The CERN laboratory is currently building the Large Hadron Collider. Four experimental groups have designed detectors able to exploit the physics potential of this collider. Among them is the Compact Muon Solenoid, a general purpose detector, optimised for the search of Higgs boson and physics beyond the Standard Model of fundamental interactions between elementary particles. The UCL, together with other Belgian universities[1] is taking part into the building of its tracker. This paper presents, in particular, the development of a Front-end Hybrid Industrial Tester, aiming at swiftly testing hundreds of hybrid electronic circuits with different levels of quality tests: connectivity, electrical and functional tests. A first characterization of a preliminary version of these hybrids is also presented.

1. Introduction

For many years now, the biggest and most powerful particle accelerator is under construction at CERN in Geneva. Such an instrument will allow high energy particles to collide and interact, giving access to the very structure of matter and bringing answers to questions and puzzles that are still unsolved after years of research in high energy particle physics. Its physics program covers the search for Higgs boson, the missing piece of the Standard Model of particles and their fundamental interactions, as well as Super Symmetry and other new physics beyond the Standard Model.

The Large Hadron Collider, will accelerate mainly two proton beams up to 7 TeV energy each. It will also be able to collide heavy ions, as ionized lead. In order to reach a luminosity between $10^{33}cm^{-2}s^{-1}$ (low luminosity phase) and $10^{34}cm^{-2}s^{-1}$ (high luminosity phase), each beam is filled with 2835 bunches of 10^{11} protons and will cross the other beam

[1] UIA, ULB, UMH, VUB.

every 25ns. During the high luminosity phase, proton-proton collisions will yield more than 20 unrelated minimum bias events at each bunch crossing, producing about one thousand particles in the detector volumes, around each interaction point [1]. There will be four of such interaction points with the corresponding detectors: ATLAS, CMS, LHCb and ALICE. The first beams are expected in spring 2007.

2. The CMS experiment

The Compact Muon Solenoid (CMS) will detect particles created at one of the four interaction points of the LHC beams. Even if it is a general purpose detector, CMS has been designed with optimized parameters for Higgs boson search. It is made of different layers, with an onion-like structure composed, from its inner part, by the tracker, the electromagnetic and the hadronic calorimeters and several muon chambers. All these layers are immerged into a strong magnetic field (up to 4T) produced by a superconducting magnet, located between the hadronic calorimeter and the muon chambers. The detector is a big cylinder, 22m long and 15m high, weighting 12,500 tons.

CMS is characterized, among different parameters, by a very accurate electromagnetic calorimeter, consisting in lead tungsten crystals ($PbWO_4$). Its resolution imposes severe constraints on tracker material budget in terms of interaction lengths, i.e. the electron *Bremsstrahlung* due to the tracker must be avoided. The focus of this work is on the tracker and some of its components.

3. The CMS tracker

The tracker aims at reconstructing tracks and at measuring momentum for charged particles with transverse momentum higher than 2 GeV/c. One of its goals is also to reconstruct and distinguish between different vertices of multiple interactions occurring at each bunch crossing [2].

As many W and Z bosons will be produced at LHC, the tracker will have to deal with their leptonic decays, which are particularly clean and easy to observe. In order to use the full power of these signatures, leptonic momenta have to be very accurately measured. The separation between different tracks is also critical, for instance in the isolation of high energy leptons in the 4 lepton decay channel of Higgs boson. B jet tagging and reconstruction is important for several possible decay channels connected to the Higgs boson and the top quark production, CP violation or physics beyond the Standard Model. This requires good abilities to separate displaced vertices. The same applies to the τ lepton observations.

As most of the studies on new physics need the highest luminosity of LHC, heavy requirements have to be encountered by the CMS tracker. The event pile-up — i.e. the production of many particles at each bunch crossing, coming from multiple unrelated proton-proton collisions — increases the constraints on track and momentum reconstruction. The radiation hardness is thus, as doses in the tracker can reach 700 kGy, a critical parameter which influenced the choice of detector technology [2]. At the same time, in order to avoid lowering the electromagnetic calorimeter resolution, the tracker material budget had to be minimized.

