CMS Electronics

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on behalf of CMS collaboration

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Abstract

This talk is the CMS response to the LEB organisers' request to develop the dialogue between the electronics community and the management of the LHC experiments. It is the view of a non-specialist, involved in CMS management, of the status and prospects for CMS electronic systems and the risks and uncertainties which appear to remain.

I. INTRODUCTION

A. Management of CMS electronics

CMS operates as a federation of sub-projects and this also applies to electronics. Resources and decision-making are largely concentrated in these projects, with very few under the control of the "management". The roles of management are principally those of achieving and maintaining consensus on general goals and schedules, resolving detailed difficulties within and between projects, oversight and reporting and, finally, (and perhaps most relevant to this discussion) co-ordination and integration to maintain technical coherence. Thus this presentation is not (and cannot be) about managing CMS electronics. It is rather the perceptions and observations of "management" about how electronics appears as a feature of the current status and future development.

B. CMS detectors and their status.

To clarify how electronics fits into the overall picture, it is useful first to list the detector hardware sub-projects required to complete CMS. Before entering production or starting major procurement, each project is required to pass an Engineering Design Review (EDR). As is apparent from Table 1, most of the sub-projects are already in production.

Table 1:CMS detector projects

Sub-Project	**Status**
Magnet Coil & Yoke	in production
Pixel Tracker	EDR in 2002/003
Silicon Strip Tracker	Pre-prod., EDR imminent
ECAL barrel	in production
ECAL endcap+preshower	EDR imminent
HCAL barrel + tail catcher	in production
HCAL endcap	in production
HCAL forward	EDR 2001
Muon barrel drift tubes	in production
Muon endcap CSC	in production
RPC barrel	in production
RPC endcap	EDR imminent
Shielding system	in production
beampipe	EDR 2001

C. CMS electronics projects and their status

The distinct electronics projects within CMS do not correspond exactly to the separate sub-detector projects.

Table 1:CMS electronics sub- projects

Sub-Project	**Status**
Pixel Tracker	Design. ESR in 2002/003
Silicon Strip Tracker	Pre-prod., ESR in 2001
ECAL	Pre-prod, ESR in 2001
Preshower	Final design, ESR in 2001/2
HCAL	Design. ESR in 2001/2
Muon barrel drift tubes	ESR September 2000
Muon endcap CSC	ESR September 2000
RPC	ESR September 2000
Trigger (level 1)	Design, ESR 2001
DAQ	Design, ESR 2002/3
Controls	Design, ESR 2002

By analogy to the EDR, an Electronics Systems Review (ESR) must be held before launching any major procurement or manufacturing. Table 2 lists the status and

Figure 1 shows a general overview of the experiment structure and the technologies in use.

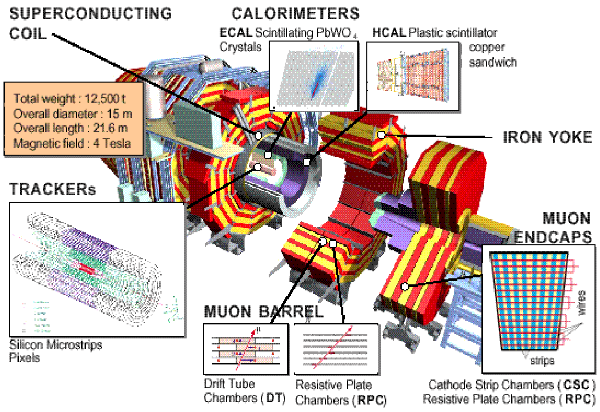

Figure 1: CMS structure and detector technologies.

