CMS Optical Links
Lessons Learned from Mass Production

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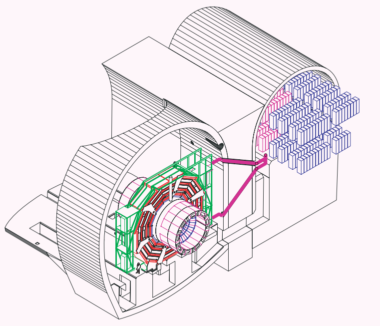
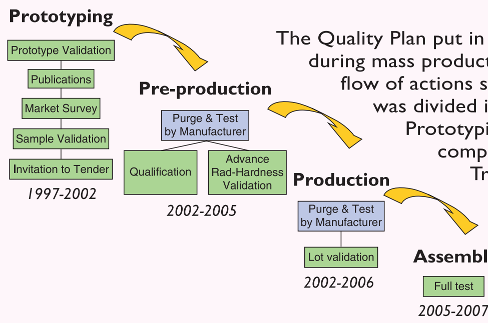
CMS Optical Links

The CMS Tracker, located at the very centre of the CMS detector at the LHC, will install over 40000 optical links in its data readout and control system, representing an unprecedented deployment of this technology in a Particle Physics Experiment. These data links connect the silicon detectors inside the tracker with the data acquisition system situated in the adjacent underground cavern, as distance of approximately 65m. The installed system has an expected lifetime of 10 years, with a limited possibility for maintenance due to the location of the front-end components throughout the complex structure at the heart of CMS. Large numbers of high quality components have thus been produced to meet the requirements.



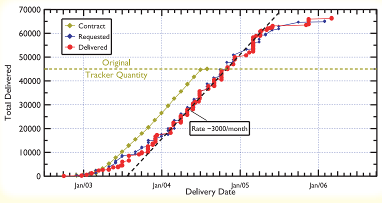


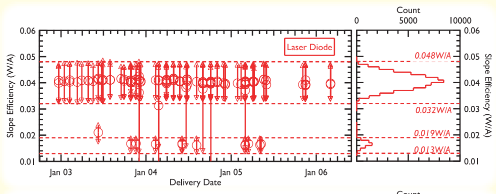
The Quality Plan put in place in order to ensure the required quality during mass production of optical link components led to the flow of actions shown in the diagram to the left. The project was divided into four distinct phases, starting with Prototyping and ending with the Assembly of the components into the structures of the CMS Tracker. Industrial partners were vital to provide the production capacity needed for the large number of components in the system. For this reason all components are COTS or COTS-based with minimal modifications.

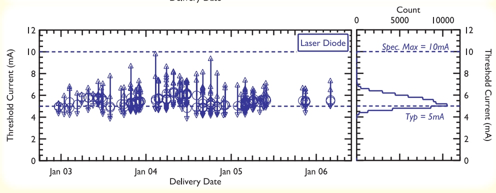
Analogue Readout

Laser Diodes

The contract for supply of laser diodes was awarded to ST Microelectronics of Milan, Italy, in 2002 for a total quantity of 45000 for the CMS Tracker Readout and Control systems. The same component was then also re-used by the ECAL readout and the ECAL and RPC control systems, leading to an increase in total quantity to over 65000 lasers. After some initial difficulties for the manufacturer to ramp-up production due to staff training issues and vacations, the target rate of 3000/month was achieved and maintained for over one year. Performance in terms of uniformity of measured parameters remained excellent throughout production, as shown in the two trend graphs to the left. Values measured during production remained centred within the specification window.

