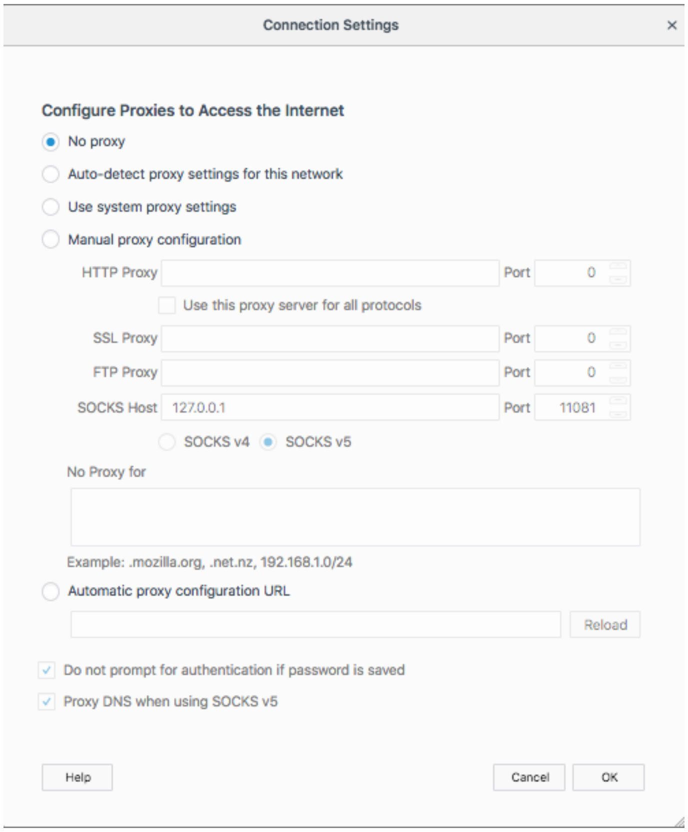
SR0 -
TTCRX READY -
DATA TO FEC -
PENDING IRQ -
LINK INITIALIZED -
TRANSMIT FIFO EMPTY -
TRANSMIT FIFO FULL -
RETURN FIFO EMPTY -
RETURN FIFO FULL -
RECEIVE FIFO EMPTY -
RECEIVE FIFO FULL -
ILLEGAL SEND -
RECEIVE RUNNING -
TRANSMIT RUNNING -

Figure 4.5: The Ring Status tab (located inside the new T2 XDAQ interface) and its contents are shown.

software is located in the control package folder and the action command to source the variable configuration file has to be executed. This script defines the environment variables hard-coded in the source code to find specific detector configuration files. Although before using the XDAQ application it is needed to check if there is one already running on the machine in background. In case there is, it is necessary to kill the process. This is done, because every time a given XDAQ application is running, a port number must be provided.

In order to use the interface a Secure Shell (SSH) tunnel was configured to access from outside CERN general network (GN). When running the XDAQ on a local machine another terminal is needed with a set of commands (the specific command line can be found in Ref.[28]) and has to be kept open all the time, if it is closed the network is then lost. Moreover, the browser also needs to be configured using the port number defined for the localhost (or local machine). The browser settings for Firefox are shown in Fig. 4.6.

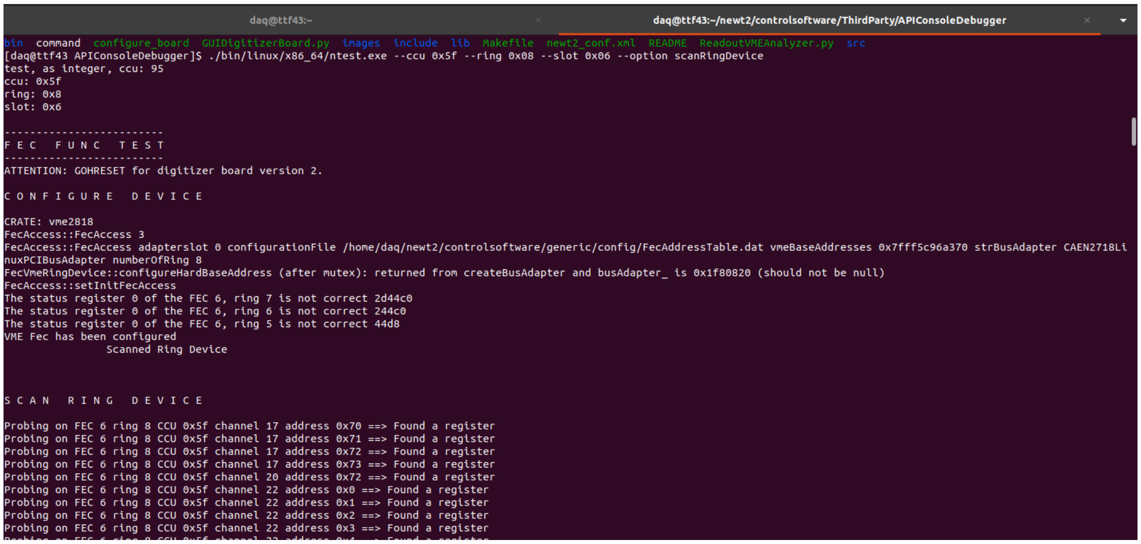
The application developed can be controlled via the command line or through the XDAQ interface, in any case the resulting configuration in the system is the same. The Scan Ring Device function, which scans the ring devices and returns all the detected devices i^2c, is activated through the command line (Fig. 4.7) and through the online application (Fig. 4.8) giving the same output. The same can be done to the rest of the configured functions, they can be activated either the command line or the XDAQ application.



