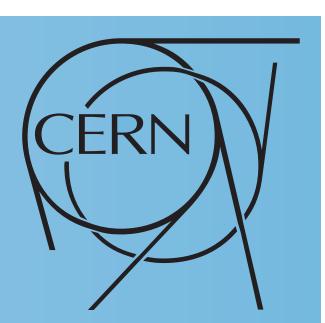


Installation and Commissioning of the CMS Timing, Trigger and Control Distribution System



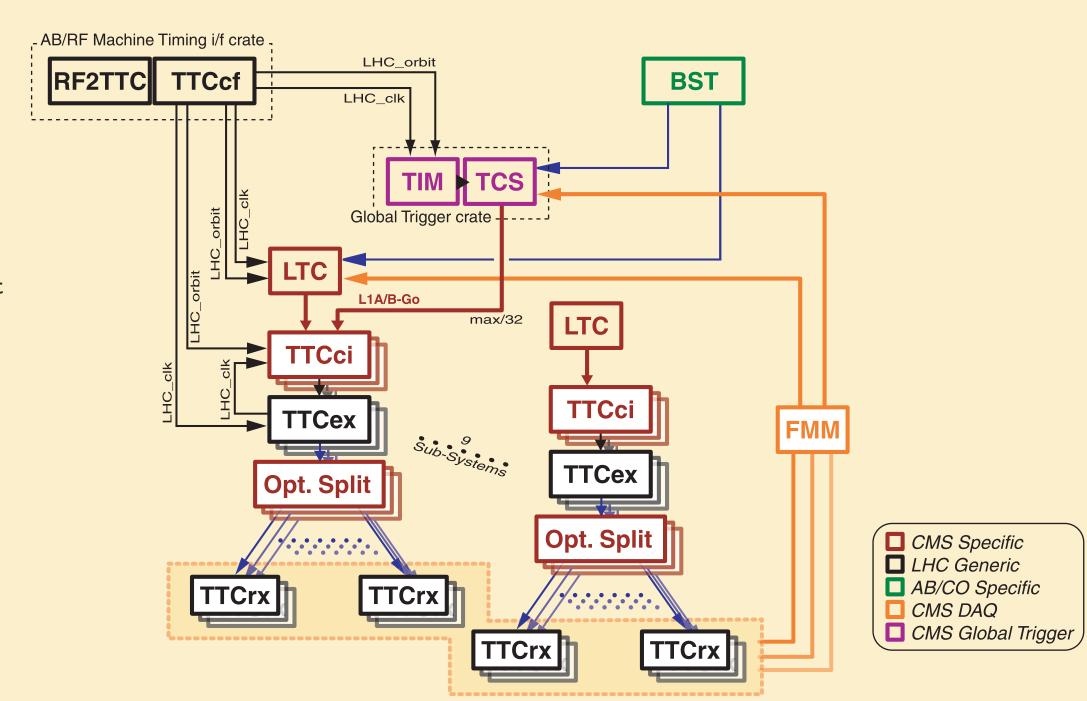
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CMS Timing, Trigger and Control System Overview

The CMS Timing, Trigger and Control (TTC) system serves to distribute the signals required to synchronise all CMS detector systems with each other and with the LHC collisions. We distinguish signals that are directly received from the LHC machine RF systems that provide the means to synchronise CMS data-taking to the beam collisions; and those that are generated centrally within CMS to maintain the synchronisation between different detector subsystems within CMS.

CMS receives 5 signals from the LHC RF system: 3 clocks - the current clock used by the RF system of the counter-circulating beams I & 2 as well as a reference clock to which those two clocks are locked at the LHC flat-top energy of 7 TeV after the energy ramp; and 2 orbit pulses that mark the passage of bunch I of beams I & 2 past a particular point in the LHC ring. These 5 signals are transmitted optically from the RF systems located at the LHC Point 4 to each LHC Experiment where they are received and conditioned by the RF2TTC module. Conditioning involves timing (delay) adjustment and alignment of the different signals before the selection of the pair of master clock and orbit signals that is to be distributed to CMS system via the fanout modules TTCcf.

Fast control signals that maintain the relative synchronization within and between CMS subsystems are generated in the CMS Trigger Controllers. There is one Global Trigger Controller that is part of the CMS Global Trigger system - this is a 9U VME module known as the TCS (Trigger Control System). The TCS module runs CMS during Global data taking. Each sub-system also has its own Local Trigger Controller (LTC) that is used for standalone testing or debugging. The main difference between the two controllers is the number of partitions that can be driven: 32 in the case of the TCS in comparison to 6 for the LTC.