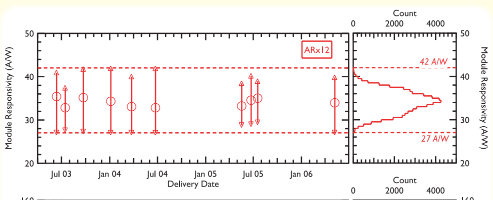


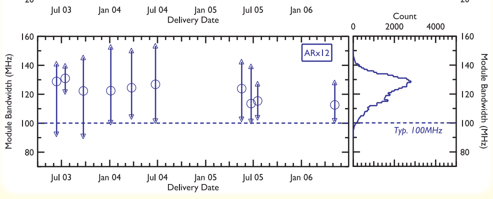




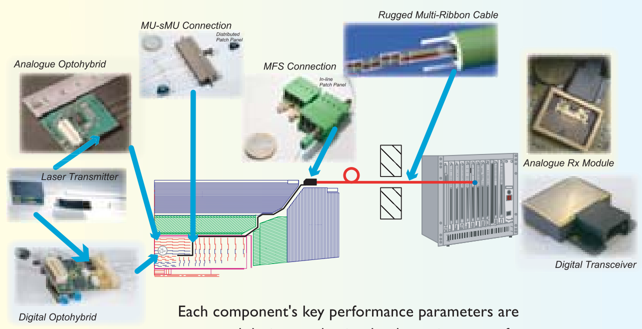
Analogue Receiver Modules

The CMS Tracker Readout system requires a total of 4500 analogue receiver modules (ARx12). NGK Ltd of Japan delivered the intitial quantity of 85% in the first 6 production batches up to July 2004 and subsequently had to wait for almost a full year before the order confirmation was granted by the Tracker for the full quantity. This explains the first gap in the trend graphs below. A final purchase was made for spares in 2006 before the supplier closed their optoelectronics manufacturing facility. This component is the only one to have passed the qualification testing in the first pass, a testament to the high production quality achieved. The two graphs to the left once again show that the production is well centred within the specification window for the gain (upper plot), and in excess of the typical specification on bandwidth (lower plot).



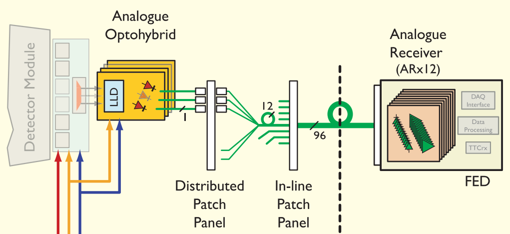


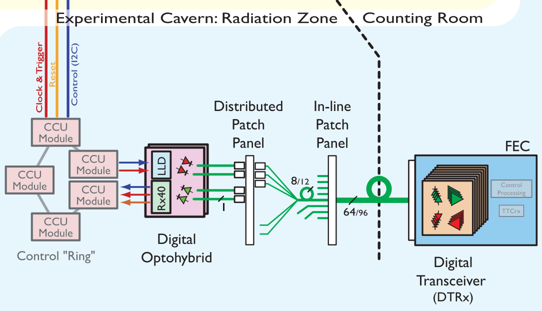
Implementation



Each component's key performance parameters are measured during production by the various manufacturers and the data are supplied to CERN.

Analogue System Overview



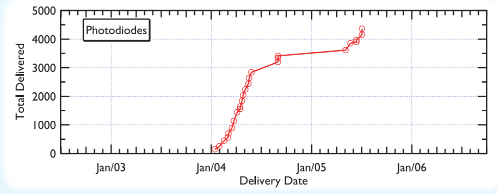


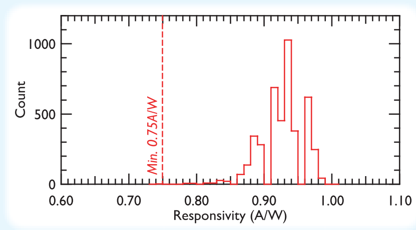
Digital System Overview

Digital Control

Photodiodes

Once development of the digital control system of the CMS Tracker had been completed, several other sub-detectors in CMS decided to use it (ECAL, RPC & TOTEM). This led to an overall doubling of the required number of links and thus of components. This change was known before the production of photodiodes had ramped-up and the bulk of the production could occur at once. The last quantities of spares and late additions were delivered in mid-2005. Production uniformity was good, with Fermionics of California, USA, taking sufficient margin for device responsivity w.r.t. the specification - as shown on the graph to the right. Other parameters showed a similarly good overall performance which gives confidence that the digital link will operate with sufficient margin.