Configure Proxies to Access the Internet

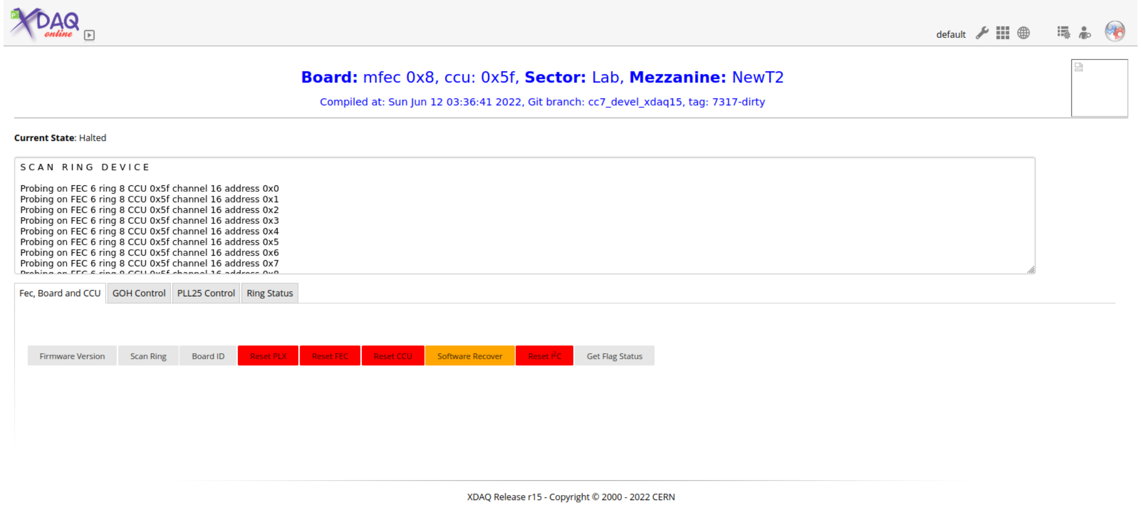
● No proxy
○ Auto-detect proxy settings for this network
○ Use system proxy settings
○ Manual proxy configuration
HTTP Proxy: Port: 0
☐ Use this proxy server for all protocols
SSL Proxy: Port: 0
FTP Proxy: Port: 0
SOCKS Host: 127.0.0.1 Port: 11081
○ SOCKS v4 ● SOCKS v5
No Proxy for:
Example: .mozilla.org, .net.nz, 192.168.1.0/24
○ Automatic proxy configuration URL
☑ Do not prompt for authentication if password is saved
☑ Proxy DNS when using SOCKS v5