The tracker of CMS is a 6m long and 2.4m high cylinder and is composed of two different types of detectors: pixels and silicon strip sensors [2]. The first ones are the closest to the interaction point and the latter ones are just behind, and cover most of the tracker volume. The total area of silicon strip sensors is greater than 220 m^2, yielding about 10 millions of analogue channels.

The silicon strip sensors consist of an **n** doped semiconductor bulk covered on one side with **p** doped microstrips. Sensor size and thickness both depend on its position in the tracker. Different parameters, as silicon crystal orientation, resistivity, thickness and strip length, were optimized to cope with the tracker requirements. Moreover, the whole tracker volume is kept at a steady operating temperature of -10°C, in order to slow down the effects of radiation damages — i.e. reverse annealing. Due to the low temperature and the material budget minimization, the power consumption of the tracker components is also heavily constrained.

The elementary piece of which the tracker consists in is a *module*. A typical module is made of three key elements: a set of two single face silicon sensors, a front-end hybrid hosting all the acquisition and control electronics and a carbon fiber structure on which these components are glued. The carbon fiber plate holds the two daisy chained silicon sensors which are connected, through a pitch adapter, to the acquisition chips on the front-end hybrid.

On this front-end hybrid are gathered several chips needed for data acquisition and tracker control, which are APV25, APVMUX, PLL and DCU chips. The APV25s are the chips aiming at reading currents flowing from sensors and at keeping this signal, amplified and sampled at 40 MHz rate, in an analogue pipeline until a CMS level 1 trigger occurs.

There are always 4 or 6 APVs per hybrid. The APVMUX multiplexes the data from two adjacent APVs and sends it out of the hybrid and the module. The PLL is a control chip that reconstructs the clock and trigger signals coming from CMS and distributes them to the APVs. It has built-in delay shifters that allow the exact synchronization of each of the 78,000 APV chips of the CMS tracker and is connected to the tracker control system. Some temperature, current and voltage control measurements are performed by the DCU chip, a 12bit ADC, which is connected to the slow control system through PLL. Depending mostly on geometrical parameters, twelve different types of hybrids were designed.

4. The Front-end Hybrid Industrial Tester

The front-end hybrids thus play a master role in the whole data acquisition chain of the tracker, as an interface between the silicon sensors and the CMS acquisition system. Their production is industrial — as mush as 16,000 hybrids are needed — but must be closely controlled by the CMS collaboration at the same time. This is the reason of an industrial tester, available for industry and the collaboration, has been designed by our Institute [3]. The Front-end Hybrid Industrial Tester — in short: FHIT — is an automatic tester that allows fast and quite exhaustive tests of the front-end hybrids, appropriate to their type. It will attest the quality of the mass production of hybrids, according to criteria defined by the collaboration [4].

An *industrial test* is a sequence of three sub-tests: the *connectivity*, *electrical* and *functional* tests. This sequence checks the hybrid in general, from the electrical connections of the components to their basic functionalities. After about one minute, an hybrid is fully tested, a grade is assigned to it and a measurement file is created. According to the grade obtained, an hybrid can be accepted (grades A and B) or rejected (grade C). The measurement file gives input for the CMS database and also the characterization of front-end hybrid parameters.

The connectivity test is *passive*, in the sense that the hybrid is not powered on during this first test. By using an internal switch matrix, FHIT accesses to many different electrical lines on the hybrid. This test makes sure of the presence of all power lines, of the absence of short or open circuits, and checks other electrical connections. Most of the errors during the connectivity test are fatal and mean hybrid rejection.

If the hybrid passed the connectivity test, it is powered on, until the end of industrial test. So both electrical and functional tests are *active*. The electrical test, among many things, checks the power supply values, tries to access to registers of every components of the hybrid, calibrates the DCU chip and measures current consumption of APVs. This test is performed at nominal, maximal and minimal hybrid voltages. The DCU calibration is an important step, as FHIT is the only device that can easily access to this calibration data.

