CMS Tracker, ECAL and Pixel Optical Cabling: Installation and Performance Verification

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Abstract

The installation of 52304 optical links for the readout and control of the CMS Tracker, ECAL and Pixel detectors is complete. 768 96-way optical cables were installed and tested using an optical time-domain reflectometer. The testing was followed by connections at high density optical fibre patch-panels. Finally, a further round of testing and troubleshooting following feedback from system commissioning with the Tracker Data Acquisition was carried out. Over 90% of the faults found were recovered, resulting overall in only 0.1% of dead optical link channels in the CMS Tracker.

I. INTRODUCTION

The Compact Muon Solenoid (CMS) [1] is one of two general purpose detectors at the CERN Large Hadron Collider (LHC) that began operation in 2008. The Pixel, Silicon Tracker and ECAL[1] sub-detectors, whose locations within the CMS detector are shown in Fig. 1, all use similar point-to-point optical links [2,3,4,5] for control and readout. These are based on 1310 nm edge-emitting lasers, InGaAs photodiodes and single-mode optical fibre cables. The Tracker uses a total of 39240 optical links, the Pixel 1456, the ECAL Barrel 7272, the ECAL End-Caps 4124 and the Preshower1592.

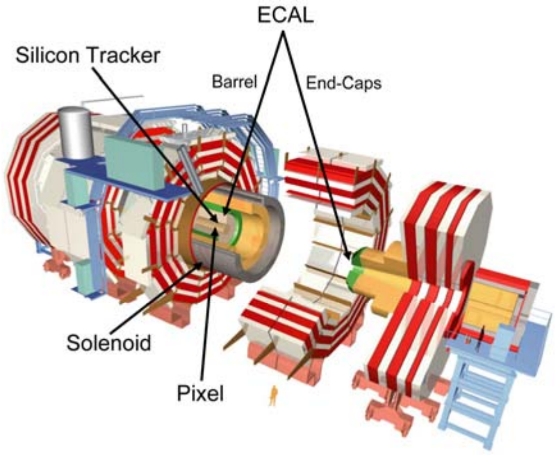

Figure 1: Exploded view of the CMS detector. Two barrel wheels and three end-cap disks for each side of the central barrel yoke (YB0) are movable along the axial direction. ECAL End-Caps and Preshower are installed on the first end-cap yoke pieces (YE+1 and YE-1).

The optical readout links are either analogue (Tracker and Pixel) or digital (ECAL), while the control links are digital with identical structure in all cases. Lasers and photodiodes are integrated onto opto-hybrids at the front-end and VME (FED/DCC/TCC and FEC/CCS) cards at the back-end as illustrated in Fig. 2.

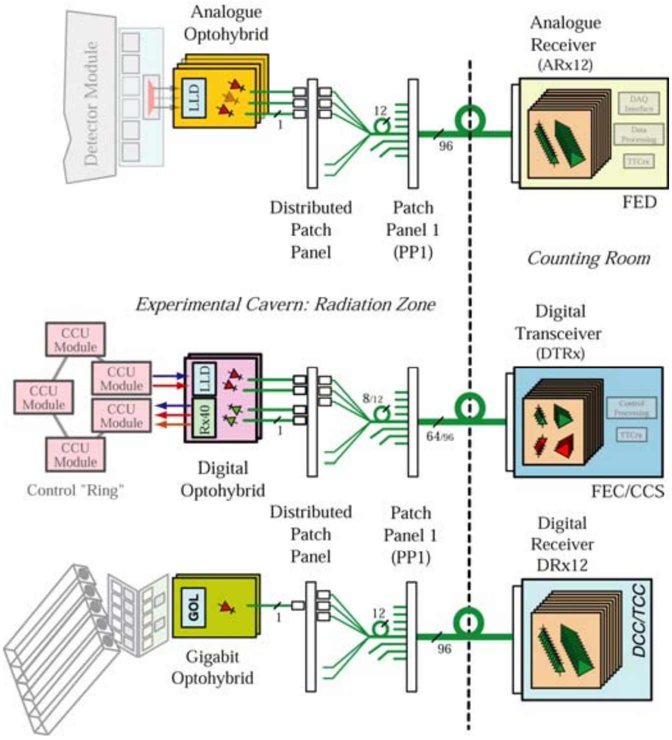

Figure 2: Optical link architectures. From top to bottom: Tracker analogue readout, digital control and ECAL digital readout links. The Pixel digital readout link (not shown) has analogous architecture and includes six laser transmitters for each optohybrid at the front-end. Also, Pixel, ECAL End-Caps and Preshower have extra in-line patch-panels (PP0) between the distributed patch-panels and PP1.