D. Assembly Schedule

The CMS master mechanical assembly sequence is constrained by the Civil Engineering of the surface (SX) and underground (UX) areas. During the surface assembly into major elements (2000-2004) the magnet, HCAL and muon system form the critical path. During the underground phase (2004-2005), the barrel ECAL, silicon strip tracker and beampipe define the critical path. The natural early tendency in both overall and subdetector schedules is to concentrate on the big mechanical units which must arrive on time to avoid assembly delays. Recently, however, scheduling attention has focussed on understanding corresponding electronics arrival and burn-in, and on calibration. The preparation of the service cavern and detector umbilical connections is now recognised as a critical path activity. Similarly the completion of the control systems before sub-detectors switch on for commissioning, and the preparation of the trigger and data acquisition for the prolonged initial integration process, are seen as vital requirements in the overall planning. In general, however, electronics tasks and milestones are still under-represented in CMS planning. This is apparent from several systems where manufacturing has been launched, but electronics now appears on or near the critical path. Also from the re-emergence of mechanical integration conflicts as on-board electronics and services become better defined, and stray outside previously agreed envelopes.

II. CMS SUB-SYSTEM ELECTRONICS

In this section the status of electronics in the sub-systems is briefly (and certainly incompletely) reviewed. The focus is firmly on the on-detector electronics which are clearly on the critical assembly path to a working CMS. Details (and most probably corrections to inaccuracies) can be found in many other talks given at this workshop. In general progress is remarkably good, but CMS has several difficulties to overcome, which will be pointed out.

A. Silicon strip tracker

A remarkably successful front-end chip development using 0.25 µm technology is now nearing completion. The expectations for yield, functionality, low power, small size, low-cost and radiation tolerance of the APV25 have all been met or exceeded. Now that a single technology (silicon strips) has been chosen for the CMS tracker, only this one variant of the front-end chip is required. A few APV25's were tested in beam at PSI earlier this year, and the measured signal-to-noise was as expected.

The optical link, second most important cost-driver in the system, is also progressing well. Using older APV6 front-ends, the full system functionality (control, synchronisation and optical links) was exercised at high rate in the CERN X5 beam with 25ns bunch repetition structure. The measured signal-to-noise was as expected.

Automated testing and assembly systems are in place, giving confidence that high quality and yield can be maintained during a distributed bulk production of silicon sensors. A Procurement Readiness Review (PRR) for sensors and electronics has been successfully passed and an ESR is planned for mid-2001 following a further full-scale system test in a LHC-like (25 ns) beam, using pre-series sensors and final choices of cables and power supplies.

Figure 2 shows an overview of the system.

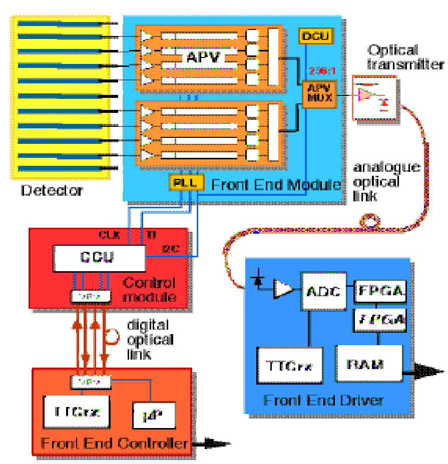

Figure 2: Tracker front end

B. Pixel tracker.

Development of the readout chip and column drain architecture continue, with submission in DMILL of a near final prototype having taken place very recently, and due for delivery by the end of 2000. For this prototype, the controls block will be added as a separate item. The bump-bonding technology to connect sensor and readout chips has been successfully mastered at PSI. Assuming good performance of the DMILL readout chip prototype, an alternative in 0.25 µm technology will be explored in Spring 2001.

C. Crystal Electromagnetic Calorimeter (ECAL)

The crystal electromagnetic calorimeter (barrel and endcaps) uses an on-detector "light-to-light" readout chain, as shown in Figure 3.

A contract with Hamamatsu for 120,000 APD's has been placed and, based on the initial production of 6000, fine tuning is being done in conjunction with the manufacturer to overcome ageing and radiation tolerance problems which occur at the few percent level. The twin-APD capsules are permanently attached to crystals during sub-module assembly, and delivery must match the assembly schedule requirements of modules and supermodules.

The first pre-production run of the Harris rad-hard floating point preamp is starting after delays while unsatisfactory yield and cost were worked on. Similar poor yield was obtained from the serializer (Honeywell CHFET) pilot production. A new run is in progress and an alternative in 0.25 µm technology is being considered.

