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Joint ATLAS-CMS working group on optoelectronics for SLHC

Report from sub-group A
Lessons Learned and to be Learned from LHC

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Abstract

This note gives a summary of the lessons learned from the current generation of LHC optical links as installed for the ATLAS SCT and Pixel detectors and the CMS tracker. A comparison of the costs for the different optical links systems is given. A discussion of the quality of the installed links and the methodology for long term monitoring of the links is given. A description of the technology choices and the reasons for these choices in the different systems is given. This historical summary is used to draw many important conclusions for the optical links to be used for SLHC.

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1 Introduction

Optoelectronics has been used at an unprecedented industrial scale for LHC detector readout and control. During the complex R&D phase which preceded the construction of the experiments, very little know how was available in the community to guide the designers. This was due to the lack of experience with large optical systems and resulted in long test campaigns and difficult decision processes in many cases. Now that the data transfer systems have finally been built and installed by all experiments, it is important to share and critically review the gathered experience and draw if possible some lessons for the future.

To this purpose, the joint ATLAS-CMS working group on optoelectronics for SLHC was formed in 2005. In September 2006, the group decided to focus its collaborative effort on three topics:

a) Lessons learned and to be learned.

Collect info on successes and mistakes of the groups involved in building the optical links for the present detectors. Follow up on the technology choices made over 10 years ago. Produce a transparent account of the costs incurred. Create a repository for all publications. Monitor and follow up the performance and ageing of the installed links.

b) Radiation hardness and reliability of optoelectronic components

Establish common procedures and common ways to represent the irradiation test data, share facilities and coordinate irradiation runs, avoid redundant tests and share results.

c) Common optical link reference test bench

Define a reference test system for multi-gigabit/s optical links. Define test procedures and evaluation criteria. Specify the interface to the links to be tested. Develop hard, software and FPGA-IP blocks. Purchase test equipment and build reference test bench. Test proposed SLHC links on common reference bench and evaluate with common criteria.

This document reports on the results of the subgroup working on topic a: lessons learned and to be learned. It summarizes in an informal way several discussions among ATLAS SCT, ATLAS Pixel and CMS tracker optical link designers. It is neither complete nor exhaustive, but highlights in a rather pragmatic way some of the salient conclusions from these meetings, in the hope of providing some guidance to the groups who will design optical links for the next generation of experiments.

In section 2 of this report, the three optical systems under review are briefly described in order to allow unfamiliar readers to understand some of their particularities. A cost comparison of the three systems is then presented in section 3; in the mid-1990's, estimated optical link cost figures were frequently presented when comparing options or even to justify technology choices. A posteriori, we demonstrate that these cost figures were systematically underestimated and often proved to be an unreliable basis to take decisions. Section 4 describes the quality of the systems as built. Impressive figures are shown, but careful monitoring will be required in future years to assess the availability and reliability of the systems in operation. Section 5 reviews the different technology choices made by ATLAS and CMS under the light of our production and installation experience. This is of particular relevance to the SLHC designers who are now drafting the specifications for their future systems. After the conclusions in section 6, the publications and references section 7 points to several of the documents published by ATLAS and CMS.

2 Systems description

2.1 CMS Tracker

The central tracker of CMS is comprised of ~10million silicon microstrips arranged around the proton interaction point at the centre of CMS. Data generated by the silicon detector modules must be sent to a remote counting room ~65m away, while timing, trigger and control (TTC) information must be passed in both directions between detector and counting room. The CMS tracker Readout and Control System is shown in Fig. 1.

Data from the Silicon Microstrips are processed by the APV front-end ASIC, which amplifies the signal, samples it at the 40MHz LHC bunch-crossing frequency and stores it in an analogue pipeline pending a trigger.

Upon receipt of a Level 1 Trigger the data are time-multiplexed (256:1) and transmitted over an analogue optical link to the counting room, where the received data are digitised and formatted on the Front-End Driver (FED) VME board before being sent onto the higher-level Data Acquisition (DAQ) system. The system requirement is for an analogue data transmission system capable of pulse amplitude modulation at 40MS/s with 8-bit resolution and 1% non-linearity.

The CMS tracker control system uses a token-ring-like architecture with a master control node (the Front-End Controller, FEC) located in the counting room and several Communication and Control Units (CCUs) located on the larger mechanical sub-structures of the tracker. Clock and control data are transmitted optically from the FEC to the front-end, passed sequentially around the ring of CCU modules electrically, then re-transmitted back to the FEC via the digital optical link. The digital optical link therefore carries both 40MHz clock and 40Mb/s digital control data. The electrical on-detector ring allows the number of optical control links to be reduced. Redundancy is provided through full duplication of the electrical and optical signal paths in the control system.

