Beam Tests of CMS HCAL Readout Electronics

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Abstract

During summer 2003 extensive tests of CMS hadron calorimetry have taken place in the H2 test beam line at the CERN Super Proton Synchrotron. The most important tests took place at the very beginning of the period and were performed with 25 ns structured beam. The system consisted of a set of two Hadron Barrel calorimeter sectors where the total of 144 channels was read out. The main goal of verifying the synchronization procedure was accomplished and several additional studies were performed, including the influence of relative phase to the energy measurements as well as event pileup.

I. INTRODUCTION

CMS (Compact Muon Solenoid[1]) is a general purpose experiment at the Large Hadron Collider (LHC) project currently under construction in European Laboratory for Particle Physics (CERN) in Geneva, Switzerland. The CMS detector is designed to study p-p collisions at 14 TeV center-of-mass energy with frequency of 40 MHz and luminosity of 10^{34} $cm^{-2}s^{-1}$. The most prominent aspect of the CMS detector is a very large 4 T magnet that houses the entire central tracking and both electromagnetic and hadron (HCAL) calorimeters of the experiment.

The chosen technology for the HCAL[2] is sampling calorimetry with a non-magnetic brass absorber and plastic scintillator plates that act as a detection medium. The plastic absorber plates are segmented into tiles whose geometry has been chosen such that tiles from successive layers of scintillator form towers pointing toward the interaction point. Light created in scintillator tiles is captured in wave-length shifting (WLS) fibers embedded in grooves in the tiles. The wavelength shifted light is further guided toward photo detectors through clear optical fibers spliced onto WLS fibers. All the light from consecutive tiles in a given projective tower is guided into the same pixel of a Hybrid Photo Diode (HPD [3]) and read-out by one channel of the read-out electronics chain. The requirement to minimize light loss in the optical waveguides has led to the installation of photodetectors and the readout and digitizing electronics on the edge of the detector, as close to the scintillators as possible. All the components of the front-end electronics are required to operate in a 4 T magnetic field and be capable to withstand $2x10^{11}$ neutrons per cm^2 during 10 years of operation. The chosen photodetectors were proximity-focused HPDs which have good linearity over wide dynamic range, relatively small size and can operate in strong magnetic field when the field is aligned with the axis of the applied electric field. Their relatively low gain of about 2000 has imposed special requirements on readout and calibration systems.

This technology of hadron calorimetry is implemented in the pseudorapidity range up to eta=3. For the high eta (3<eta<5) region the expected radiation doses exclude use of plastic scintillators and the chosen technology for the Hadron Forward (HF) calorimeter is the detection of Cherenkov light produced by hadron showers in rad-hard quartz fibers that act as both detection medium and light guides. As HF is situated outside the central magnetic field, the readout of the produced light is performed with photomultiplier tubes. The front-end and readout electronics for HF are the same as for the rest of HCAL.

II. DESCRIPTION OF THE SYSTEM

A. Front-end electronics

Operation in LHC conditions demands that the HCAL front-end electronics has low noise (less than 4000 electrons), high frequency (40 MHz), high sensitivity (1/3 fC least count) and wide dynamic range (16 bit). In addition, there are requirements on reliability, radiation tolerance, magnetic field immunity, cross talk, and capabilities for DC current measurement.

The front-end boards consist of six charge integrating and encoding ASICs (QIEs[4]) controlled by three Channel Control ASICs (CCAs). Digitized data are fed into two gigabit optical link ASICs (GOLs) that drive vertical cavity surface emitting lasers (VCSELs). In this way only two optical fibers are needed to transfer the data from the six channel readout board to the data acquisition system.

The CMS QIE ASIC is an improved version (QIE8) of an ASIC originally developed for the KTeV experiment at Fermilab. The QIE has an embedded non-linear FADC that digitizes signals in an 7-bit pseudo floating-point format with 2 bits of range (exponent) and 5 bits of mantissa. The QIE operates in 4-step pipeline mode and the digitized data are accompanied with the time slice information, which is referred to as CapID.