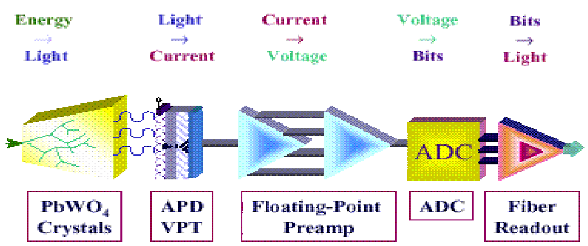

Figure 3: ECAL front end.

Despite these difficulties, the full light-to-light chain works and is rad-hard. Similarly the clock and data chip is ready to produce. Although the test of several hundred front-end channels has been delayed by more than a year, it is now intended to conduct this as part of an comprehensive system test in beam during 2001. The delivery schedule must be matched to the fitting-out of supermodules for beam calibration starting in 2002. Thus, though little time contingency remains, the ECAL electronics can still be delivered on a schedule matching the ECAL detector hardware, which is itself probably the most critical CMS sub-system with respect to contingency.

D. Preshower

The requirements of 5% charge measurement and 1-400 mip dynamic range distinguish this silicon detector from the tracker. The front-end ASICs will now be switchable gain, and the preamp and analog pipeline have been physically separated. A prototype DELTA preamp exists in DMILL and preamp + multiplexor prototypes have just been received. The PACE ADC/memory submission is imminent and the data concentrator chip is being prototyped.

The ADC is the AD9042 (as ECAL) and the optical link is also from ECAL. The control (CCU) is taken from the Tracker design and the biggest unknown is clock-compatibility between this and the ECAL opto-link. The Preshower is on target for an ESR in about 12-18 months.

E. Hadron Calorimeter (HCAL)

Final prototypes of the 19 and 73 channel variants of the Hybrid Photo-Diode (HPD), which is the photo-transducer in the HCAL "light-to-light" on-board front-end, are expected by the end of 2000. Work is going on with the manufacturers (Canberra/DEP) to solve minor problems of HV breakdown and cross-talk.

The QIE (charge integrator and encoder) development is now near the critical path for HCAL lowering into the underground area. However, Fermilab has now committed the engineering resources needed to complete the development in time, providing there are no bad submissions or other delays. It is important that the time for burn-in of HCAL front end electronics, on the detector half-barrels and endcaps in the surface building, should not be treated as contingency.

Access to the 36 HCAL barrel readout boxes containing HPD's and QIE's is the source of a re-emerging mechanical integration challenge because of the densely packed tracker cables passing in front of these boxes as they exit the detector through the gap between barrel and endcaps. The bulk of these cables carry low voltage and are in the course of being defined.

F. Muon System: endcap cathode strip chambers

The on-detector system is shown in Figure 4.

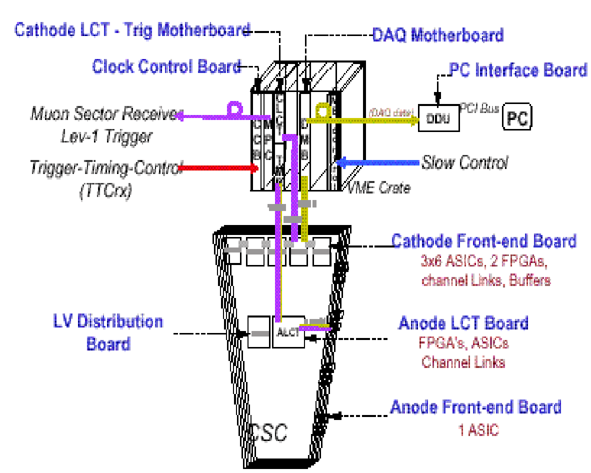

Figure 4 : Muon endcap on-detector electronics

Final prototypes of the on-board cards have been fully tested for functionality and integration onto the chamber, including cooling. Radiation testing was recently finished and formed a major topic of the ESR completed in September 2000. This review raised the strategy for SEU mitigation as an important issue not only for the muon endcap, but for CMS as a whole. In particular it is likely that the on-board Anode Local Charged Track (ALCT) board may have to be revised as a result of these concerns. This may absorb the remaining few months schedule contingency and bring the on-chamber electronics close to the critical path for cathode strip chamber (CSC) installation. A recent trigger integration test was successful and a good example for other sub-systems. First prototypes have been tested of off-chamber trigger and control boards, which are mounted on the magnet yoke periphery, in VME crates exposed to considerable radiation and magnetic fields.