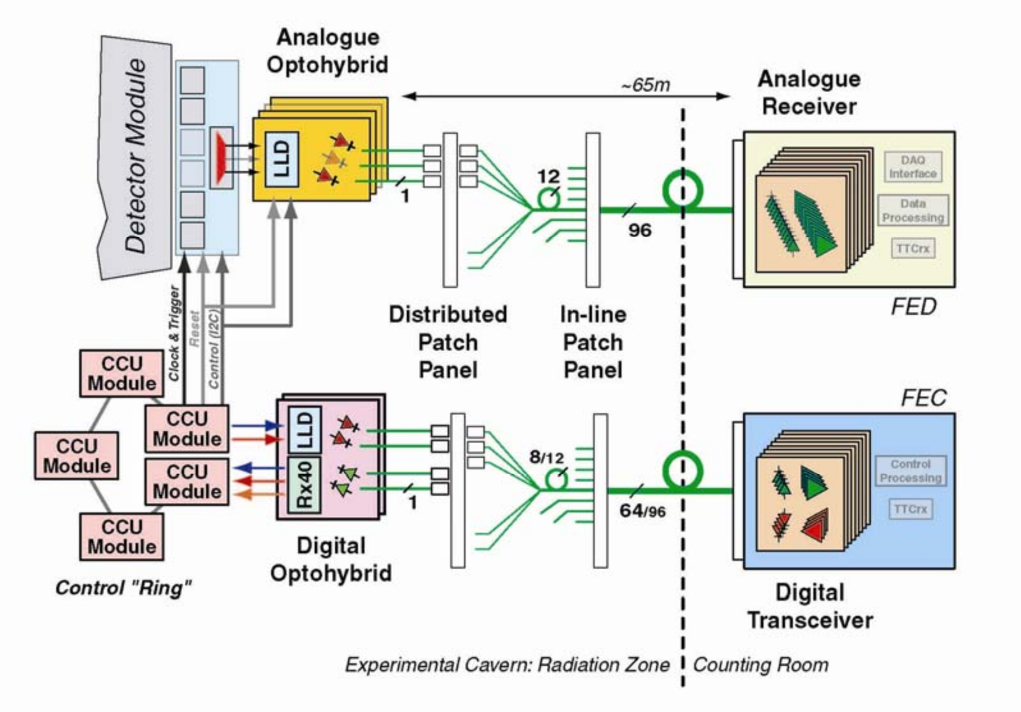

Figure 1 Overview of the CMS tracker Readout (top) and Control (bottom) Systems with the optical links carrying data from the experiment to the counting room.

The analogue optical readout system operates single-mode at 1310 nm wavelength. The custom-designed laser driver ASIC (LLD) directly modulates the edge-emitting laser diode drive current to achieve light amplitude modulation. Single fibres from the pig-tailed lasers are connected at the periphery of the tracker via small form-factor MU-type single-way connectors to a fan-in, which merges single fibres into a 12-fibre ribbon. There is a second break-point within the CMS detector where the transition to a rugged multi-ribbon cable (8× 12-fibre ribbons/cable) is made via 12-channel MFS-type array connectors. In the counting room each ribbon connects directly to a 12-channel analogue optical receiver (ARx) module on the FED.

Digital control and timing information generated on the FEC is output by the transmitter half of a 4-channel digital transceiver. After passing through an identical fibre system to the analogue link, the data are detected by pig-tailed InGaAs photodiodes and recovered by a custom-designed digital receiver ASIC (Rx40). Data are returned to the FEC via the same transmitting components used in the analogue link after passing around the control ring. Data are received at the FEC by the receiver half of the digital transceiver. Additional details are available in [1].

An identical system architecture with identical or similar components has been implemented for the digital optical links of CMS ECAL [2].

2.2 ATLAS SCT

The ATLAS SCT consists of 6.2 million silicon microstrips arranged in cylinders and disks around the interaction region. As for CMS, data generated by the silicon detector modules must be sent to a remote counting room. TTC data is sent from the counting room to the front end modules.

The communication between each SCT module and the off-detector data acquisition system is made by individual optical links. The system is illustrated schematically in Figure 2, with the upper part of the figure showing the data links and the lower part the TTC links. The links are based on GaAs Vertical Cavity Surface Emitting Lasers (VCSELs), emitting light around 850 nm, and epitaxial Si *p-i-n* diodes.

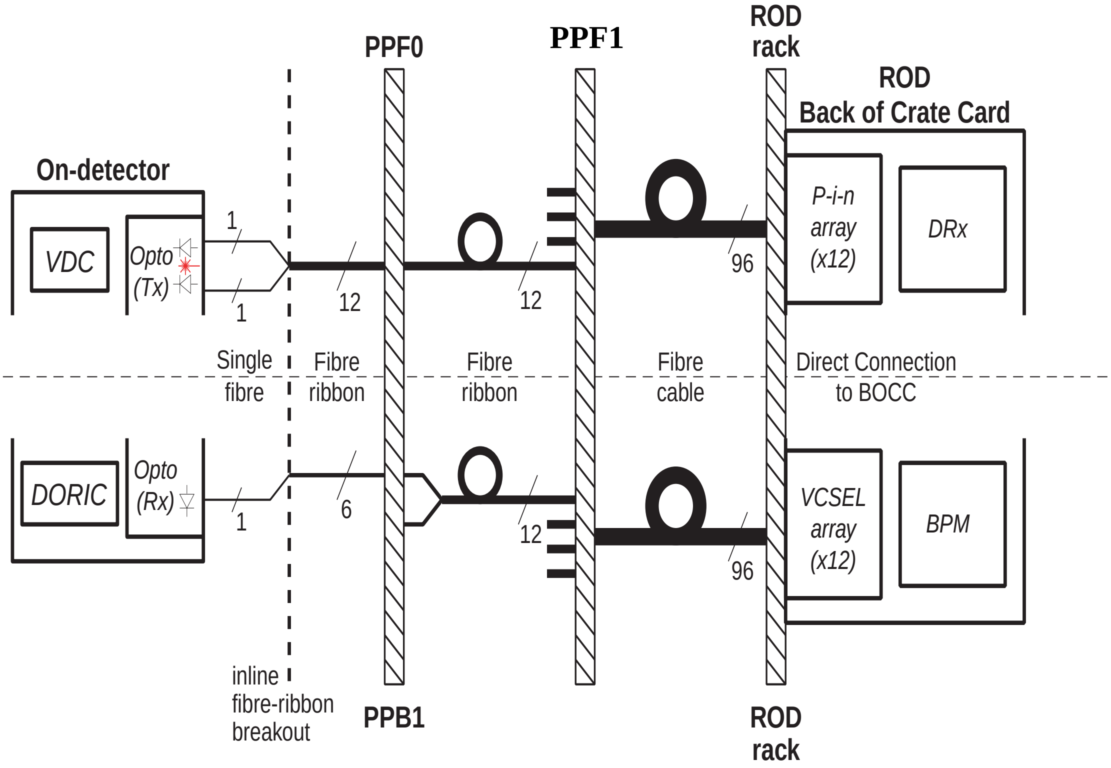

Figure 2 Overview of the ATLAS SCT Tracker Readout (top) and Timing Trigger and Control (bottom).