Then comes the functional test, where data from APVs is taken with the internal ARC system of FHIT. The ARC system is developed by RWTH Aachen [5] and allows data acquisition with hybrids or modules. Every FHIT needed for full industrial test is provided with an internal ARC board. While performing the functional test, I²C lines are tested, MUX gain is tuned and APV behavior is scanned with pedestal, noise — both raw and common mode substracted noises — and gain fast analysis, on a 1,000 event basis.

All the information from the different tests, as well as other automatisms — such as the handling of 4 COM ports, the control of the barcode scanner, the remote control of the power supply and the attribution of the hybrid grade — and the sequence of the different tests, is handled by an interface software, FHITS. Its code is compiled with LabVIEW, with C++ methods for the functional test encapsulated into *dll* files.

5. Hybrid charaterization

FHIT was used for the first time in industrial like conditions in May 2002, with the test of 62 front-end hybrids in the IReS laboratory in Strasbourg. During this first intense use, FHIT proved to be reliable and properly working. Moreover, it was the first time that data were available for such a number of hybrids. We analyzed the industrial test files in order to compute statistics and output characterization data for front-end hybrid parameters. Of course, due to the lack of hybrids and the narrowness of the sample, there is few statistical significance in the results. However, broad trends can already be seen and the results of this analysis is a first estimate of the hybrid parameter characterization, that will be refined later on, when more statistics are available.

Every hybrid tested was a TOB type hybrid — "Tracker Outer Barrel" (Figure 1), in opposition to "Tracker Inner Barrel" and "Tracker End Cap" types. These types differ from each other with their connector position, *top* or *bottom,* and with the number of APVs, 4 or 6. Further references to these types will be the following (obsolete) *part numbers*: **1663** is "TOB top 4", **1664** "TOB bottom 4" and **1665** is "TOB top 6".

Among the 62 hybrids, only 46 passed the connectivity test. This is a first, expected, result: most of the hybrid failures occur at connectivity test. The 46 front-end hybrids left were distributed as 38 **1663-**hybrids, 7 **1664-**hybrids and 1 **1665-**hybrid. In the following plots, we always drew the dots as follows: the central value is the mean of the corresponding distribution and the error bars correspond to ± 1 RMS. "V_{nom}" refers to the application of nominal voltage supply on the front-end hybrid during electrical test. Here are some results of this characterization.

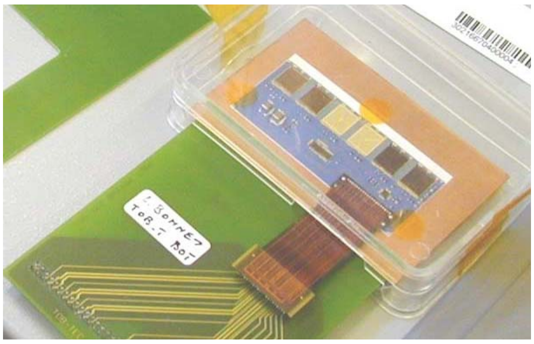

Figure 1: TOB hybrid with 4 APV25s (1664).

The APV current consumptions seem to be independent of hybrid type and of APV position on hybrid, as one could expect. The Figure 2 shows the current consumption with respect to the hybrid type and the APV I²C address — which is directly connected to the geometric position of the APV on the hybrid.