The smallest functional unit that can be independently controlled using the TTC system is known as a partition. At the head of each partition the TTCci (TTC CMS Interface) VME module translates the fast commands issued by the active Trigger Controller into the actual commands that are understood by the attached detector system. Thus at the level of the Trigger Controller all partitions understand the same commands, whereas flexibility in the actual definitions in hardware at the command receivers is maintained by the translation provided in the TTCci modules.

TTC data are transmitted optically using the system developed by the RD12 collaboration. This system uses a time-division multiplexing scheme to send two channels of data (A & B) down one optical link to a remote receiver (TTCrx). Channel A is reserved for commands that have single clock-cycle duration - typically the Level I Accept Trigger. Channel B transmits framed commands that are decoded by the TTCrx and act either upon its internal settings or are placed on its output bus to control the attached electronics. The encoding of A & B Channels and optical transmission of signals is done by TTCex modules, which emit 10 copies of the same optical data, each of which may be optically split up to 32 ways. CMS gains some transmission margin by only splitting 16 ways, thus feeding a maximum of 16 destinations per optical channel.

Fast status, or throttling, information (Error, Out of Sync, Busy or Ready) is returned to the Trigger Controllers from the attached partitions via the Fast Merging Module (FMM) system that presents a summary "intelligent OR" of the state of a partition to the TCS and LTC. The Trigger controllers can thus automatically take actions like reducing the Trigger rate or initiating a re-synchronisation procedure.

Board Descriptions

RFRX

Receives the clock and orbit signals that are transmitted optically from the RF generators at LHC Point 4 and converts them into an electrical signal that can be processed further. Each module has three inputs and a monitoring circuit to measure the frequency of the incoming signal. These monitoring data are made available to the LHC team that is responsible for the integrity of the signal transmission.

RF2TTC All 3 clock a

All 3 clock and both orbit signals can be re-phased inside the RF2TTC to adjust the overall Experiment timing with respect to the LHC bunch train. Each clock channel is fed first to a QPLL and then a Delay25 circuit for jitter reduction and delay respectively. Both clock and orbit signals can be internally generated when the LHC beam is off.

BOBR

This is the timing receiver for the LHC Beam Instrumentation BST system. It receives data on beam conditions such as the machine mode and beam energy which are decoded and used in the CMS monitoring systems.

LTC

The CMS Local Trigger Controller can drive up to six partitions for standalone testing and commissioning. Each sub-detector has one module that can produce all fast control signals necessary to synchronize its partitions and issue test triggers while taking the Trigger Throttling System (TTS) signals into account.