The final optical cabling, connections and tests took place in 2007 and 2008 as part of the overall CMS integration and services installation project. The Cabling and connection experience, Quality Control (QC) activities and early results on the link performance verification are reported in the following sections.

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[1] Electromagnetic CALorimeter.

II. CABLING AND CONNECTIONS

A. *Cable-plant layout*

Single pigtailed fibres are routed from the front-end optohybrids to a first distributed patch-panel that is embedded within the structure of each sub-detector (Fig. 2). At this patch-panel, groups of 12 individual pigtails are connected to optical fan-outs by means of flat-polished MU-type connectors. The rugged ribbon of the fan-outs crosses the bulkhead of the sub-detector to reach an in-line patch-panel (PP1) where the connection to the Multi-Ribbon (MR) cables is made using angle-polished 12-fibre ribbon connectors. The MR cables (containing 96 fibres made up of 8 12-fibre ribbons) cover the span from the experimental cavern to the racks in the service cavern. Their overall length varies between 50 m and 70 m depending on the sub-detector and the assigned path. The path of cables for the barrel-detectors (pixels, Tracker, ECAL Barrel) is shown in Fig. 3. At the back-end the connection to the VME modules is implemented with angle-polished MPO-type connectors.

Pixel and ECAL End-Caps have a slightly different optical link topology with additional 12-fibre patch-cords inserted between the MR cables and the fan-outs in order to cover the additional length necessary to reach the edge of the sub-detector (Fig. 4). Thus the connection between the patch-cords and the fan-outs takes place at an additional intermediate patch-panel (PP0). For Tracker, Pixel and ECAL Barrel the intermediate connectors are angle-polished (MFS-type) with PP1 and PP0 located inside the solenoid vacuum tank in YB0. In particular the Tracker and Pixel share the same PP1 which results in a very high density of connections.

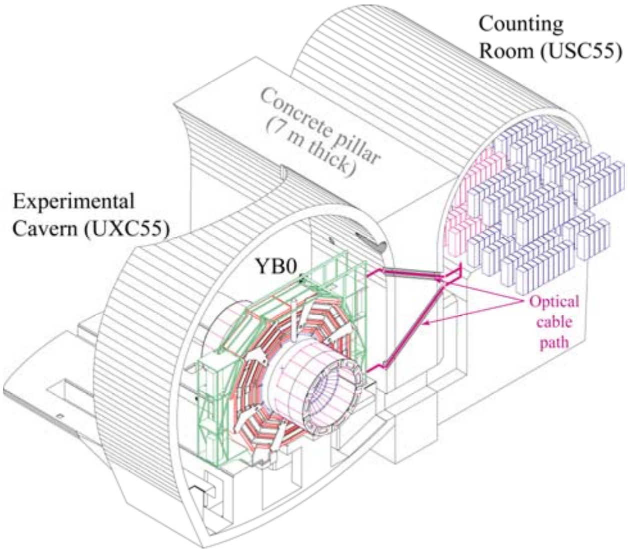

Figure 3: The CMS central barrel (YB0) is fixed in the middle of the UXC55 cavern. The optical cables for Tracker, Pixel and ECAL Barrel take the shortest path to USC55 crossing the pillar in the two diagonal tunnels.

For ECAL End-Caps and Pre-shower the equivalent of PP1 is placed at the base of YE-1 and YE+1 while PP0 is integrated in the detector bulkhead. Both patch-panels incorporate MPO-type connectors with the patch-cords spanning a length of 18 to 42 m across the End-Cap wheels.

The entire optical cabling system [for both readout and control] of Tracker, Pixel and ECAL comprises 4928 fan-outs, 684 patch-cords and 768 MR trunk-cables. During the cabling at LHC Point 5 (P5) the inner segments of the optical links, including the 52304 pigtails, the distributed patch-panels and part of the fan-outs, were already sealed in the sub-detectors volume and no longer accessible[2] (see Fig. 4).