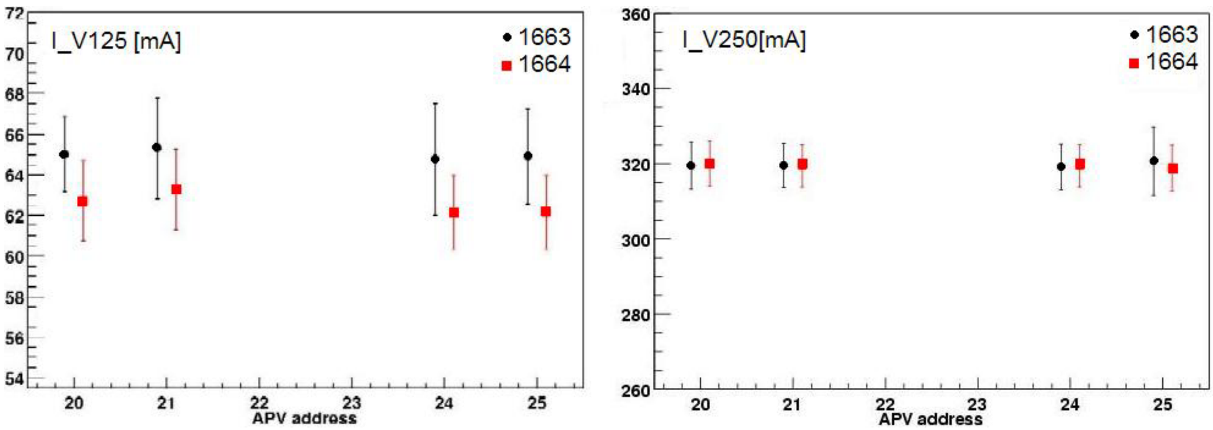

Figure 2: Current consumptions on different supply lines (V125: left and V250: right) with respect to hybrid type and APV address. Central value is the mean of the corresponding sample and the error bar is ± 1 RMS. Note that the measurement resolution is 4 mA.

The DCU calibration data (Figure 3) is taken for both linear and non-linear regions of this ADC. One can see the strange behavior of the error bars in the plot for the linear region. This could be explained by the existence of different sets of DCUs, according to the slope of their linear region. The behavior of the DCU corresponding to the last input voltage sent for the calibration of the linear region shows clearly that the linear region is left.

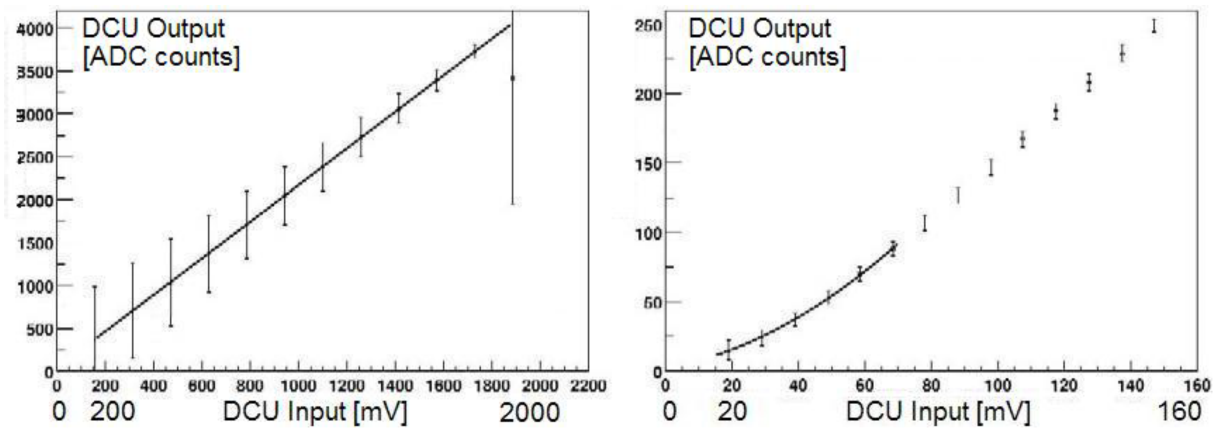

Figure 3: DCU calibration data for linear and non linear regions (1663-hybrid, V_{nom}). Central value is the mean of the corresponding sample and the error bar is ±1 RMS.