TTCci

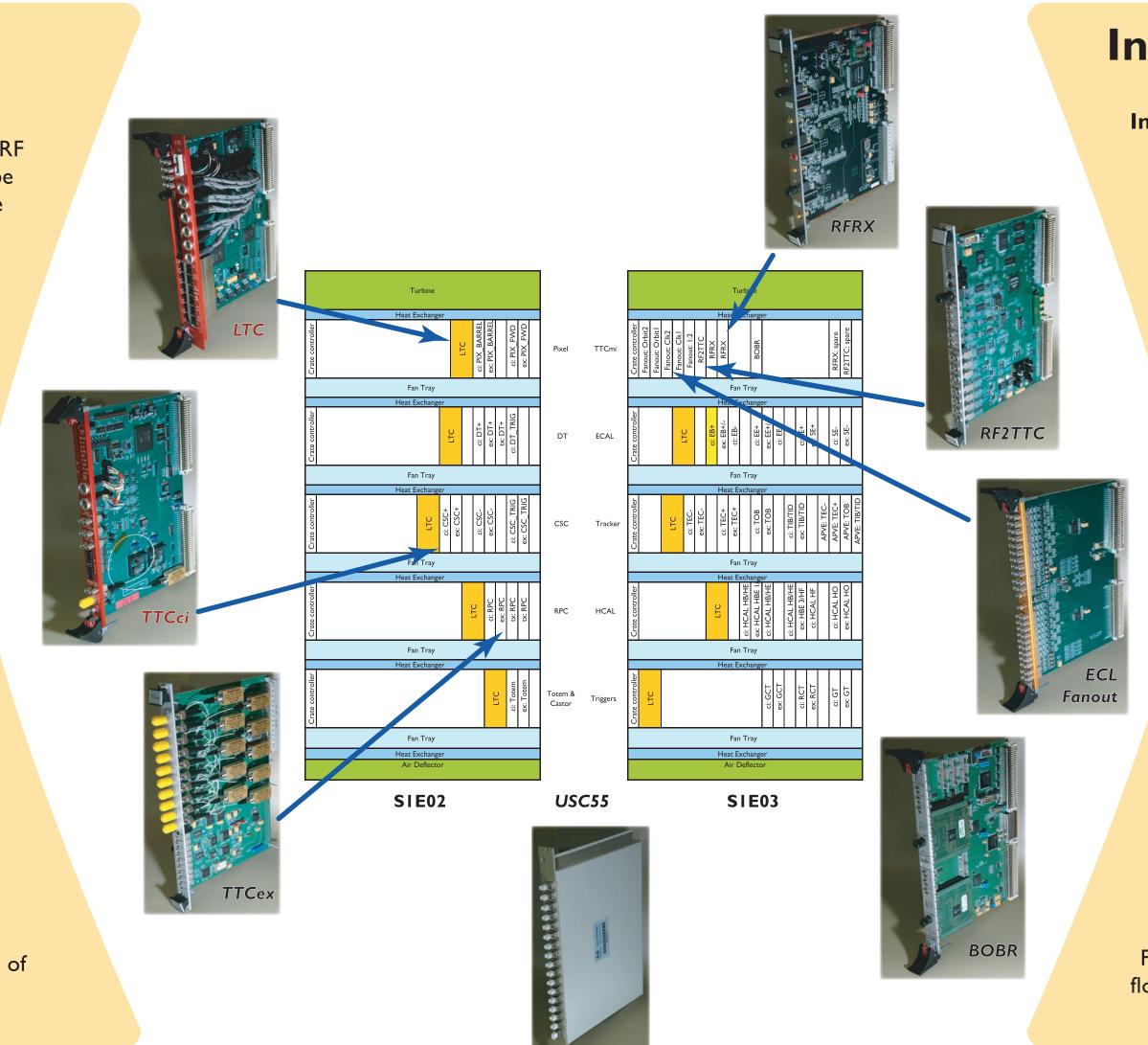
Partition-dependent coding for the fast control signals are stored in this module that carries out the translation of fast commands received from the active (Local or Global) Trigger controller. It can also act as controller for a single partition.

TTCex/tx

Ex: Encodes and transmits TTC commands to each partition; Tx only transmits.

Optical Splitter

The optical transmitters in the TTCex have sufficient output power to allow a split of up to 32 ways. CMS uses 16-way optical splitters in a compact VME-slot form factor.



Installation & Testing

Installation in the CMS Underground Counting Room USC55

All CMS TTC equipment resides in two racks in the lower level (S1) of the CMS

Underground Counting Room USC55. These racks are immediately adjacent to the Global Trigger rack on one side and very close to the shielding wall that separates USC55 from the Experimental Cavern (UXC55) to minimise the latency of the Level One Trigger (LIA). Within these two racks each sub-detector (of which there are nine in CMS) has a 6U VME TTC crate which is under their control. The tenth crate is the Machine Interface crate that houses the boards for LHC RF signal reception and distribution within the nine sub-detector crates.

Each sub-detector crate contains a crate controller, one LTC and a number of TTCci/ex pairs corresponding to the number of partitions within that sub-detector as shown in the schematic to the left. Single-mode optical fibres run from the TTC crates to the relevant sub-detector racks (both in USC55 and UXC55) where the optical splitters are housed. From there the signals are either distributed over fibre to the detector front-ends or used directly by the local electronics.

DT SIE02
CSC
RPC
SIE03

Machine Interface
ECAL

Tracker HCAL

Triggers

Post-installation testing

All boards and their interconnections within the TTC crate and the Global Trigger are tested post-installation using test patterns. The correct installation of optical fibres is verified by measuring the magnitude of the optical signals arriving at the destination. Finally, each sub-detector carries out a functional test of the system to check that data is flowing through the system.