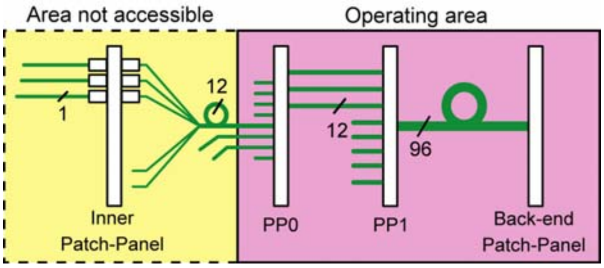

Figure 4: Inaccessibility of distributed Patch Panels. PP0 and intermediate patch-cords exist only for Pixel and ECAL End-Caps.

B. *YB0 cabling*

672 pre-connectorized MR cables for Tracker (530), Pixel (34) and ECAL-Barrel (108) were installed in 2007 on the CMS central barrel wheel YB0 during a 6-week cabling campaign that took place just before the Tracker was inserted. The cabling of YE-1 and YE+1 for ECAL End-Caps (72 MR) and Pre-Shower (24 MR) was done after both end-caps had been lowered into the cavern, during the first quarter of 2008.

The YB0 cabling procedure for Tracker, Pixel and ECAL was extensively practiced during the past years [6]. The cables were individually labelled and pre-assigned to a specific path according to their length and the length of the particular route before transportation to P5. Thus the intended connections were already frozen in a cabling map and corresponding database at this stage. Custom mechanical protection elements were added on both ends of each MR cable to protect the naked ribbon portions during handling and installation.

The optical cable installation and test commenced with the first six ECAL Barrel sectors (3 MR cables/sector). The cabling and test crew was then sufficiently trained to start the large installation of Tracker optical cables in parallel with remaining ECAL barrel cables that shared the same cable trays. The Tracker cabling is split into 32 sectors, with 16 PP1s on each side of YB0. Each PP1 houses an optical patch panel with four aluminium cassettes with total dimensions of 60 x 9 x 15 cm^3 (l x w x h). Each PP1 houses up to 20 MR cables and associated slack ribbon (up to 50 cm). The cables with their MFS connector blocks are arranged as in Fig. 5.

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[2] The front-end components were installed during the sub-detector construction phases (before the transportation to P5). The maximum fan-out tail length left out of the bulkhead is about 3.8 m (Tracker).

The cabling procedure is described next with the numbers of people involved shown for information in parentheses. To avoid kinks and twists in the cables, which were found previously to lead to losses in the transmitted signals, installation was made one cable at a time. Starting from one of the entrances to the tunnels on UXC55 side of the concrete pillar between the two caverns, the MFS terminated end was threaded along the cable trays (8 people) to the corresponding PP1 cassette where the cable was fixed in a strain relief. After a given cassette was filled (2 people), the MR cables were then bundled and fixed in the cable trays (2 people) at the same time as the next set of cables was being pulled in parallel elsewhere on YB0. Once a bundle was fixed along the entire length within UXC55, the cables were pulled one by one through the tunnel into USC55 (3 people) where they were individually routed (4 people) along the trays beneath the racks (in the 1.8 m tall false floor) to the final destination. The cable was then pulled up to the rack (2 people) and fixed to the corresponding crate. Finally the slack for a given cable was then wound onto a custom figure-8 support located below the rack.

At the peak of the cabling activity, the cabling and test team numbered 25 people and up to 35 cables could be laid per day (in a single 10-hour shift). All the procedural actions were tightly coordinated to fit together, the slowest action being the fixing of the cables in the trays, which required care to follow a precise path in order to fit up to ~200 optical cables into a given tray that often varied in cross-section as it followed the changing contours of YB0.

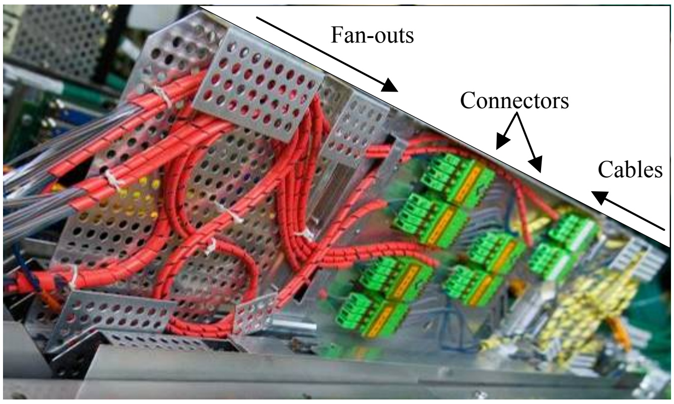

Figure 5: A fully occupied Tracker PP1 patch-panel cassette. The MFS ribbon connectors are positioned in the middle. Up to 50cm of slack per ribbon can stored on each cassette. Silicone spiral-wrap was added to organise and protect the bare fibre ribbons.