The pedestal data for each APV of each type of hybrid is computed during functional test, with 1,000 events. The plots in Figure 4 shows the pedestal values for two given APV addresses of one given hybrid type, with respect to the channel number — an APV25 has 128 input channels. It seems that pedestal values are compatible whatever the APV address, for a given hybrid type. They are also compatible within 1 RMS for different hybrid types (not shown here). A global linear increase is always visible, with superposed border effects. Moreover, the error bars show clearly strong correlations between channels.

The same analysis has been performed on the measured noise. Two kind of noise are computed during the functional test: raw noise and common mode substracted noise. The difference between these two types of noises is precisely the channel correlation underlined in the pedestal analysis. The raw noise for two given APV addresses of a given hybrid type is plotted in Figure 5. Channel correlation is still visible. Its mean value and general behavior seem to be independent on the APV address.

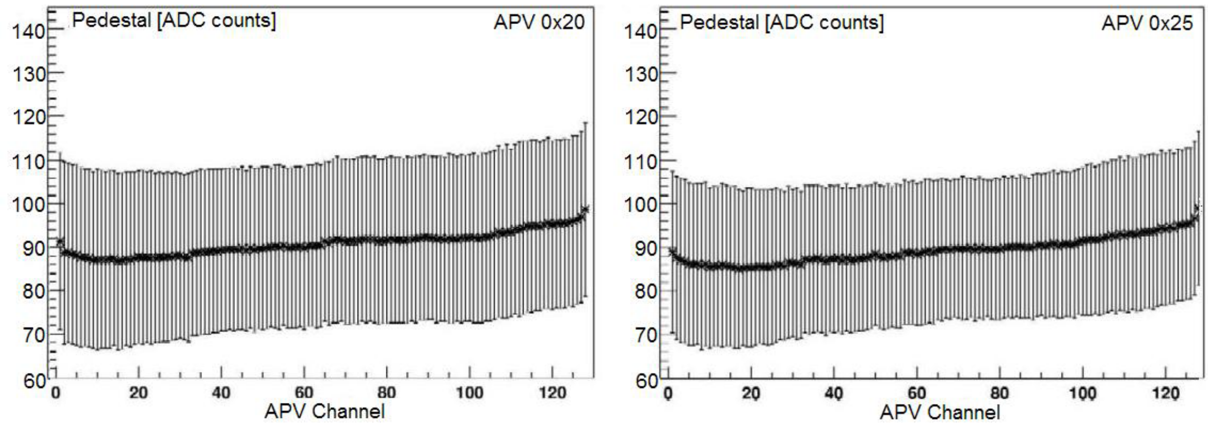

Figure 4: Pedestal values for two given APV addresses and a given hybrid type (1663), with respect to the APV channel number. Central value is the mean of the corresponding sample and the error bar is ± 1 RMS.