2.2.1 The data links architecture and components

The binary data from each channel of an SCT module are stored in a pipeline memory of the ABCD3TA ASIC and those corresponding to a first level trigger signal are read out. The data from each side of the module are read out serially via a “master” ABCD3TA. Two data links operating at 40 Mbits/s transfer the data from the two master ABCD3TA ASICs of each module to two channels of a custom ASIC, the VDC which drives two VCSEL channels. The VDC, developed specifically for the SCT project, translates the approximate LVDS signal produced by the ABCD3TA into the drive signal required to operate the VCSEL. The VCSEL is contained within the on-detector opto-package, where the light is coupled into a step index multi-mode (SIMM) custom optical fibre with a pure silica core (50 µm diameter) to ensure radiation hardness The data are sent in non-return-to-zero (NRZ) format to a Back of Crate (BOC) card in the counting room which provides the interface between the optical signals and the off-detector electronics in the SCT Readout Driver (ROD). In the BOC, Si *p-i-n* diode arrays provide electrical signals that are discriminated by another custom SCT ASIC, the DRX-12, which provides the LVDS data used in the ROD.

Some redundancy is built into the data links in that two independent links are provided for each SCT module. In normal operation, each link reads out one of the sides of the module, but if one link fails then all the data can be read out via the working link. The redundancy mode reduces the available bandwidth, but this will not cause any loss of data at the expected rates.

2.2.2 The TTC links architecture and components

Optical links are also used to send the TTC data from the RODs to the SCT modules, as indicated in the lower part of **Figure 2**. Within the BOC, the custom BPM-12 ASIC uses biphase mark (BPM) encoding to send a 40 Mbits/s control stream in the same channel as the 40 MHz LHC bunch crossing clock. The outputs of the BPM-12 ASIC drive an array of 12 VCSELs which transmit the optical signal into 12 SIMM fibres. The signals are converted from optical to electrical form by the on-detector Si *p-i-n* diodes within the Opto-package indicated in **Figure 2**. Finally, these electrical signals are received by the SCT custom DORIC4A ASIC, which decodes the BPM data into a 40 MHz bunch crossing clock and a 40 Mbit/s control data stream, for transmission to the front-end ABCD3TA ASIC.

Redundancy is built into the TTC system by having electrical links from one module to its neighbour. If a module loses its TTC signal for any reason, an electrical control line can be set which will result in the neighbouring module sending a copy of its TTC data to the module with the failed signal

2.3 ATLAS Pixels

The ATLAS pixel detector consists of three barrel layers, three forward, and three backward disks which provide at least three space point measurements. The detector were constructed of 1,744 pixel modules, each containing a silicon sensor readout by 16 front-end chips controlled by a Module Control Chip (MCC). Each module contains 46,080 channels, yielding a total of ~80 millions channels in the system. The architecture of the optical links is similar to the SCT system and the only significant different is in the on-detector implementation as shown in Fig. 3.

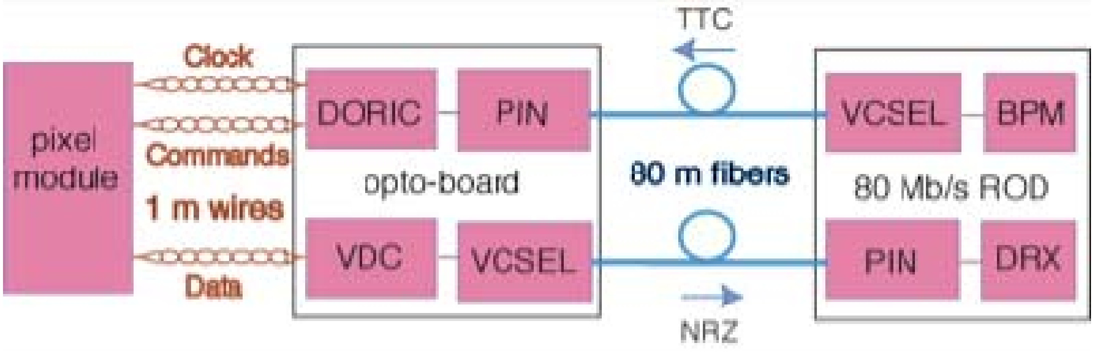

Figure 3 Architecture of the optical links of the ATLAS pixel detector.

2.3.1 *D*ata links architecture and components

The binary data from each pixel are stored in a pipeline memory of the frond-end ASIC and those corresponding to a first level trigger signal are read out by the MCC. After the event building, the MCC transmits the data at 80 Mbits/s via ~ 1m of micro twisted-pair cable to a VDC to drive a VCSEL. The VDC is an updated version of the SCT ASIC but developed with IBM 0.25 µm technology. As the SCT, the VDC converts the approximate LVDS signal into a single ended signal appropriate to drive the VCSEL. Unlike the SCT, we use a VCSEL array instead of a single channel device. Two 4-channel VDCs plus one 8-channel VCSEL array are mounted on one side of an optical module (opto-board). For the inner (B) layer, there are two more VDCs plus one more VCSEL array to handle the higher occupancy. The other side contains two 4-channel DORICs plus one 8-channel *p-i-n* array (see below). There are a total of 272 opto-boards mounted on patch panels (PP0). The substrate of the opto-board is BeO with excellent thermal conductivity. Each array is housed inside a compact optical package coupled to a fibre ribbon terminated with a removable 8-channel MT ferrule. The fibre ribbon is the same radiation-hard SIMM fibre as used in the SCT. Each fibre ribbon is ~ 3 m long and extends from the PP0 to another patch panel, PP1, where it is terminated with a MT16 ferrule. This special ferrule was used to couple to two 8-channel ribbons to satisfy the stringent space constrain. Beyond PP1, there is another ~ 4 m of SIMM fibre before it is fusion spliced to 70 m of graded index (GRIN) fibre to the counting room. As in the SCT, the data are sent in the NRZ format to a BOC card and the rest of the system is identical to the SCT. Unlike the SCT, there is no redundancy in the data links.