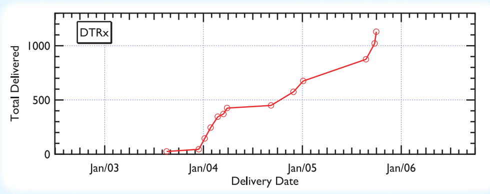


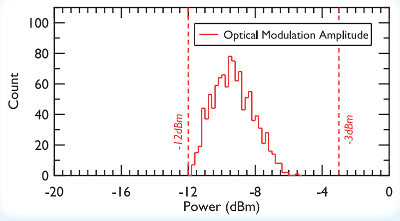
Digital Transceiver Modules

The digital transceiver (DTRx4) is the only part in the entire system that was a pure COTS part from NGK of Japan. This module was designed for digital operation at 2.5Gb/s per channel, which would yield a bi-directional 10Gb/s link with 4+4 (Tx+Rx) channels between modules.

The first task of qualification was thus to ensure that the modules would operate at the CMS Tracker Control System data rate of 80MB/s. Production of DTRX4 started before funding was fully available for the parts of CMS that were late to make use of the Tracker Control System, which led to a distinct step in the production with a 6-month gap. Finally, funding for spares was long in being made available and came just in time for the last buy notice that preceeded the closure of the manufacturing facility.

Once again the manufacturer's production measurements show that production met the specified performance targets. The Optical Modulation Amplitude is the size of the signal produced by the Transmitter portion of the DTRx.



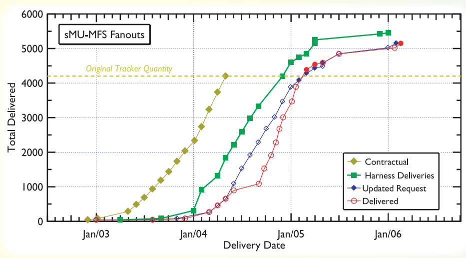


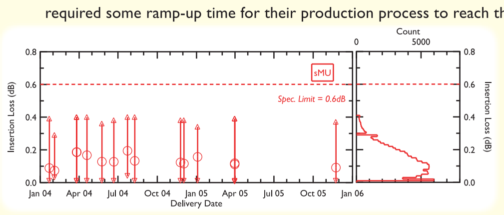
Fibre Plant

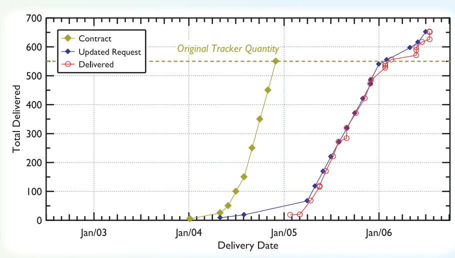
Single-fibre connectors are used in the CMS Tracker to connect the highly distributed transmitters and receivers of both the control and readout systems to high-density 12-fibre ribbons. The connector type chosen by CMS for this task is the industry-standard MU, which provides the highest stacking density of any standard connector. This high density is required due to space constraints inside the Tracker.

Production of the sMU-MFS (single-fibre to multi-fibre ribbon) fanouts proceeded in two steps: in the first Sumitomo of Japan produced symmetric harnesses with individual fibres broken-out of the ruggedised ribbon at both ends; this assembly was then cut by Diamond of Switzerland who terminated the ribbon directly with the chosen ribbon connector. Both manufacturers required some ramp-up time for their production process to reach the specified performance. Once this stage was overcome both manufacturers were able to sustain a high production rate over approximately one year. The last deliveries were delayed by the need to reach a consensus within the user community for final needs and funding.

The graph to the left shows that the high performance of the single-fibre sMU was achieved throughout the production. The low losses achieved are in marked contrast to the expectation that the distribution would be a rectangle within the specification window.

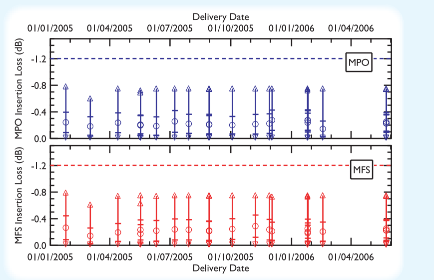


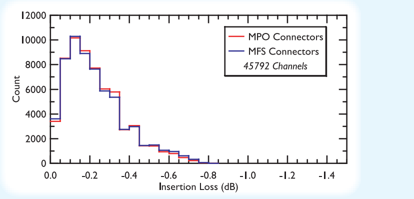




Rugged high-density multi-ribbon cables carry the signals over the longest span in the CMS Tracker Readout and Control links. These cables were the last items to be produced due to the long time required to obtain accurate lengths for these cables. Lengths must be known before cabling since the termination must be carried out in a controlled manufacturing environment.