Figure 4.6: The settings configuration in the Firefox Web Browser is shown with the adequate port number.



```
bin  command  configure_board  GUIDigitizerBoard.py  images  include  lib  Makefile  newt2_conf.xml  README  ReadoutVMEAnalyzer.py  src
[daq@ttf43 APIConsoleDebugger]$ ./bin/linux/x86_64/ntest.exe --ccu 0x5f --ring 0x08 --slot 0x06 --option scanRingDevice
test, as integer, ccu: 95
ccu: 0x5f
ring: 0x8
slot: 0x6

-------------------------
F E C   F U N C   T E S T
-------------------------
ATTENTION: GOHRESET for digitizer board version 2.

C O N F I G U R E   D E V I C E

CRATE: vme2818
FecAccess::FecAccess 3
FecAccess::FecAccess adapterslot 0 configurationFile /home/daq/newt2/controlsoftware/generic/config/FecAddressTable.dat vmeBaseAddresses 0x7fff5c96a370 strBusAdapter CAEN2718Li
nuxPCIBusAdapter numberOfRing 8
FecVmeRingDevice::configureHardBaseAddress (after mutex): returned from createBusAdapter and busAdapter_ is 0x1f80820 (should not be null)
FecAccess::setInitFecAccess
The status register 0 of the FEC 6, ring 7 is not correct 2d44c0
The status register 0 of the FEC 6, ring 6 is not correct 244c0
The status register 0 of the FEC 6, ring 5 is not correct 44d8
VME Fec has been configured
                Scanned Ring Device



S C A N   R I N G   D E V I C E

Probing on FEC 6 ring 8 CCU 0x5f channel 17 address 0x70 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 17 address 0x71 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 17 address 0x72 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 17 address 0x73 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 20 address 0x72 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 22 address 0x0 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 22 address 0x1 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 22 address 0x2 ==> Found a register
Probing on FEC 6 ring 8 CCU 0x5f channel 22 address 0x3 ==> Found a register
```

Figure 4.7: new T2 XDAQ interface running the Scan Ring Device function by using the command line. The ccu, ring and slot addresses are needed to perform any action.



Board: mfec 0x8, ccu: 0x5f, **Sector:** Lab, **Mezzanine:** NewT2

Compiled at: Sun Jun 12 03:36:41 2022, Git branch: cc7_devel_xdaq15, tag: 7317-dirty

Current State: Halted

```
SCAN RING DEVICE

Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x0
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x1
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x2
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x3
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x4
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x5
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x6
Probing on FEC 6 ring 8 CCU 0x5f channel 16 address 0x7
```

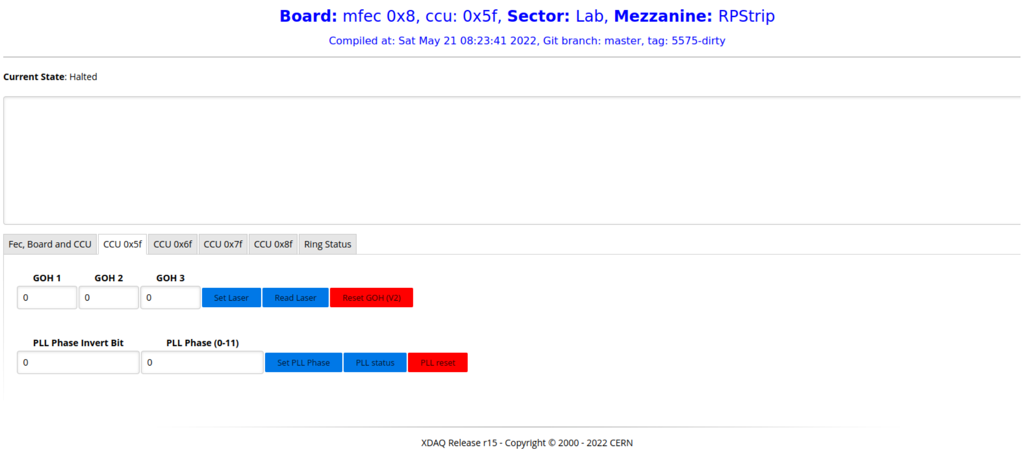
XDAQ Release r15 - Copyright © 2000 - 2022 CERN

Figure 4.8: new T2 XDAQ interface running the Scan Ring Device function by clicking the button on the application.

4.1 Control interface for the RP Si-Strips

Furthermore, a similar process was performed adapting this interface (XDAQ) in order to provide the control software for the Roman Pot Si-Strips detectors.

As previously mentioned, in section 2.3.2, TOTEM is conformed by the Roman Pots (RP). Sectors 45 and 56 have each two pairs of top and bottom vertical RPs that use strips technology are controlled by a single slow control loop (CCU25). Another XDAQ application for controlling the detectors will be developed and will have two instances for the control in each sector. As a reminder, these detectors are also used for the PPS special alignment runs, where the beam spot is found for further usage in the proton reconstruction.