2.3.2 TTC links architecture and components

Optical links are also used to send the TTC data from the RODs to the pixel modules as the SCT. The DORIC used is an updated version of the SCT ASIC but developed with IBM 0.25 µm technology. The decoded clock and TTC data are transmitted to the MCC via micro twisted-pair cables. As noted above, two 4-channel DORICs plus one 8-channel *p-i-n* array are mounted on one side of an opto-board. The fibre ribbons used are identical to those for the data links. Unlike the SCT, there is no redundancy in the TTC system as for the data links.

3 Cost

It is instructive to compare the cost of the opto-links for the three systems in view of the SLHC upgrade. However, there is a large uncertainty in estimating the cost and cost difference of 10-20% should not be viewed as significant. The manpower used is even more difficult to estimate and an uncertainty of up to a factor of two is possible. **Table 1** summarizes the production and development cost. The production cost is for material only. It is evident that all links are expensive, ~300 CHF/link. The development incurs another 10-30% of additional cost. As expected, this cost is highest for the system with the smallest number of links. However, it should be emphasized that the development costs for the three systems are not precisely known.

The above production cost includes 30-40% of overproduction to cover the assembly yield, test systems, prototypes, installation yield, and unforeseen problems. The final spares are usually down to a few percent. This overproduction cost was usually underestimated in the initial cost estimate.

The breakdown of the material cost is shown in **Table 2**. About 70% of the cost is in the active components and the rest in passive components (cables and connectors). However, the latter fraction is significantly higher for the ATLAS pixel detector due to the high cost of ribbonization, fusion splicing, and custom fabrication of the patch panels (PP1) with gas-tight MT16 connectors.

The manpower deployed in the R&D, production, and installation of the opto-links are listed in Table 3. It is evident that the R&D effort is comparable to the production. The installation effort accounts for 10-20% of the total manpower consumed. This was usually underestimated or neglected in the initial estimate of the project cost. The manpower cost per link was similar for the ATLAS SCT and the CMS tracker. The cost is significantly higher for the ATLAS pixel detector because of the smaller number of links produced. Overall 180 man-year (MY) were used over 11 years to develop and install the three systems from 1996 to 2007. As an order of magnitude estimate 1 MY of effort is required to develop 300 links.

Given the large material and manpower cost, we should reduce the number of links by maximizing the bandwidth usage and sharing as much R&D effort as possible in the future system.

Table 1 Summary of the production and development cost for the opto-links of the three systems.

	ATLAS Pixel	ATLAS SCT	CMS tracker
Quantity	4,144	12,264	42,800
Production cost (CHF)	1,693k	3,486k	12,597k
Development cost (CHF)	398k	250k	2,000k
Production cost/link (CHF)	409	284	294
Development cost/link (CHF)	96	20	47

Table 2 Breakdown of the material cost (CHF) per link for the opto-link production of the three systems.

	ATLAS Pixel	ATLAS SCT	CMS tracker
Fibre, connectors & cable	174	91	67
On-detector opto-package	58	74	118
Off-detector arrays TX & RX	85	36	80
Opto ASICs & packaging	13	16	15
Opto-hybird/flex	79	67	14
Cost/link	409	284	294

Table 3 Summary of the staff-years [SY] deployed in the R&D, production, and installation of the opto-links of the three systems. Also included are the number of links produced per SY.

	ATLAS Pixel	ATLAS SCT	CMS tracker
Quantity	4,144	12,264	42,800
R&D [SY]	12	17	50
Production [SY]	11	23	55
Installation [SY]	5	5	10
Total [SY]	28	45	115
Links/SY	148	273	372

4 Quality

The current quality of the links can be quantified by the fraction of dead and problematic channels. Some conclusions about how to avoid these problems in future systems are given. This section gives these numbers for the different systems for the current status in summer 2007. It also gives brief explanations for these problems and some conclusions about how to avoid them in future. Brief summaries of the methods that will be used to monitor the long term performance of the different systems are also given.

4.1 CMS Tracker

Fraction of dead links: 0.04%

Fraction of problematic links: 0.33%

The quantity of optical channels installed in the three CMS-tracker sub-detectors (tracker inner barrel/disk TIB/TID, tracker outer barrel TOB, tracker end caps TEC) is shown in Table 4 below. This quantity grows as one goes from pig-tails to ribbons and from ribbons to multi-ribbon cables since the system architecture did not achieve 100% cable fill factors. As a result, about 20% of the fibres in the CMS tracker are dark.

Table 4 Dead and problematic optical channel distribution in the four sub-detectors of the CMS-tracker.

CMS Tracker Optical System Quality Status, 28 Feb 2007

	TIB/TID	TOB	TEC+	TEC-	TOTAL	Fraction
Installed						
OH+pig-tails	10152	12832	8128	8128	39240	100.00%
Ribbon fanouts	11568	13488	9216	9216	43488	110.83%
Multi-Ribbon Cable	13056	14016	10176	10176	47424	120.86%
Dead						
OH+pig-tails	7	1	2	6	16	0.04%
Ribbon fanouts	0	0	0	0	0	0.00%
Multi-Ribbon Cable					0	0.00%
Total Dead channels	7	1	2	6	16	0.04%
Problematic						
OH+pig-tails	26	0	48	4	78	0.20%
Ribbon fanouts	4	5	32	36	77	0.18%
Multi-Ribbon Cable					0	0.00%
Total problematic channels	30	5	80	40	155	0.33%

4.1.1 Explanation of dead channels:

Broken fibres due to mishandling during detector construction.

4.1.2 Explanation of problematic channels:

Channels with unexpectedly high attenuation due to dirty connector or fibre break, kink or bend.

Broken ribbon channels could be bypassed or repaired with no effect on the final system thanks to the availability of redundant dark channels.

Channels with high attenuation will have little effect on final system performance thanks to gain equalization possibilities at the front-end (laser driver with selectable gain) and at the back-end.