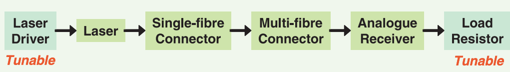
Performance of ribbon connectors is generally worse in terms of insertion loss than that of single-fibre connectors due to the difficulty in achieving geometrical alignment between multiple fibres simultaneously. Insertion loss of the connectors manufactured by Diamond of Switzerland (shown in the graphs to the right) was uniformly good throughout production for the connectors at both ends of the cable (MFS at front-end & MPO at back end).



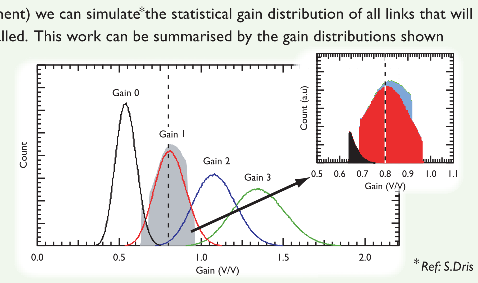


Simulating the System Performance Spread

In the analogue readout system of the CMS Tracker the gain is a critical parameter. The overall gain is the product of the gains of all of the components in the chain, as represented schematically below:



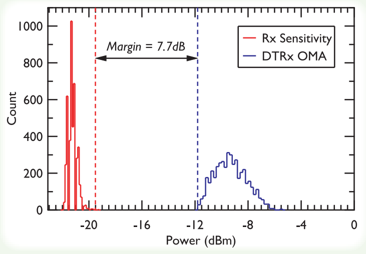
Since we have access to the production data (that includes the gain of each component) we can simulate* the statistical gain distribution of all links that will be installed. This work can be summarised by the gain distributions shown below:



*Ref: S.Dris et al, LECC 2004

Having access to the detailed performance measurements has been invaluable to implementing a fully functional analogue readout system. The high delivered performance of all components, especially the optical connectors, would have caused the final installed links to have too high a gain and thus a reduced dynamic range had it not been for the fact that it could be detected early enough to act. By reducing the size of the load resistor at the end of the chain it is now possible to have a system that will meet the overall dynamic range requirement. This would not have been possible without the detailed production measurements carried out by all the manufacturers. System testing using samples from production also allowed the scaling of gains measured during production at room temperature to the low (-10C) operating temperature of the final installed system.

Using the production measurements of digital link components it is also possible to predict the margin of operation of the installed system. This is shown in the graph below, which compared the signal output of the DTRx module with the minimum allowed signal size (sensitivity) of the front-end receiver with which it must operate. The system thus has a comfortable margin of operation.



Lessons Learned

For a large scale production such as this it is imperative to have detailed specifications, derived from user requirements, in order to have fruitful discussions with manufacturers at a sufficiently detailed level to overcome the inevitable problems related to the ramp-up of production.

The procedures used to qualify and accept production components must be in place before production starts for discussion with the manufacturer. Failure to do this leads to delays as discussion on how to do testing is re-opened when a component fails a test.

Ramping up of production took longer than predicted in all cases. This was due to a number of things, including optimism about the complexity of producing custom parts and poor quality of initially delivered components. The timescales on which problems were solved was measured in months, due to the complexity of the processes & components and the need to understand the root causes of problems.

The funding profiles available to large particle physics experiments appear to leave large gaps in procurements as decisions are taken to fund additional parts and/or spares. Where the manufacturer is dealing with a relatively standard product, such as connectors, this only poses a problem of fitting the new requirements into their production plan. However, where the components are customized the knowledge of how to produce them may go stale, leading to poorer performance of components produced later.

Overall, production of components took over three years to complete and, barring problems in start-up and re-starting, went very smoothly thanks to good preparation.

http://cern.ch/cms-opto