CCA[5] is a custom built ASIC developed at FERMILAB whose basic functions are to supply clocks for QIEs with individually programmable delays, align the data received from QIEs and send them to the GOL chips. Other CCA functions are to provide a serial interface for programming the CCA, adjust QIE pedestal values, set QIEs to fixed or auto ranging modes (for calibration or physics), as well as to issue resets, test patterns and test pulse triggers.

Control of the front-end cards as well as delivery of clock and Trigger Timing Control (TTC) signals is performed through a Clock and Control Module (CCM[6]) that communicates with the Detector Control System through an optically isolated RS 422 interface.

B. *Readout electronics*

Data from the front-end cards arrive into HCAL Trigger and Readout (HTR) modules through optical fibers. HTRs are designed to receive data on optical links, determine the energy for each tower, identify the bunch crossing and send trigger primitives to the regional calorimeter trigger module at 40 MHz. If a trigger is asserted, the raw data are transferred from pipeline storage to a data concentrator card (DCC[7]) over copper twisted-pair cables. This year we used a new version of HTR cards that could read 48 channels.

The DCC receives data over up to 18 serial links from the HTR cards, performs error checking and monitoring and transmits the data to DAQ system through 64-bit Slink interface. It has event-building logic, error-checking and monitoring logic as well as data buffering and formatting logic. There is a possibility to read the data through VME interface for monitoring purposes. At the very beginning of the test period we used last year's version of DCC card read-out through VME bus and later on switched to the new one that could use Slink64.

C. *Data acquisition*

A data acquisition system (DAQ) for the test beam was developed in Princeton University following the recommendations of CMS TriDAS group. It was based on the XDAQ toolkit package version 1.2 and contained a custom built single component event builder. Run configuration and management tools were built using MySQL database and Java editing tools. A light-weight Java-based Run Control was developed at Fermilab. Communication with readout and trigger electronics was done using SBS (ex-Bit3) PCI-VME interfaces.

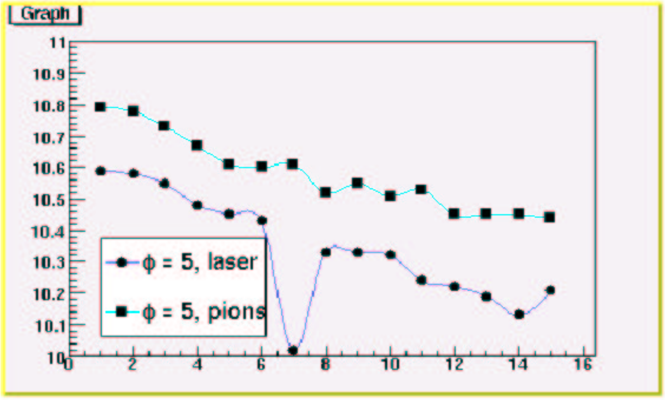

Figure 1: Plot of mean arrival times in units of 25 ns as a function of tower number (increasing eta) for laser pulses and pions. Note that tower 7 has a bad laser injection fiber.

The DAQ hardware system consisted of a 9U VME crate housing a fanout card for clock and TTC signals, as well as HTR cards and the DCC. A second 6U VME crate contained TDCs and ADCs as well as TTCvi, TTCex and a custom built Trigger card that performed delivery of trigger signals to the TTC system, triggering of calibration pulses (LED, laser) and generation of gates for TDCs and ADCs.

The system clock has been provided from the main transmitter and after processing in the TTC machine interface crate (TTCmi) it was distributed through TTC opto coupler module (TTCoc) to front-end and readout cards. Triggers were obtained through a coincidence of two scintillating counters situated upstream from the detector.