4.1.3 Methods for long term monitoring of data links:

The analogue nature of the CMS readout link allows for easy monitoring of the transmitter operating point and link power budget. Automatic monitoring routines based on the measurement of the analog amplitude of test pulses generated by the APV front-end chip have been written and embedded into the CMSSW framework. They will provide a homogeneous assessment of the link performance across the 3 CMS tracker sub-detectors and of its evolution with time.

Spare fibre channels have been optically looped back at the front-end to monitor from the back-end the darkening of the fibre under irradiation.

4.1.4 Methods for long term monitoring of TTC links:

The CMS tracker control system is a closed ring. The performance of the ring is constantly monitored and the occurrence of lost tokens is flagged, allowing for an early warning in case of link degradation. Bias point and gain of the front-end transmitter are user-selectable.

4.1.5 Conclusions:

1. Avoid fibre pig-tails.
2. Do not allow excessive fibre-slack without corresponding management scheme.
3. Use ruggedized ribbon/fibre only.
4. Avoid simplified and/or compact connectors which are difficult to dismount and clean.
5. Develop and distribute fibre-test tools which allow on-line channel quality testing, providing immediate feedback during construction.

4.2 System: ATLAS SCT

4.2.1 Sub-system: Data links

Fraction of dead links: 0.8%

Fraction of problematic links: 0.6%

4.2.2 Explanation of dead channels:

The main cause of dead links is believed to be due to low level ESD during the manufacture. This low level damage allowed the VCSELs to pass the manufacturer’s QA and the QA at the assembly sites. The total operational time for these tests was about 30 minutes. However some of the VCSELs have died during longer running periods after installation onto the structures, at which point it was no longer possible to exchange them. Some of the single fibres in black furcation tubing were broken during the 4 barrel assembly. The fibres had to be potted in the thermal enclosure feed thorough. Once the damage was detected it was impossible to access the damaged fibres. Some of the dead data links are due to damaged tracks on the Al/Kapton power tapes that supply the control voltage that sets the VCSEL current.

4.2.3 Explanation of problematic channels

The main cause of problematic channels was due to "slow turn-on" VCSELs. The SCT uses NRZ data so it is sensitive to VCSELs whose power output increases significantly over a timescale of micro seconds. Those channels which have such severe slow turn-on behaviour so as to be not usable are counted as "dead" and those which have a less severe behaviour and can be operated with careful tuning of the RX threshold value are classified as problematic. Data links which work but which have an anomalously low value of the RX threshold are also classified as problematic.

4.2.4 Methods for long term monitoring of data links

Perform scans of BER versus the threshold that is used to discriminate the signal in the DRX-12 receiver chip. For each links calculate the maximum (RXmax) and minimum value (RXmin) for which there were no bit errors. In principle the RXmax values would give the best monitoring of the system performance, however in practice than the RXmax values are usually equal to the maximum DAC value so only the RXmin values can be used. The values of RXmin are correlated with the optical power of the VCSELs. The long term monitoring of the data links will be made by comparing the values of RXmin in a run with the values from a reference run. This is illustrated in **Figure 4** which shows a comparison between data taken for the barrel after installation in the pit with QA data from RAL taken before the optoelectronics was mounted on the barrel. The mean value is less than 1.0 and is compatible with the expected attenuation of ~ 1dB from the long SIMM fibre cable in the pit. There is an asymmetric tail in the low side of the distribution which suggests that ~1% of the VCSELs might be damaged. The long term monitoring will also involve looking at the variation with time of other parameters like the mean value of RXmin, the number of VCSELs with low values of RXmax and the fraction of VCSELs showing severe slow turn-on effects.

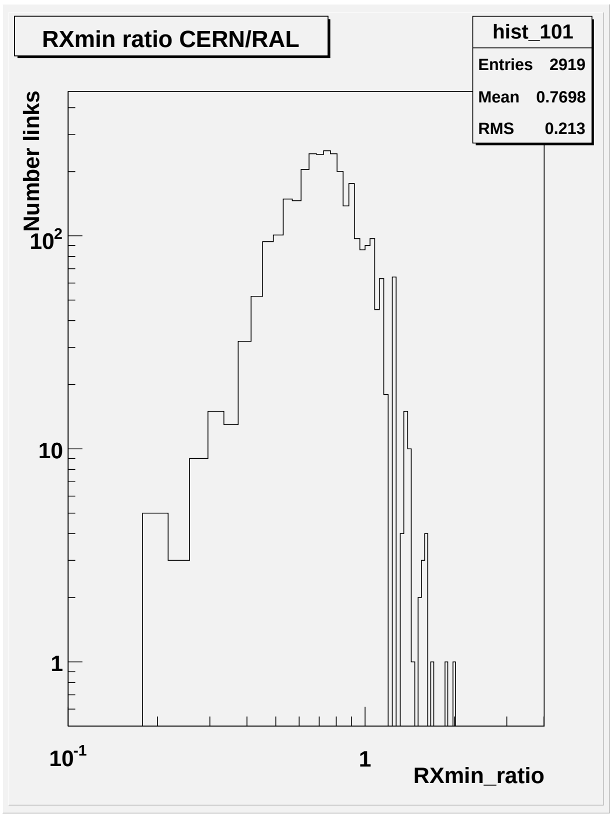

Figure 4 Ratios of RXmin from CERN pit and RAL QA data.

The VCSELs are expected to anneal sufficiently fast that only a very small decrease in light output is expected after irradiation. If necessary the VCSEL drive current can be increase from the default value of 10 mA up to a maximum of 20 mA to accelerate the annealing and to compensate for small threshold shifts.

4.3 System: ATLAS SCT

4.3.1 Sub-system: TTC links

Fraction of dead links: 0.2%

Fraction of problematic links: 37%

4.3.2 Explanation of dead links

Broken fibres (see data links above). Broken tracks on Al/Kapton power tapes that supply the bias voltage for the on-detector *p-i-n* diode.