C. *PP1 and PP0 connections*

ECAL Barrel cables were the first to be connected at PP1 right after the MR cable validation test (see Section III). ECAL Barrel PP1 is made of aluminium boxes mounted on the edge of the sub-detector elements (supermodules) in which the fan-out tails (which were very short, only 10 cm long[3]) and MFS connector blocks are housed. The MR cables were pulled directly to the box and strain relieved. This allowed the rest of the cable length to be laid and fixed all the way to USC55 whilst leaving the connector block temporarily fixed at PP1. The validation test was then carried out (typically in the same day) after which the connection could be done and the patch-panel closed.

Tracker MR connections at PP1 had to wait for Tracker insertion, which took place in December 2007. The ribbon fan-outs, which were already connected to the Tracker distributed patch panels, had been pre-grouped, labelled according to their final PP1 destination and stored on mechanical support frames attached to Tracker bulkheads. The fan-outs were unbundled and carefully laid, sector by sector, PP1 cassette by cassette, in cable channels (3 m long x 30 mm wide x 100 mm deep per sector) going from the Tracker bulkhead up to the PP1 cassettes. Inside the channels the fan-outs were laid precisely in parallel layers and taped in place to make best use of the limited space in the channel. The naked portion of the fan-out ribbon at the PP1 end (80 cm long) was arranged in the cassette in the characteristic S-shape shown in Fig. 5, after the connection to the MR. During cabling of the Tracker sub-systems there were some mismatches in length (typically 10cm within a bundle of 4 neighbouring fan-outs) and this difference in length was absorbed in a small volume between the cable channel and the cassette which was reserved for this purpose.

The PP1 fibre connection procedure had been practiced in the previous months on a Tracker PP1/cable channel mock-up at CERN. The effort required to connect 40 fan-outs in a cassette was initially 4 hours (for the first 4 sectors) with a crew of 4 people. After this initial trial the procedure was streamlined, requiring typically only 2 hours and a crew of 2 people per cassette. The Tracker fibre connection activities had, however, to be fully integrated with the rest of the sequence of Tracker connections (including pipe-connections, barrel fibres, pipe insulation, barrel electrical cables, end-cap fibres, end-cap cables). In essence this was achieved by asking the crew to participate in all tasks besides piping which allowed the connections work to be evenly distributed in two daily 8-hour shifts spread out over many sectors in parallel (the maximum occupancy inside YB0 was 2x10 people per side) over a period of 2 months.

The Pixel detector patch-cords were installed and connected at PP1 after the Tracker fan-out installation. In this case the routing was from PP1 to the Tracker bulkhead where the pixel PP0 is located. After insertion of the beam-pipe and the Pixel sub-detector, the patch-cords were connected to the fan-outs at PP0 (August 2008).

The connections at the equivalent PP1 for the ECAL End-Caps and Preshower followed a similar procedure except that the patch-cords mounted on YE+1 and YE-1 were already installed before the CMS end-cap disks were lowered into the cavern. At the end of July 2008 the PP1 connections were completed. In parallel the sub-detector internal cabling was terminated and the various parts lowered. The connections at PP0 were done and tested immediately afterwards.

III. QUALITY CONTROL

The Quality Control procedures followed in P5 were originally defined for the Tracker and extensively practiced

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[3] With hindsight, this pigtail was too short as it did not allow easy manipulation of connectors or any possibility of repair.

during the previous 3 years [6]. A detailed description of the QC programme and the various test tools can be found in [7].

The test system is based around a high-resolution Optical Time Domain Reflectometer (OTDR) which can be combined with an optical switch or a custom-developed optical splitter for testing single fibres (switch) or full ribbons (splitter, 12 fibres at a time). The splitter option reduces the time of testing to one third with respect to testing a single fibre at a time (20 minutes/cable versus 1 hour/cable) and was thus used predominantly in P5.