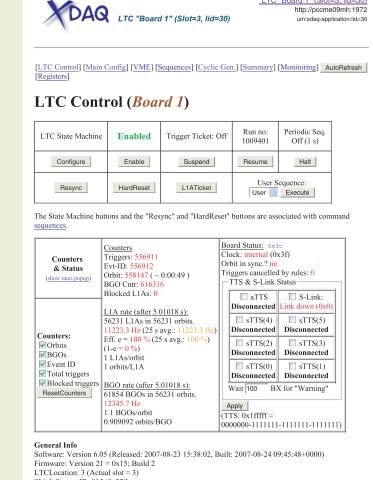
Control Software

All CMS VME crates are controlled via a VME-PCI bridge by rack-mount PCs located together in horizontal-airflow racks in one section of the Upper level of the CMS underground counting room. The connection between VME-crate and PC is via Optical fibre. The PCs run the CERN Scientific Linux operating system.

The CMS DAQ group provides a CMS-standard software framework for communication with VME-based boards called the Hardware Access Library (HAL) and another higher-level software framework for remote control of data acquisition processes (XDAQ). We have built a TTC-specific software library to control the VME-enabled TTC boards (RFRX, RF2TTC, LTC & TTCci) based upon HAL and XDAQ that is used by all CMS sub-detectors to control their LTCs and TTCcis.

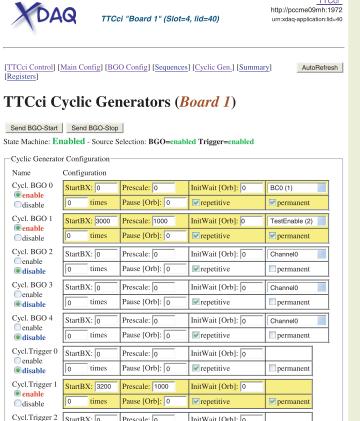
The XDAQ framework provides a very convenient method of creating a Graphical User Interface in a web-browser. To the right we show how the LTC and TTCci can be controlled (remotely if desired) via the hardware-specific interface provided by our TTC library. This interface has proven extremely easy for newcomers and experts alike to use for control and debugging of hardware and systems.

In addition to handling the http form submissions used to pass commands from a web-browser to the XDAQ process actually controlling the hardware, this process listens to SOAP messages - which allows any network-capable process control over the hardware. This fact is exploited by higher-level run-control software in CMS to control the TTC boards of the sub-detectors in parallel, for example to configure them at the start of global data-taking.



This is the first page seen by the user, where highlevel tasks like initial configuration, enabling and disabling the board can be carried out. The board configuration is stored in a text-based configuration file which can be selected and loaded into the hardware from this page. After manual configuration using the other control pages the current configuration can be stored for future recall. This page also provides

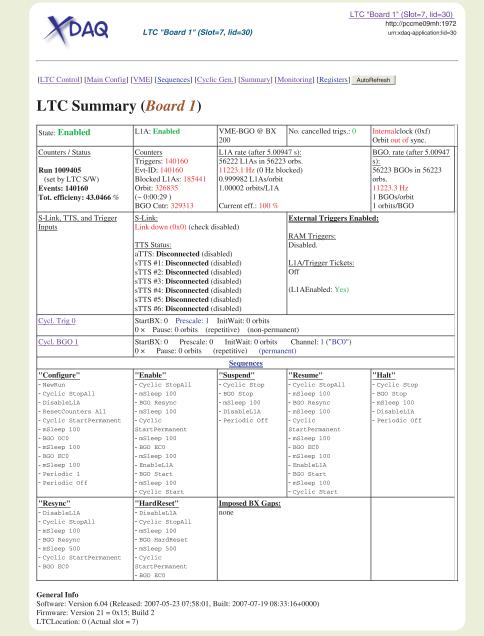
basic status information that includes the number of Triggers and fast commands that have been issued and the status of the timing. The summary status of the Readout boards in the attached partitions (sTTS info) is also visible, along with the selector that decides if the LTC should react to sTTS state changes (e.g. loss of synchronization) in certain partitions.



the Cyclic Generators that are present of both TTCci and LTC. These allow the periodic generation of fast B-Go commands (the LTC has 8 such generators while the TTCci has 5) and Triggers (6 and 3 for LTC and TTCci respectively). These generators are very flexible and allow quite complex repeating command patterns to be sent to the attached partition(s) for detector commissioning and

In this example we show

debugging. Here, as a simple example, we have the BC0 every orbit and a pre-scaled Test Enable with its associated Trigger every 1000 orbits, positioned near the end of one orbit.