4.3.3 Explanation of problematic channels

Poor coupling of light from VCSELs into the SIMM fibre, resulting in shorter than expected effective attenuation length in the fibre (can be resolved by production of better off-detector TX VCSEL arrays incorporating micro lens arrays).

4.3.4 Methods for long term monitoring of TTC links:

Measure the currents in the *p-i-n* diodes in the on-detector opto-packages that receive light from the TTC fibres. This current is measured by the SCT power supply system so is easy to monitor. The distribution of *p-i-n* currents from measurements after installation of the barrel SCT in the pit is shown in **Figure 5**. In order to operate the links with low BER a *p-i-n* current greater than 0.02 mA is required. However to minimise SEU during high luminosity LHC operation a *p-i-n* current greater than 0.1 mA is required. The long term monitoring of the TTC links can be performed by looking at this distribution as a function of time.

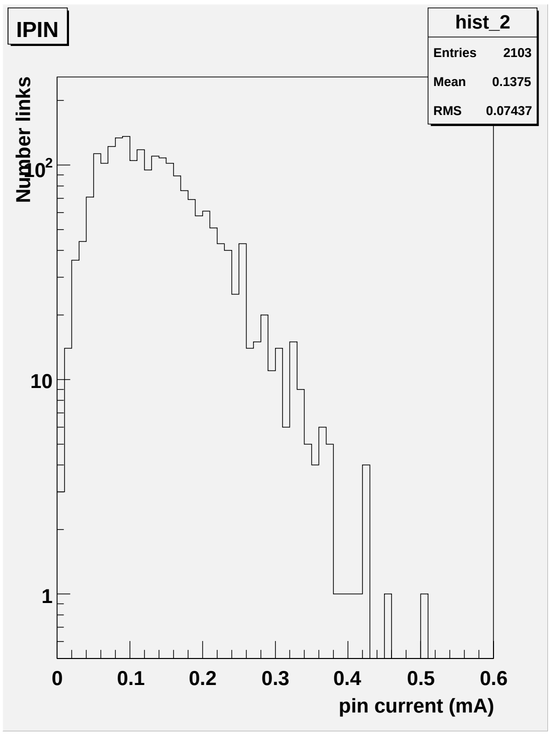

Figure 5 Distribution of the measured *p-i-n* currents when operating the TX VCSELs at the nominal 10 mA current.

The responsivity of these *p-i-n* diodes is expected to decrease by about 30% after a low fluence and then not show any further decrease.

4.3.5 Conclusions

1. Better ESD precautions.
2. More longer term testing of the VCSELs at an earlier stage in the assembly to weed out any damaged devices.
3. Avoid all use of fragile single fibres on the detector.
4. Always used balanced codes.
5. Ensure that QA is performed for identical conditions to the final system.

4.4 ATLAS Pixel

4.4.1 Sub-system: Data links

Fraction of dead links: 0.06%

Fraction of problematic links: ~ 4%

4.4.1.1 Explanation of dead links

One out of the 1788 links was found to be dead after the opto-boards became inaccessible on PP0. The link was replaced by moving the (Type0) cable to an unused channel on another opto-board. The failure is probably due to low level ESD during the production/installation and hence better ESD precaution is recommended.

4.4.1.2 Explanation of problematic links

Some of the links (~1%) has shown sign of slow turn-on which result in some loss in the upper RX thresholds. This is not unexpected because we cannot reject all opto-boards with mild slow turn-on arrays. Some links (~3%) have limited range of the operation parameters and hence require manual tuning of the parameters. This is due to a combination of factors:

1. the limited dynamic range of the receiver on a BOC.
2. the slow tail in the signal from the Si *p-i-n* diode in the RX plug-in.
3. the same VCSEL drive current has to be set for all channels on an opto-board.

The first two factors mean that if the VCSEL is too bright then the error free range of RX thresholds is greatly reduced. The third factor means that if there is a large spread in the light output, the VCSEL drive current cannot be reduced to solve this problem for the bright channel(s).

4.4.1.3 Methods for long term monitoring of data links

The links will be monitored by adapting the procedure used by the SCT.

4.4.2 Sub-system: TTC links

Fraction of dead links: 0.06%

Fraction of problematic links: 0%

4.4.2.1 Explanation of dead link

One out of the 1744 links was found to be dead after the opto-boards became inaccessible on PP0. The link was replaced by moving the (Type0) cable to an unused channel on another opto-board. Major software changes are needed to use this link. The failure is probably due to a detached lead (cold solder) on an opto-pack. In the future, we should avoid the soldering of micro-leads (250 µm width) to material with excellent thermal conductivity such as BeO.

4.4.2.2 Methods for long term monitoring of TTC links

The links will be monitored by adapting the procedure used by the SCT.

4.4.2.3 Conclusions

1. Better ESD precautions.
2. Longer term testing of the VCSELs at an earlier stage in the assembly to weed out any damaged devices.
3. Ensure that QA is for identical conditions to final system.
4. Always use balanced codes.
5. Avoid soldering of micro-leads to material with excellent thermal conductivity such as BeO.

The architecture of the opto-links of the ATLAS pixel detector allows the replacement of broken and problematic links until very late in the detector integration. This is made possible by using the micro twisted-pair cables which allow the links to be installed at a more accessible location, ~ 1 m away from the detector. We should try to preserve this architecture at SLHC if possible.

5 Lessons learned summary

The first lesson learned is that the costs of optical links for tracking detectors are large and they also require a large staff effort for development, production and installation. In order to minimise the costs for SLHC detectors we will need to reduce the number of links by significantly increasing the bandwidth used and to share as much as possible the R&D effort between experiments.

The quality of the installed links is generally very high. The QA for analogue links requires more testing and this resulted in the CMS system having very high quality. However there were problems with a small fraction of the links for all systems as discussed in section 4. The detailed arguments about the pros and cons of the different technology choices are given in the appendix. It is clear from this summary that the apparently small details can make a big difference to the system performance. A good example of this is given by the fibre cables, which turned out to be problematic for both CMS and ATLAS SCT. For CMS there were problems with single fibres until the buffer material was changed and the fibre cable required a long development time. For the ATLAS

SCT, there are still problems with some of the fibre cables which are not completely understood.