Board: mfec 0x8, ccu: 0x5f, **Sector:** Lab, **Mezzanine:** RPStrip

Compiled at: Sat May 21 08:23:41 2022, Git branch: master, tag: 5575-dirty

Current State: Halted

GOH 1: 0
GOH 2: 0
GOH 3: 0
PLL Phase Invert Bit: 0
PLL Phase (0-11): 0

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Figure 4.9: RP Si-Strips XDAQ interface running in a VM located within CERN network and is accessible by an internet browser. In order to open it outside CERN network, a SSH tunnel is needed. In this case, there are four CCUs in the same interface.

The main goal of the RP Si-Strips Control is to quick configure all the GOHs and PLLs without requiring to much actions from the detectors operators. The system for each sector hosts four CCU25 chips (one per RP Si-Strip detector), so changes were implemented in order to include them all with their corresponding elements for configuration, GOHs and PLL configuration necessary for each CCU. PLL or GOH actions such as resetting, reading status or setting their internal registers are included for each CCU. Figure 4.9 is showing the strips XDAQ user interface which is accessible by an internet browser with the needed configurations.

4.2 Software Repositories

The software for controlling the Roman Pot Strips is still under development but further details can be found in Ref. [29]. At the moment, it was not being tested with RP Si-Strips frontend boards.

The software repository for the new T2 detectors can be found on [43].

Further instructions on how to use it are present on [28] for the new T2 and on [29] for the Si-Strips.

Chapter 5

Summary, Outlook and Conclusion

The TOTal cross-section, Elastic scattering, and diffraction dissociation Measurement (TOTEM) is one of the Large Hadron Collider (LHC) experiments. TOTEM originally consisted of a set of movable detectors named Roman Pots (RPs) and two charged particle telescopes, known as T1 and T2. The T2 telescope surrounded the beam pipe at 13.5m from the CMS interaction point (IP5). Since the CMS beam pipe was upgraded, the T2 detector needed upgrades as well. Therefore, a new detector has been built and is in the commissioning phase to be ready for Run 3, in which TOTEM will complete its physics program.

TOTEM DAQ has been integrated with the CMS environment and the new T2 detectors' will also be merged into this system. The CMS DAQ system utilizes software tools to configure the detector Finite State Machines (FSM), which are well-defined transitions that prepare the detectors for the read-out. The communication between central DAQ and its subsystems is linked by XDAQ, a middleware software.

The aim of this project was the development of a new online control software for the new T2 mezzanine, through a slow control optical link that relies on the CCU25 radiation hardness communication ASIC and has been greatly used within CMS. The tool developed integrates the communications between the PPS/TOTEM DAQ.

The development of the software tool was not an easy task, but a lot of knowledge was gained and the goal was achieved. The development of the new online software utility, written in an object-oriented programming language, that controls the new T2 detectors through a slow control optical link was presented.

Major challenges are presented in order to meet the TOTEM and CMS physics programs but as technology progresses, upgrades to fulfill the goals can be performed. The implementation of a control software based on the CMS XDAQ framework represents an advantage as it optimizes many tasks. Also, being an online software it can be developed, maintained, tested, and improved from anywhere in the world which allows having better collaborations and updates.

The resulting software tool is intended to be a simple yet effective and safe way for CERN researchers to operate the detectors. Especially through XDAQ as the interface is intuitive and in a necessary case, the buttons dedicated to tasks that should be performed by experts only can be locked. Therefore, it provides good security measures as well.

The software was tailor-made for the new T2 detector and it is linked to the CMS DAQ but it may be possible to learn from the project and implement its advantages in different systems (like in the case of the RPs silicon strips) or even completely different fields as well.

Further improvements to the new T2 control software will be developed by the deadline of August 2022. Collaboration with TOTEM-PPS is still ongoing and the software is expected to be in production by September 2022.

Appendix A

CMS Coordinate System

The CMS detector utilizes the right-handed coordinate cartesian system, with the interaction point as the origin. The x-axis is pointing to the center of the LHC ring, the z-axis along the beam axis in anticlockwise direction and the y-axis is perpendicular to the plane of the ring. Given that the detector has a cylindrical design, polar coordinates are also used. The azimuthal angle is defined by the angle with respect to the x-axis in the x-y plane, the polar angle is measured from the positive z-axis in the y-z plane and r is the radial coordinate. Figure A.1 shows a scheme of these coordinates.