III. RESULTS

A. *Synchronization procedure*

Two main issues have been addressed: synchronization of signals coming from different detector segments (wedges) and synchronization of signals from the same phi sector. The first issue was solved by cutting the digital optical fibers that transmit digitized data from the front end cards into readout electronics to the same length. The checks of relative timing of signals from different phi sectors of two detector segments have shown that they are synchronized to within 0.2 ns. This indicates that apart from fiber length there are no other effects that could influence this synchronization.

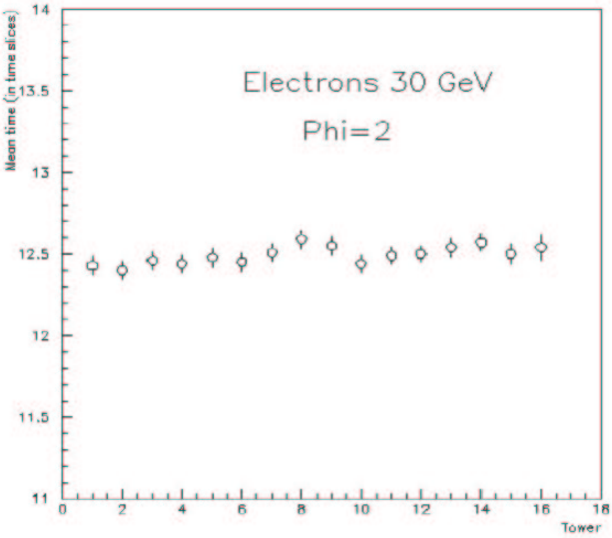

Figure 2: Plot of mean signal arrival times in 25 ns units as a function of tower number (increasing eta) for 30 GeV electrons after adjustments of delays.

The need to synchronize signals coming from the same segment appears because analog signals travel different lengths of optical waveguides before they are detected in HPDs. This effect is partially compensated by the time of flight of particles between the interaction point and the detector: particles entering the detector at low eta have shorter times of flight, but the produced light has longer distance to travel through optical waveguides. For the high eta towers the time of flight is longer, but the transmission time through waveguides is shorter. This compensation is not complete and there is still a need to change delays, so that all signals arrive at the same time.

The laser calibration system was used to determine how much signals from a given eta-phi tower should be delayed. During the construction of the scintillators, the fibers that inject laser light into selected layers of the calorimeter have been cut so that the relative time of light injection into towers corresponds to relative times of arrival of particles. By measuring timing distribution of laser induced signals we could derive a distribution of mean arrival times shown on Figure 1. It can be seen that the laser system and the beam particles give the same timing up to a constant. Adjusting delays for each individual read-out channel can be done in steps of 1 ns by re-programming the corresponding CCA. Checking that the delays are properly set was performed by sending electrons into each eta tower of a given phi sector of the calorimeter, and the results are shown in Figure 2. The mean time shown on Figures 1 and 2 was calculated as a mean value of the response after pedestal subtraction.

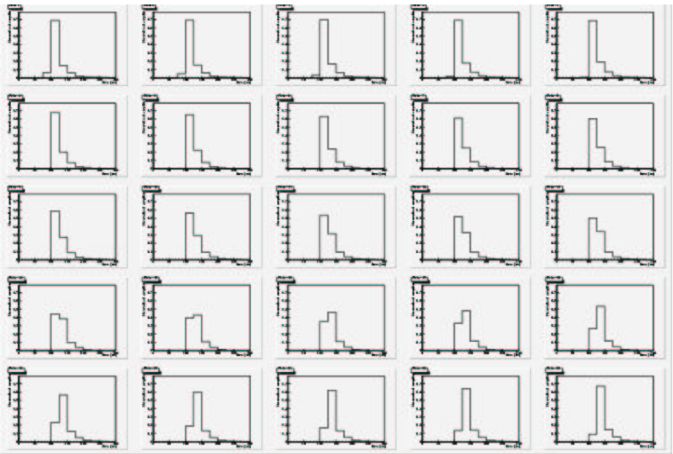

Figure 3: Plot of linearised response of the calorimeter to 100 GeV pions as a function of time (units are 25 ns time slices). Successive plots show the response when changing delays in steps of 1 ns (from left to right, top to bottom).