The final example shows a summary page that allows the expert user to quickly check that the status and configuration of the board is as expected. This has proven very valuable when trying to diagnose problems related to the configuration of this rather flexible system. A concept visible here is the one of command sequences that comprise multiple actions to be carried out a predetermined times. This for instance is used to define the sequence of actions needed to achieve system synchronization at the start of data-taking.

Synchronization Procedures

Overall Strategy

Each sub-system has defined a strategy for time alignment of the sampling of its front-ends with the passage of particles coming from LHC collisions through its detectors. This strategy also includes the alignment of these samples to a CMS-wide definition of bunch and event number. The bunch number is defined as a number between I and 3564 that situates the bunch within the well-defined structure of the beam within one orbit of the LHC. The event

number is a count of the number of Level-I Triggers issued by the Trigger Controller.

In general, all sub-detector synchronization procedures allow for a coarse alignment of the front-end sampling before beam is available in the LHC that will require fine-tuning with data generated by particles coming from interaction point at the centre of CMS. Bunch and event number alignment between CMS sub-systems requires the use of a trigger for particles that can be observed in all the sub-systems that are to be aligned. This can be done by successively aligning sub-systems to one another using cosmic rays before the LHC beam turns on, as demonstrated by the CMS Magnet Test Cosmic Challenge (MTCC) carried out in 2006.

Finally, when beam becomes available in the LHC, a global shift of the clock and orbit signals in the RF2TTC module will be required to bring CMS into overall alignment with the LHC bunch structure. Histograms of hit-count per bunch crossing number for each sub-detector will provide the final verification of the correct timing in all parts of CMS when they are aligned with the bunch structure of the LHC machine.

Sub-System Procedures

The CMS **Tracking Systems** use the time of arrival at the Data Acquisition (FED) boards of the periodic tick marks inserted into the readout data by the front-end ASICs to determine the synchronization of the front-ends. This scheme depends upon knowing the length of the fibres that connect each front-end to its FED to better than 20cm in order to achieve the required sampling accuracy of Ins. Thus all readout fibre lengths are measured after installation as part of the acceptance procedure of the cabling.

Both **Calorimeter Systems** make use of the fact that they read out multiple time-samples and re-construct the pulse shape to aid in timing synchronization. In addition, these systems participate in the trigger and thus their front-ends send regular signals once per orbit as a synchronization check. Knowing the cable lengths from the detector to the counting room it is possible to check synchronization from the arrival time of these signals. Both systems also have calibration systems that can inject pulses simultaneously in several front-ends. Measuring the arrival time in the Data Acquisition boards provides a further timing cross-check.

All three **Muon Systems** have a very similar synchronization scheme to that of the Calorimeters, except that test pulses are generated electrically in the front-ends and not optically. Knowledge of the relative cable lengths between front- and back-end is also important here. The muon systems are unique in that they also have particle triggers from cosmic muons available to them to aid in the timing-in of geographically distant parts of their systems without having to rely on triggers produced by other sub-systems to compare to.

Local direct verification of LHC bunch structure

In order to aid the final timing verification, both within one bunch and to the overall bunch structure, CMS uses beam pickups provided for Experiment use directly on the LHC beam line. Button electrodes used by the LHC beam instrumentation group to measure beam position around the LHC ring are configured to provide beam-derived timing information for the Experiments. CMS has two such BPTX detectors, one for each beam - located at ~175m on each side of the CMS interaction point, assigned to it. The signals from the BPTX are analysed in the underground counting room to provide the phase relationship of the bunches at CMS with respect to the timing signal received at CMS from the LHC RF system. Monitoring of this relative phase allows corrections to be made globally to CMS at the level of the RF2TTC module without having to carry out the entire fine-synchronization procedure at the CMS subdetector level.

The BPTX system also provides a direct cross-check for the location of the first bunch in the train at CMS with respect to the Orbit signal received from the LHC RF system. CMS is thus able to verify that both types of timing signals received from the LHC RF system are stable with respect to the actual bunches in the machine. This could become important if propagation-delay changes are observed in the optical links between the LHC RF systems and CMS, something that might occur with seasonal variations in temperature for example - although as the cables travel in the LHC tunnel such variations are expected to be negligibly small in the CMS case.