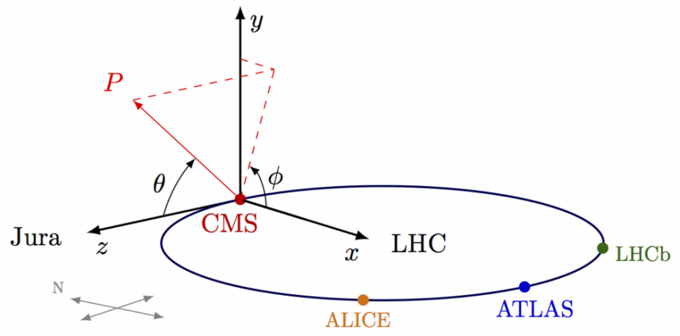

Figure A.1: Compact Muon Solenoid coordinate system diagram. The figure is taken from Ref. [37].

Another variable that is often used for the description of the geometry of the detector is the pseudorapidity, which is defined as

$$\eta = -ln\left(tan\frac{\theta}{2}\right) \tag{A.1}$$

Appendix B

Nomenclature

AD. Antiproton Decelerator, part of the CERN accelerator complex.
ALICE. A Large Ion Collider Experiment.
ASIC. Application Specific Integrated Circuit, device with internal circuits designed for a specific task.
ATLAS. A Toroidal LHC ApparatuS.
BE. Backend, refers to the electronic devices and systems that are located away from the detector.
BR. Branching Ratio.
BU. Builder Units.
CC. Coincidence Chip.
CCU. Communication and Control Unit.
CERN. Conseil Européen pour la Recherche Nucléaire (European Council for Nuclear Research).
CMS. Compact Muon Solenoid.
CNGS. Cern Neutrinos to Gran Sasso, part of the CERN accelerator complex.
Cross-section. Refers to the probability of two particles interacting in a specific way after a collision.
CTF3 Click Test Facility, part of the CERN accelerator complex.
DAQ. Data Acquisition.
DCS. Detector Control System.
DOH. Digital Opto Hybrid.
DOHM. Digital Opto Hybrid Module.
FE. Frontend, refers to the the electronic devices and systems that are located in a region close to the detector.
FEC. FrontEnd Controller.
FED. FrontEnd Driver.
FPGA. Field Programmable Gate Array.
FSM. Finite State Machine.
FU. Filter Units.
GN. General Network.
GOH. Gigabit Optical Hybrid.
GOL. Gigabit Optical Link.
HLT. High Level Trigger.
HPTDC. High Performance Time to Digital Converter.
I^2C. Inter-Integrated Circuit.
IP. Interaction Point, the location where particles collide in the accelerator.
ISOLDE Isotope Separator OnLine DEvice, part of the CERN accelerator complex.
Jet. A composition of many particles originating from a quark or gluon.
JTAG. Joint Test Action Group.

L1. Level 1.
LEIR. Low Energy Ion Ring, part of the CERN accelerator complex.
LHC. Large Hadron Collider.
LHCb. Large Hadron Collider beauty.
LINAC. LINear ACcelerator, part of the CERN accelerator complex.
LONEG. Level ONe triggEr Generator, TOTEM's final trigger stage.
LXPLUS. Linux Public Login User Service.
MET. Missing transverse energy, also denoted as E_T^{miss}
n-ToF. neutrons Time of Flight, part of the CERN accelerator complex.
Pile-up. Is used to refer to the additional interactions generated in pp collisions in the same bunch crossing.
PLL. Phase Locked Loop.
POH. Pixel Opto Hybrid.
Primary vertex. The point where the main collision is produced.
PS. Proton Synchrotron, part of the CERN accelerator complex.
PS. Power Supply.
QCD. Quantum chromodynamics.
QPLL. Quartz crystal Phase Locked Loop.
RP. Roman Pot, PPS detector.
RU. Readout Units.
scCVD. Single Crystal Diamonds.
SPS. Super Proton Synchrotron, part of the CERN accelerator complex.
SSH. Secure Shell.
T2. Telescope 2.
TOTEM. TOTal cross-section, Elastic scattering, and diffraction dissociation Measurement.
TOTFED. TOTEM Front EnD.
TTCci. Timing, Trigger and Control CMS interface.
UFSD. Ultra Fast Silicon Detectors.
VFAT. Very Forward Atlas and TOTEM chip.
VME. Versa Module Eurocard .
XDAQ. Cross-platform DAQ framework.
XML. eXtensible Markup Language.

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