After adjusting the relative delays of eta-phi towers we performed a set of measurements where the adjusted delays were incremented in steps of 1 ns. The obtained time distributions are shown on Figure 3. Abscissa on these plots is time divided into twenty time slices of 25 ns each that were readout from the pipeline and recorded for each event. Ordinate on the plot is a linearised response in fC. Note that recording of twenty time slices was done for debugging purposes only; in the real experiment it will not be necessary.

With these tests we could prove that we can really control the timing of individual channels and study the distribution of energy in successive time slices which is a necessary input for development of firmware performing generation of trigger primitives. A possibility to satisfy physics requirements by deriving energy information from a single time slice would speed up the trigger primitive generation and reduce total latency of the calorimeter trigger.

Figures 4a) and b) show summary plots of response in two adjacent time slices when compared with response in only one slice for different relative delays of signals. First important observation is that the distributions for both electrons and pions look very similar. Another one is that by changing the phase of the signals we can obtain up to 70% of the signal in a single time slice and that ~90% of the signal are contained in two time slices.

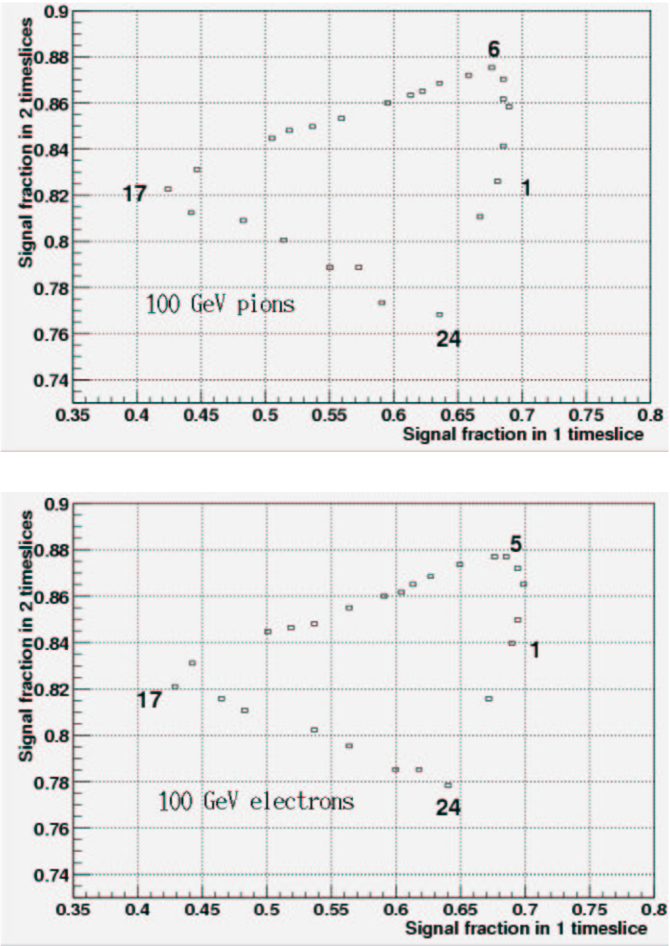

Figure 4: Plots of response contained in two adjacent time slices as a function of energy contained in a single time slice for different relative phases of signals produced by 100 GeV pions and electrons. The numbers next to the points correspond to relative phase in nanoseconds.

D. Pile-up studies

Although the phenomenon of pile-up is expected to be rare during normal operation of LHC, in view of super-LHC and the consequent considerable increase of luminosity, it was considered useful to check if there is a possibility to separate these events. These studies were performed by creating NIM trigger logic where trigger was issued only if there were particles hitting the same HCAL tower in two adjacent time slices (see Figure 5).

The obtained timing distributions when phase has been changed in steps of four nanoseconds are shown in Figure 6. It is obvious that changing relative phase of the triggers with respect to the edge of the time slice does not allow for any separation of two signals.