G. Muon System: barrel drift tube chambers

Figure 5 shows the overall on-board system layout.

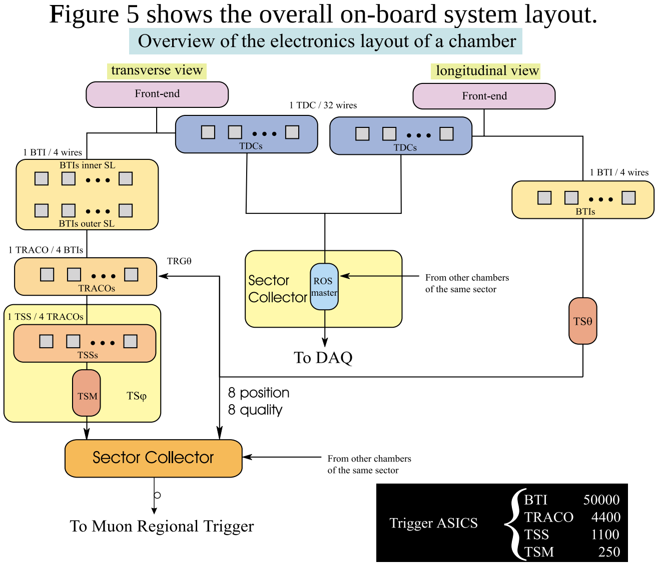

Figure 5: Muon barrel drift tubes on-detector scheme.

The front-end (MAD) ASIC and high-voltage distribution/signal pick-off cards, mounted within the drift tube (DT) chamber gas volume, were approved in a PRR in late 1998 and are in bulk production.

The remaining local electronics (TDC's and trigger track element processors) are mounted in custom mini-crates on the chamber structure, though outside the gas volume. The bunch-crossing and track identifier (BTI) and part of the trigger chain are fully prototyped and were reviewed in the September 2000 ESR. Pre-production HPTDC's, developed at CERN in 0.25 µm technology, are due for delivery to the muon system users in October.

The BTI in particular is sensitive to foundry delays and the overall schedule risk here, as for the endcap CSC's, is not the rate of electronics delivery, but the delay in starting manufacture, which will likely determine the earliest date at which muon chambers can be inserted in the magnet yoke in the surface building at point 5. Modifications to simplify installation of mini-crates on already installed chambers are being actively considered.

H. Muon System: resistive plate chambers (RPC)

The RPC front end chip (AMS 0.8 µm CMOS) showed good yield from a 1000 chip pre-production. Automatic testing has been commissioned and radiation tolerance tests of the on-detector front-end plus control board are now complete following some delays.

Here again, foundry delays in RPC electronics manufacture could become critical for the overall CMS schedule, because in all 4 barrel layers, and the first layer in the endcap, RPC's are mechanically constrained to be installed simultaneously with the drift tubes and CSC's.

J. Level 1 Trigger

The first phase of the level 1 trigger design has been successfully completed, with all boards prototyped and tested, and a Technical Design Report (TDR) in the final stages of editing. Figure 6 shows the schematic layout of the level one trigger system, the only hardware trigger level in CMS, which must reduce the 40 MHz beam crossing rate to 100kHz (without loss of physics!).