It is essential that an extensive system test be carried out with the final components before the full production is started. If this is not done correctly, then problems with the system design will only be understood after it is too late to change anything. A classic example of this type of problem is given by the difficulty in setting the parameters for the ATLAS pixel data links.

The QA must test all the components in exactly the way they will be used in the final system. Any attempts to simplify the tests which violate this rule can result in problems only being discovered during final assembly. An example of this is given by the “slow turn-on” VCSELs in the ATLAS SCT data links (see section 4.2.2). After the ATLAS pixel group were informed of this problem, they improved their QA but did not find any problems. However they did discover that some of the links suffered from slow turn-on problems when they installed the final links. This was due to the bevelled edges of the MT connectors in the final system (as opposed to flat for the MT connectors on the test fibres), allowed the connectors to be positioned closer to the VCSEL array. This illustrates how small details, can have a dramatic impact on the system performance.

The main conclusions on the technology choices are summarized in Table 5 below and are given in detail in the appendix.

Table 5 Summary of technology choices and lessons learned.

Components	
Laser type	EEL lasers at 1310 nm excellent for analogue readout. Sufficiently radiation hard for LHC but would have large threshold shifts if used at SLHC VCSELs ok for digital readout. VCSELs show smaller threshold shifts after SLHC fluences. More consideration of transverse mode structures, thermal resistance and forward voltage drop required. VCSELs at 1310 nm would be an interesting option for SLHC (radiation hard, low power dissipation and high bandwidth in SM fibres).
Wavelength choice and fibre type.	Wide range of commercial 1310 nm SM fibres are radiation resistant. Bandwidth of SM fibres much larger than MM fibres, More difficult to find array receivers at 1310 nm. 850 nm MM fibre compatible with VCSEL and cheap. 850 nm is compatible with cheap radiation hard Si *p-i-n* diodes. Radiation hard SIMM fibre was available but only from one source. Bandwidth of SIMM fibre is very low. Radiation tolerant 850 nm GRIN fibre also available for mixed SIMM/GRIN applications as in pixels. The radiation resistance of high bandwidth GRIN fibre to SLHC doses at 850 nm wavelength needs to be confirmed.
Packaging	
lasers and p-i-n diodes	For on-detector miniature pig-tail-less Optical Sub-Assembly-based package would be ideal. For off-detector, arrays would be preferred.
Connectors	Use standard connectors. Cleaning and inspection tools must be made available (together with documented procedures) at the same time as the cables are installed.
Optical Cables	There were serious problems with optical cables in both CMS and ATLAS SCT. Optical cables must be tested in conditions identical to the ones they will experience during operation, installation and also manufacturing. The lengths tested must be similar to the ones of the final objects
Optohybrid	Should have both electrical and optical connector interfaces. Minimise number of flavours (aim for one flavour).
ASIC packaging	Packaged chips should be used if space is available. The package choice to be made in close collaboration with the hybrid designers. However it is

	possible to use bare die if they are potted or protected with a plastic cover.
Architecture	
From single to ribbon, redundancy	Use ruggedized cables throughout the system, even in the case of space constraints. Avoid locating fibres in inaccessible regions of the detector**.**
Dark fibres and spare cables	CMS installed a large fraction of dark fibres and spare cables which were not needed. The SCT used a more cost-effective solution; 2 spare cables were purchased but not installed. These were not yet needed in the experiment. The pixel detector installed 4 spare cables and three of these were used because of damage to ribbons during installation.
System capacity	Fully use the bandwidth of the fibre to minimise the number of fibres required.
Environmental Effects	
Radiation	All components must be qualified as being radiation hard but it might be possible to limit the effort in validation of production lots, based on positive experience at LHC.
Mechanical	Testing for mechanical reliability was very difficult and problems were seen**.** Refrain from using non-qualified products.
Magnetic field	Strictly adhering to the rule of no magnetic components, severely limits the packaging options. We should investigate if small magnetic packages would be acceptable.
Reliability and quality	
Qualification	include a reasonable qualification duration in the project schedule (i.e. 6 months).
Production supervision	Include production ramp-up and ramp-down time in the schedule (i.e. plus 6-12 months)
Component Tracking	Should be implemented from one centralised DB where the performance history and connectivity of all active components can be tracked.
Reliability	A large effort was put into verifying lifetimes after irradiation. A longer term test of a significant fraction of the final system as was done for CMS gives additional confidence in the reliability.
Miscellaneous	
Modulation	Analogue modulation in CMS required more development but works very well. However to achieve higher bandwidths need to use digital modulation. We should always use balanced code and we recommend to use standard digital modulation formats in the future.
Installation	Ensure sufficient number of test stations are available and budgeted for during construction phase
Cables	At SLHC, either reuse the existing cables or minimise the number of cables by fully utilising the fibre bandwidth. From the SCT experience more care is needed in the evaluation of the lengths of fibre cables.
Patch panels	Avoid non-standard connector solutions. Avoid fibre pig-tails and have a clean fibre connector break at the end of the barrels and disks.
Monitoring	Performance monitoring is more straightforward in an analogue system. However from receiver threshold scans, the performance of digital links can also be monitored. Envisage self-test modes at SLHC.

6 References

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[3] A. Abdesselam et al, The Optical Links of the ATLAS SemiConductorTracker, accepted for publication in JINST.

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7 List of Publications

[1] CMS optical links publication list, CMS-TK-GP-0010, https://edms.cern.ch/document/862663/1 .

[2] ATLAS SCT optical links publication list, EDMS, ATL-IS-QN-0001, https://edms.cern.ch/document/863278/1 .