The main goal of the test was to verify the mechanical integrity of the installed fibres and the good quality of the connections at the patch-panels. We were thus able to quickly give feedback to the cabling crews so that any problems observed could be corrected by planning an appropriate intervention and/or changing the cable-laying/connection procedures. A second objective was to measure the total length of the installed optical links with a precision better that 20 cm (necessary for the synchronization of the Tracker [8] and other sub-detectors). This requirement and the fact that only one end of the optical system was accessible for the measurements led to the choice of using a photon-counting OTDR during the tool selection process.

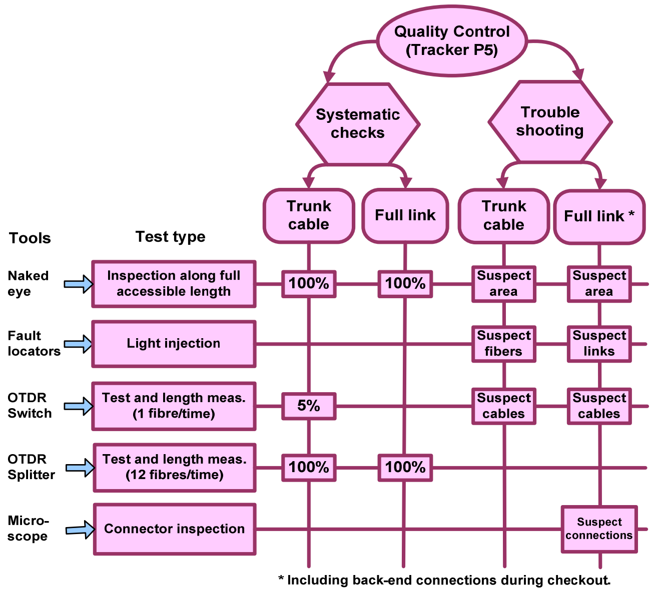

Figure 6: Example of the QC scheme followed for the Tracker. Similar procedures were followed for the other systems.

The scheme in Fig. 6 summarizes the Tracker QC procedure adopted in P5. The Pixel and ECAL groups adopted the same procedure. The test crew was typically composed of two experts and two technicians sharing two OTDR test systems (one provided by Tracker, one by ECAL) combined as necessary with either a switch or a splitter, plus two microscopes (600x magnification) for connector inspection. A variety of cleaning tools (5 different types for all kind of installed connectors/adapters), ribbon and single-fibre fault locators and two fusion splicers were also commonly used for troubleshooting interventions.

A. *Test activity*

To be efficient in indentifying problems and planning adequate interventions the test activity had to closely follow the installation progress. The test started immediately after the first ECAL Barrel cables were pulled (test of the trunk-cables) using the OTDR combined with the switch to gain a detailed picture of fibre integrity along the cable path. After testing 20% of the cables without observing problems, both the testing and cabling crew were judged to be sufficiently well-trained. This also allowed the testing to continue using the splitter configuration and thus speed up the testing by 60%. ECAL Barrel cables were entirely tested from the back-end (their installation in the rack patch-panels followed immediately after routing) and connected at the front-end sector by sector after each test. Afterwards the cables were re-tested again (test of the full-link) and the connectors re-cleaned/re-mated if necessary before final validation and connection at the back-end.

The Tracker and Pixel procedures were similar, with the difference that the connections at PP1 did not immediately follow the cable installation (the Tracker was not inserted yet) and the test of the trunk-cables had to be carried out from the front-end side (from inside YB0) due to the fact that the back-end cable protections were not removed until all cables were installed. After completing 30% of ECAL cabling, the Tracker/Pixel MR cables started to be laid and a second test crew started the test from PP1. The OTDR was equipped at the beginning with the switch (5% of the cables for validating the installation) and then with the splitter. Custom-built patch-cord adapters were used for the connection to the cable MFS blocks. Once the cabling installation was complete, preparation was made for Tracker insertion and the last 20% of cables were tested from the back-end.

After Tracker insertion and its connection at PP1 the testing was done entirely from the back-end with 2 OTDRs and 4 people working in parallel. Two more people focused on the troubleshooting at PP1 based upon feedback from the back-end crew.

For ECAL End-Caps and Pixel the OTDR testing was done in three steps: 100% of the MR cables; 100% of the patch-cords; then a fraction of full-links - those requiring troubleshooting for pixels after feedback from the DAQ system; and 60% of ECAL End-Cap links - only 60% were tested due to the limited time available.