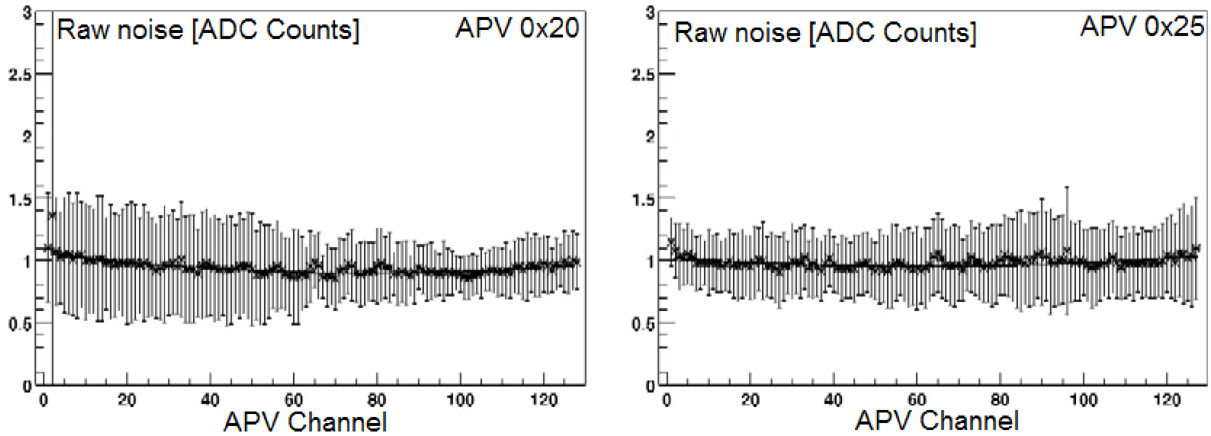

Figure 5: Raw noise values for two given APV addresses of a given hybrid type (1663), with respect to the APV channel number. Central value is the mean of the corresponding sample and the error bar is ± 1 RMS.

The APV channels are supposed to be less correlated with the common mode substracted noise. This can be seen in Figure 6 (left) from the global shape of the error bars. The horizontal lines show the limits of the acceptance interval for this noise, as defined by the collaboration [4]. One clearly sees that this criterion is too restrictive, as the acceptance interval has the same order of magnitude as the RMS of the noise distribution. This means that a noise value for any channel could be out of the acceptance interval due to statistical effects. The criterion does not work mainly because of the bad resolution on common mode substracted noise. In Figure 6 (right) is also visible the distribution of common mode noise mean with respect to the APV address and the hybrid type. This shows that there is no difference of noise, within 1 RMS, for different APV address of any type of hybrid.

Lots of other plots were computed for the charaterization of the front-end hybrid parameters and only few of them are shown here. More information is available in refs [6] and [3].

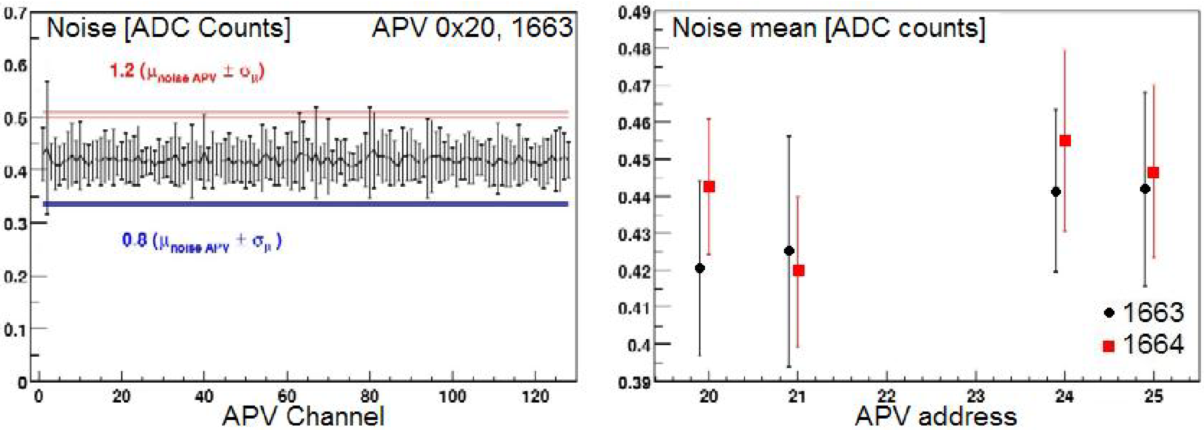

Figure 6: Common mode noise for one given APV address of a given hybrid type (left), with respect to the APV channel number. Distribution of common mode noise mean with respect to the APV address and the hybrid type (right). Central value is the mean of the corresponding sample and the error bar is ± 1 RMS.

6. Conclusions

An industrial tester had been developed in order to test CMS tracker front-end hybrids reliably, automatically and fast during mass production. This setup makes a full *industrial* test of all basic functionalities of hybrids via a connectivity, an electrical and a functional tests. Data taken with FHIT in May 2002 also provided information for a first front-end hybrid parameter characterization. This characterization suffers from the lack of data for real statistical significance but is still meaningful for broad trends. It will be updated when more data are available.

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