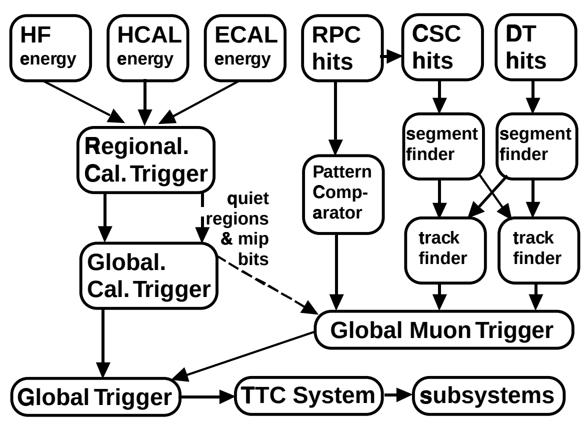

Figure 6: Schematic layout of Level 1 trigger system

The functional parts located in the experimental cavern are : the CSC/DT track segment generation, the RPC muon hit generation and the calorimeter digitisation (only). The remainder of the system is located in the shielded underground service cavern (USC) and comprises the CSC/DT muon trigger track finder, the RPC muon trigger pattern logic, the calorimeter regional and global trigger and the global Level 1 trigger.

Phase 2 (pre-production prototypes) will be launched upon completion and acceptance of the TDR. Concerns are that latency may be too close to the limit (particularly in the pre-shower, where a re-design of the front end chip may be indicated) and that a simplification of the DMILL TTCRx (timing and control) chip could also be considered. In general more tests of sub-system compatibility are needed, in addition to the formal interfacing checks made as part of the ESR process.

The layout of trigger cables between the detector and the USC and the allocation of USC racks have been carefully modelled in 3-D CAD in order to respect the path-length limits from latency, the population limits on cable chains and ducts and the maintenance principle that no disconnection should be necessary to permit opening of CMS into separate sections.

K. Data Acquisition

The Technical Design report for the DAQ system is due in November of 2001, thus it is currently still in a research and development phase. A series of 4 increasingly complex demonstrators of the event builder and filter functionality is scheduled to be built during 2000/2001. The first, currently operational, uses 33 PC's, has a 20Gb/s event builder and allows comparison of GEthernet and Myrinet 16 x 16 switching networks.

The equipment of the USC counting room and the provision of trigger signals and DAQ system integration at the appropriate time for CMS sub-system and experiment commissioning are recognised as schedule-critical activities for CMS. The intention is to start data-taking with 25% of the full capacity, doubling for each of the subsequent years. Thereafter, one third the full capacity system will be upgraded every year. Based on current technology trends, this will lead to a constant funding profile being required from 2005 onwards.

L. Controls

This vital part of CMS falls under the general umbrella of the DAQ project, but requires very close collaboration with the sub-detector hardware and online software projects and a CMS critical delivery date of summer 2004. The CMS Detector Controls System (DCS) architecture envisages two broad functions The first is to monitor and/or control such quantities as gas-flow, voltage, temperature, coolant flow, magnetic field etc - the classical province of "slow controls". The second is the control of the download of constants and software to the front-end systems, and the supervision of calibration data-taking within the local DAQ of each sub-detector. The development is taking place within the framework of the LHC Experiments Joint Controls Project, which envisages a common commercial platform as the foundation of the controls system and recognises that a scalable, hierarchically organised and fully partitionable system will be needed, with availability before the first sub-detector starts to commission underground. User requirements have been defined and a yearly review meeting organised, but the participation of CMS sub-detector groups is not yet at an adequate level.

CMS will also implement a standalone Detector Safety System, independent of DCS, but communicating closely with it, which is designed to protect the capital investment in the apparatus. This consists of a set of independent "hard-wired" sensor-actuator logic loops each configured to prevent specific potentially damaging situations from developing.

III. CMS ELECTRONICS COORDINATION

A. Electronics Systems Co-ordinator

The need for an electronics co-ordination structure was realised early in CMS, but the current working solution was developed quite late and after considerable difficulties. The Electronics Systems Co-ordinator and an associated electronics integration group were initially envisaged as a direct parallel with the Technical Co-ordinator and the Engineering Integration Centre. First attempts to implement this led to much progress (eg in establishing radiation testing criteria and in launching the muon DT front end) but also much strife. From the resulting vacuum, a pragmatic scheme arose which takes account of the CMS structure and "management" (see section I), and also of the resources available. The appropriate parallels with engineering co-ordination were seen to be: that each sub-project has a parameter space to work in, within which details are largely their choice; that common projects are relatively few and evolve naturally; that internal review is the best guarantee of detailed design and component choice and that Electronic System Reviews, following general and agreed guidelines, and including external experts, are the best guarantee of overall compatibility between systems. The Electronic Systems Co-ordinator is now fully integrated into the CMS technical co-ordination and management teams, provides the link between the CMS Management Board and the Electronic Systems Steering Committee, and is supported by a small technical task group from the collaborating institutes.