B. *Test results*

Table 1 summarizes the test results. For the MR cables (including the extension patch-cords) only 0.27% of the total ribbons were found to be broken and in all cases a repair (splice) or a replacement with an installed spare ribbon was possible. For the full-links it is worth distinguishing between damage along the fan-out tails and problems caused by dirty, scratched or badly mated connectors. In the first case only one Tracker fan-out was broken so close to the bulkhead that no repair was possible. Hence the corresponding 12 optical channels were lost (0.03% of the total). In the case of problematic connections at PP1/PP0, the re-cleaning/re-mating interventions were highly successful although 25% of the problems required from two to four troubleshooting

Table 1: Summary of test results.

	Trunk-cables (100% tested)			Full-links						
	Total ribbons	Broken/ Stressed	Repaired/ Replaced	Connected fan-outs	Total tested	Broken/ Stressed	Repaired/ Recovered	Dirty/Bad connections	Recovered	MU flagged for DAQ
Tracker	4240	10	10	3600	100%	10 broken 6 stressed	12 (1 lost; 3 stressed)	125 PP1 (3.5%)	107 (86%)	1075 (2.7%)
Pixel	500 (228[a])	2[a]	2[a]	184	16%[b]	0	0	16[d] PP1 (7%) 0 at PP0	15 (93.7%)	19 (5.5%[e])
ECAL Barrel	864	2	2	720	100%	0	0	38 PP1 (5.3%)	no action taken	344 (4.7%)
ECAL End-Caps	1032 (456[a])	3[a]	3[a]	424	94%[c]	0	0	44 PP1 (11%[e]) 41 PP0 (10%[e])	25 (29%) 60 no action	24 (1.3%[e])
Preshower	344 (152[a])	2	2	System not yet installed						

[a] number of PP1 to PP0 patch-cords; [b] troubleshooting only; [c] in 61% only 2 fibres/ribbon tested;
[d] PP1 connections 100% tested in this case; [e] of total tested.

interventions. Each intervention lasted in average 2 hours and required gaining access to the related PP1/PP0, removing the fibre protection, extracting of the block of connectors from the cassette (in the Tracker case) and various re-cleaning/re-mating cycles followed by as many OTDR tests as necessary until the problem was fixed or judged unsolvable.

All cases in which the connection could not be fixed were flagged for further investigation by DAQ experts. All those MU connections suspected to contribute to a reduction of the corresponding link gain were also flagged.

IV. PERFORMANCE VERIFICATION

As natural extension of the Tracker QC program, the performance verification aims to verify the achievement of the specification targets for the analogue optical links when the system is operational. In the Tracker analogue readout links it is possible to measure different parameters including the laser threshold/bias and the overall link gain at the operating temperature. The initial QC phase started in July 2008 when the cabling functionality was checked by progressively powering up various parts of the detector (checkout). This required some troubleshooting, especially at the back-end where the connections could not be checked with the OTDR. The interventions on the back-end connections were based on a dry cleaning followed by a microscope inspection on both connector sides and additional cleaning cycles if the problem persisted. If necessary an OTDR test was repeated to exclude the presence of new damage that may have occurred along the cable path.

Table 2: Tracker checkout troubleshooting results

Total channels	Blind/Low gain	Recovered cleaning	Still recoverable	Other causes	Total lost
36392	391* (1%) in 163 connectors	255 (0.7%) 74 connections inspected	24 (0.07%)	74 (0.2%)	38* (0.1%)

*including lost known from integration and OTDR test on full-links.

Table 2 summarizes the results of this activity. Those channels for which the connections were not cleaned successfully are flagged as still recoverable with a more aggressive cleaning action or by replacement of the receiver modules. The problems on those channels for which the connections were found to be clean and the OTDR did not reveal anomalies are thought to be due to other causes within the Tracker system. At the end of August 2008 the Tracker was more than 99% functional with only 0.1% of fibre-channels lost. The possibility of recovering a few low gain channels still remains. Fig. 7 shows the measured gain of the links after optimisation to bring the output gain as close to the target value of 0.8 V/V as possible. The noise of the links is under study, as is the laser threshold current. All these parameters are temperature-sensitive and will be tracked by making periodic scans of the optical link characteristics as the Tracker operating temperature is decreased in steps towards the intended operating temperature of -20°C.