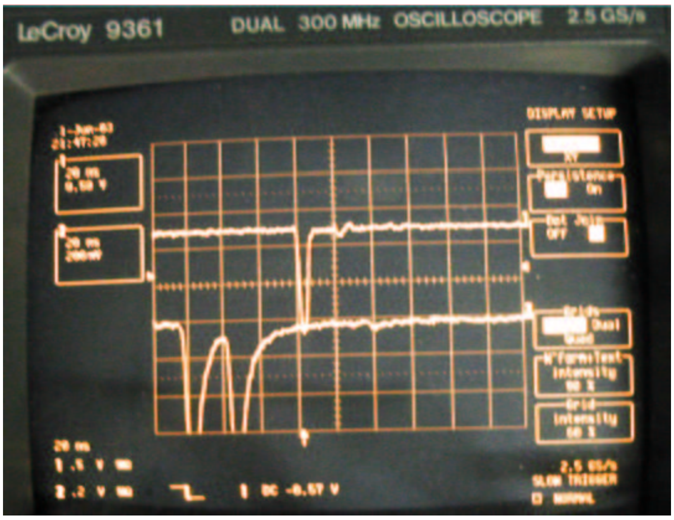

Figure 5: Signals used for trigger during pile-up studies.

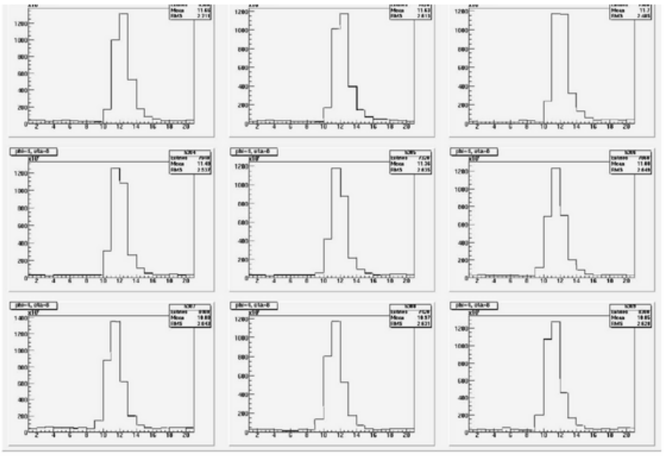

Figure 6: Timing distributions for pile-up events. Successive plots show the response when changing delays in steps of four nanoseconds (from left to right, top to bottom).

E. *System operation*

During this run we concentrated more on synchronisation issues than on studies of front-end and readout electronics which, in general, gave satisfactory performance. As usual, the hostile test beam environment has brought to our attention which parts of the system may need further attention.

We observed an unexpectedly high number of synchronization losses. Laboratory measurements of bit error rate (BER) performed with a clone of the system and clocked by a very stable signal generator show that the probability for such a loss is of the order of 10^{-15}. However, in the test beam we were observing them at much higher rates of one every 10-20 minutes. Detailed studies of error rates could not be performed as the available time was short and the main goal was to take data with the beam. The use of real accelerator signals and the lack of proper crystals for QPLL (Quartz crystal based Phase Lock Loop) chips is considered to be responsible, but additional laboratory tests are under way to see if there is another cause.

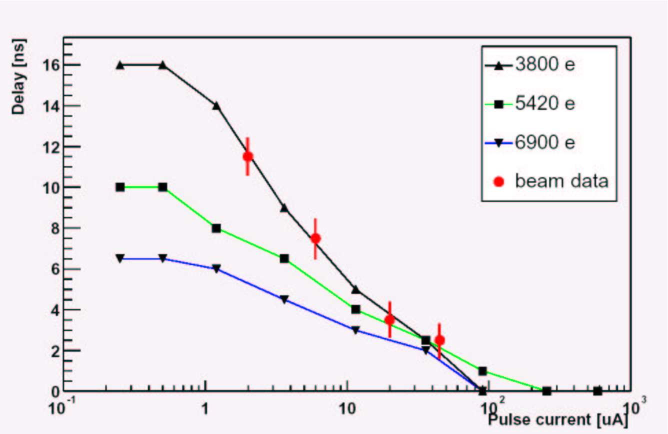

Figure 7: Time slewing of QIEs as a function of input current. Three curves correspond to three different bias currents, i.e. three different levels of noise.