B. Electronic Systems Steering Committee

The membership of this body (ESSC) are the electronics experts from each sub-system plus the controls co-ordinator, the deputy technical co-ordinator, the services and radiation issues co-ordinators, and other members of CMS technical co-ordination as needed. Its mandate is to establish and modify guidelines by consensus, to provide the co-operative environment in which co-ordination can work, to act as a forum for informal exchange of ideas and practical experience and to support and monitor the few common projects.

The committee is chaired by the Electronics Systems Co-ordinator and is delegated some steering functions for electronics matters. (eg validation of ESR reports, establishment of cross-project task forces).

IV. PERCEIVED RISKS

A. On-detector Electronics

This is the main focus of attention at present:

It is apparent that on-detector parts are already generally late due to a variety of development delays of which the most common are failed or poor yield submissions, radiation tolerance issues and testing, and lack of engineering resources. For several systems (HCAL, muons) action has been necessary to keep on-detector electronics off the critical path. It is clear that treating burn-in time as contingency must be avoided despite the schedule pressures.

The second class of problems and risks are in the transition to manufacturing, where there is vulnerability to foundry delivery schedules, to technologies disappearing, and to dependence on one (or few) key individual(s). Several systems could suffer these to some extent, which in many cases could have implications for the overall schedule.

Finally, system aspects which have not been tested could lead to unpleasant surprises later. These include EMC and grounding issues, where development of a compatibility policy is rather late, the absence (except for Tracker) of fully integrated system tests in beam with 25 ns structure, and the provision of design and maintenance tools for the lifetime of the system. Accessibility of the front ends for maintenance is in some cases hardly better than for satellite-mounted systems in space and it is difficult to judge whether reliability will be good enough.

B. Off-detector Electronics and Services

Although the off-detector systems and services seem less crucial at this stage, they easily become irrecoverably critical during installation, commissioning and subsequent maintenance phases. Underestimation of service volumes can lead to integration and material budget problems re-emerging and the procurement and installation of services must be carefully matched to the windows available in the overall schedule. Low voltage supply to a hostile environment has lead to several sub-detectors (Tracker, ECAL) choosing to supply over long cables at low voltage, from supplies located outside the experimental cavern. This requires cooled service-ways and complicates the establishment of thermal balance and the maintenance procedures. The controls system development merits more attention, given that it must be ready before the first sub-detector starts to commission underground. Similarly the trigger and DAQ integration period is likely to have been underestimated and is liable to shrinkage from wishful thinking as schedule pressures increase.

V. CONCLUSION

CMS on-board electronic systems are advancing well and approaching final review before launching procurement or manufacture. Most have encountered unexpected problems with schedule or integration, and remedial action has been necessary to keep electronics off the assembly critical path. The emphasis is now changing from chip development to system aspects and inter-system compatibility. Few sub-detectors have yet conducted full system tests.

A workable electronics co-ordination structure is now in place, and guidelines have, or will be, evolved for several crucial areas such as radiation testing and grounding. Many others need more study to establish consensus and ensure compatibility.

The biggest risks are vulnerability to delay during the transition to the manufacturing phase (leading to burn-in time being used as contingency), underestimation of the time for services and off-detector electronics installation, and similar underestimation of the time for commissioning, including integration with controls, trigger and data acquisition.

VI. ACKNOWLEDGEMENTS

I would like to thank the organisers for inviting this contribution to a very well managed workshop. I am also grateful to my colleagues in CMS for providing source material at rather short notice. The local hospitality in Krakow was memorably warm and this contributed much to the informal and constructive atmosphere.