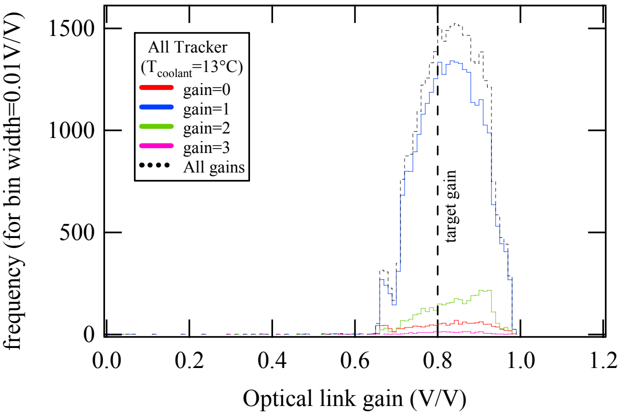

Figure 7: Measured Tracker analogue optical link gains with Tracker coolant circulating at 13°C. The target gain is 0.8 V/V. Front-end AOH gain setting (0, 1, 2 or 3) has been automatically selected to optimise the resulting output. Low gain values can be due to problems not related to the optical links. For more details on switchable gain function and expected distributions, see Ref [9].

V. DISCUSSION

With hindsight and given the very good results of the fibre-optics installation, it is useful to consider whether it was worth the effort and resources that were devoted to the thorough test and measurement campaign. Developing the custom OTDR test setup (hardware/software), practicing the procedure and training the crew (4 people plus 2 experts) required more than a year of specialized engineering work. In addition a year was then spent testing and troubleshooting.

Considering first the choice to use an OTDR for testing: we recall first of all that this choice was originally also motivated by the wish to measure the full-link lengths with high precision, as required as an input to the Tracker synchronization procedure [8]. This point proved less important than other factors: the first of which is that the optical links are accessible only from the back-end connection, once connected at (PP0 and) PP1 patch-panels. This means an OTDR is the ideal instrument as it works with reflected light signals. In addition, when a fibre is broken it is very important to know which cable section contains the break. For example, in a PP1 the MR cable is relatively easy to remove and repair (in 2 hours of access) but the fan-outs are much more fragile, being densely packed where a repair can require as much as 2 days of uninterrupted access to PP1.

Considering the argument that the small number of eventual problems did not warrant the large effort expended on testing, we note that the success of this activity largely originated from the fact that precise and punctual feedback was available from the test activity. This allowed efficient refinement and evolution of the details of the cabling and connections procedure. This capability provided the confidence to increase the installation rate as needed to minimize the time spent on the 'critical path' of CMS installation.

A standalone test-setup was chosen mainly in order to avoid needing to wait a long time for feedback on link performance based on the quality of data coming from Tracker operations. The Tracker, like other CMS systems could not operate and provide feedback until all parts of the system were available such as cooling, power, slow control, safety and DAQ. Due mainly to problems with the Tracker cooling, it was several months after cabling finished before performance data was available, by which time there was no longer access to the PP1s as CMS was closing ready for LHC operation. In addition, the problems found during Tracker operations might have a variety of causes, given the complexity of the system. Having a standalone system meant that all the problems in the fibre system were traced quickly and efficiently, with those originating inside YB0 volume being diagnosed and solved during the relatively brief access period.

VI. CONCLUSION

In 2008 a major milestone was reached with the completion of integration of the CMS experiment. The optical cabling and connections for Tracker, Pixel, ECAL and Preshower went smoothly and was carried out as an integral part of the wider services installation. In this context the detailed planning for fibre installation and test was combined with other neighbouring tasks allowing a smooth and predictable workflow over what proved to be a demanding task.

Rapid feedback on the quality of cabling and connections was provided using a test system based on a high resolution OTDR, which was also later used for further troubleshooting as well as providing the lengths needed for Tracker synchronization.

The quality of the cabling and connection work was excellent. The number of broken/stressed ribbons was well below 0.5% with only one broken ribbon proving to be unrepairable. Also, the troubleshooting capability for the problems discovered at connections in the patch-panels was very high (over 80% success) leaving the Tracker, for example, with only 0.1% of lost fibre channels.

Ultimately the quality of the cabling and connections, as well as the test and measurement programme was built on good preparation, training and an excellent team spirit during 15 months of optical cabling activity in CMS.

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