Another issue that is under study is a known time slewing of signals in QIE: the requirement to minimize noise of the system has led to use of intrinsically slow inverting amplifier with a dynamic input impedance. The outcome is that higher signals give faster response time as shown on Figure 7. This effect means different arrival times for signals of different amplitude and can worsen the detector performance. Detailed simulations of the detector performance with the measured time slewing and different noise levels are under way to see whether physics requirements can be satisfied with the current design or compensatory measures have to be implemented.

A minor change of clock lines routing and their better shielding on HTR cards appears to be necessary for more stable operation. Firmware for both HTR and DCC cards has gone through several modifications during test beam period, most of which were motivated by improving performance and monitoring.

We have confirmed strong attenuation effect of dust particles on optical fibers and/or connectors reported in TTC documentation[8]. Cleaning of fibers and optical connectors with compressed air and impregnated optical instrument tissues very quickly became part of regular procedure when changing readout configuration.

This run period was marred with instabilities of the DAQ system that were eventually traced to a bug in the XDAQ library. The bug was fixed and a patch submitted to the developers. Another issue related to DAQ performance is that the SBS driver version 1.0 was eventually replaced by much better performing version 2.3beta.

Several new tools were implemented and proved to be very useful. One of them is a searchable run database using, for the time being, MySQL. Run number, type, number of events, type of the beam as well as date and time have been recorded. We also implemented and tested an electronic logbook developed at FNAL for D0 and CDF. Its constant use in combination with the run database enabled easy following of data taking by physicists on remote sites and considerably facilitated off-line analysis. Additional benefit came from system settings and status recorded by the Detector Control System.

An important new hardware addition for this year's test beam was the inclusion of a Trigger board developed at Princeton University. It is basically a programmable I/O module with four NIM inputs and four outputs, 12 ECL inputs and 16 ECL outputs. By appropriate programming of a Spartan 2E FPGA we could obtain all delays, gate lengths and output signals needed for correct delivery of Level 1 Accepts (L1A) to the TTC and the readout systems. This module was used for numerous run configurations: beam data, calibration with laser, LED, or radioactive source. It also allowed multiple triggers to be enabled at once as well as a possibility to issue multiple triggers within the same readout cycle. The complexity of delivered and required hardware signals for all these configurations was very easily handled by the FPGA firmware and the Trigger board effectively replaced more than a whole rack of NIM electronics.

Another very useful tool was daily video conferencing and practically permanent access to VRVS. This allowed to have daily meetings of all interested parties as well as occasional debugging of the system by combined efforts of the person on shift and an expert from a remote institute.

IV. SUMMARY

In May 2003, the CMS HCAL group performed tests of two calorimeter sectors with 25 ns structured beam in the H2 line of the CERN SPS accelerator. Total of 144 channels were read out during these tests and the full chain of front-end and readout electronics was implemented. A CMS-style data-acquisition system was used. Given the short time for installation and commissioning of the hardware and software, the system performed remarkably well and we were able to take a large data set of valuable data. We were able to confirm our synchronization paradigm and demonstrate the capability to control phase of different parts of the detector. The demanding environment of the test beam required that several new versions of firmware and software be made during data taking. Based on the test beam experience, certain improvements are planned for the next generation of hardware.

V. ACKNOWLEDGEMENTS

The 25 ns structured beam was very stable and the support from SPS operators and Experimental Area physicists was very valuable. The installation and initial checks of the TTC system obtained on loan from RD12 collaboration was done B. G. Taylor. We are grateful for his generous help and numerous advices that saved us lots of time and effort.

VI. REFERENCES

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