[3] ATLAS pixel optical links publication list, EDMS, *** missing ***

8 Appendix: Technology Choices

8.1 Lasers and Fibres

8.1.1 Lasers

EEL vs VCSEL

CMS

Edge Emitting lasers were selected by CMS in 1997 for their good linearity and mature technology. The procured Mitsubishi devices were indeed found to be very linear, highly reliable and of high overall quality. Across the 66435 lasers tested, the mean threshold current was 5.3mA at room temperature. The operating current and the forward voltage drop are typically 10mA and 1.3V. Retrospectively, this laser was an excellent choice.

ATLAS SCT

VCSELs were selected by ATLAS SCT in 1997. Initially the plan was to use LEDs based on the idea that they were easy to drive. In fact the radiation hardness of LEDs is rather poor and would have been very marginal for LHC operation. It turns out that VCSELs are very easy to drive and essentially the same simple chip that was designed for driving LEDs also worked fine for driving VCSELs. VCSELs have very low threshold and high slope efficiency which allows them to be operated at low drive currents (typically we use 10 mA). The threshold shifts with radiation and after annealing are very small. The manufacturer's data on reliability indicated that the proton implant VCSELs had excellent reliability. We performed some accelerated aging tests of irradiated VCSELs and found no evidence for any radiation induced degradation of the lifetime. We have seen a few cases of VCSEL death but we believe that this was due to ESD.

ATLAS Pixels

The ATLAS pixel detector uses 8-channel VCSEL arrays instead of single channel devices. These oxide confined VCSELs produce high optical power, in excess of 3 mW of coupled power for some channels. Some of the VCSEL arrays showed large increases in the threshold currents at low temperatures, producing low or no optical power.

8.1.2 Wavelength

850 nm vs 1310 nm, GaAs vs InGaAs

CMS

The selection by CMS of the 1310 nm operation wavelength was a consequence of the single mode fibre choice. The long wavelength had advantages in terms of eye safety and radiation induced attenuation, but with limited impact for short distance links. As a matter of fact, 1310 nm turned out to be a disadvantage when looking for array receiver modules, devices typically developed for short distance applications were 850 nm dominates. The entire CMS TK/ECAL optical system is classified as eye safe (class 1).

ATLAS SCT

The SCT chose to work at 850 nm because of the initial decision to use GaAs LEDs working at low speeds. This choice was maintained when we moved to VCSELs. The other advantages of 850 nm turned out to be the availability of cheap and radiation hard silicon p-i-n diodes and of a radiation hard multi mode fibre. The SCT links are classified as laser safety class 1M. Interlocks are installed in the racks in the counting room, so that the laser light is cut if the door at the back of the racks is opened. There are no interlocks on the detector. There are laser warning stickers on the patch panel covers and a tool is required to open the cover to access the fibre connectors.

ATLAS Pixels

The Pixel links use the same wavelength and have the same type of laser safety issues.

8.1.3 Fibre type

MM vs SM, SI vs GRIN, Flat vs Angle polished

CMS

A SM fibre with angle polished connections was specified by CMS for its analog readout links to suppress modal noise effects and limit back reflections that could degrade the laser noise performance. The selected fibre, Corning SMF28, is the most common fibre type in the world today and is thus well characterized, well known and well understood by all component manufacturers. Its radiation resistance turned out to be good with a measured value of ~20dB/km at 100kGy cumulated dose and a very uniform performance across all samples and preforms tested.

ATLAS SCT

The SCT chose Step Index Multi Mode (SIMM) fibre because it was thought that it would be easier to align the emitters and because this provided sufficient bandwidth for the selected system with a very large number of low speed links. All the connectors were flat polished. At the time of the selection, we had a sample of a special fibre developed by Fujikura for fusion research. This fibre has a pure silica core and a F spike doping and is therefore radiation hard by design. Our radiation tests have confirmed the expected radiation hardness. The measured loss is 50 dB/km after 330 kGy and the radiation hardness was verified on samples from each perform. The bandwidth of this fibre is rather low (80 MHz km) and hence its potential use for high speed links at SLHC would be limited to a short length (less than 10m) in the high radiation region nearest the detector.

ATLAS Pixels

The optical link of the ATLAS pixel detector use only fibre ribbons, which are much less fragile than single fibres. Each ribbon consists of 7 m of SIMM fibre ribbon fusion spliced to 70 m of GRIN fibre ribbon. The hybrid solution was dictated by the limited quantity of SIMM fibres ordered for cost saving. However, there is no significant cost saving after including the labour cost for the fusion splicing. For the signal transmission from the pixel modules to the counting room, each 50 μm SIMM fibre ribbon was spliced to a 62.5 μm GRIN fibre ribbon to reduce the signal lost. For the transmission in the other direction, 50 μm GRIN fibre ribbons were used.

8.1.4 Modulation format

Binary, Digital, Analog

CMS

The choice of an analog modulation format by the CMS tracker significantly constrained the technology choices for its optical link, pushing its design towards a high end telecommunication-type system. This may have had an impact on the cost of some components, but this impact doesn’t seem to be visible at the full link cost level (see link cost comparison). More importantly, the selected analog modulation format required the development team to specify several parameters which would have remained undefined in a less constrained system, and hence had a positive impact on the level of quality control implemented and achieved. On the down side, it must be stated that the analog modulation scheme made it impossible to use standard off the shelf receiver modules (a custom ASIC had to be developed for the backend multi-channel receiver module), and made collaboration across experiments more difficult, if not impossible. In the future, we would recommend the use of **standard digital modulation formats** across all experiments.

ATLAS SCT

The SCT considered binary, digital and analog architectures for the readout. While there was a general preference for an analogue system, the binary readout was chosen on grounds of cost. Note that although it turns out that the costs of optical links in LHC experiments seems to be about constant, the binary architecture is still significantly cheaper than analog, simply because it requires fewer links. The concerns with the binary architecture were based on system issues, like grounding and possible fluctuating pedestals. However all the integration tests up to now have shown that the SCT module performance remains excellent after the full detector integration.

The SCT chose a very simple NRZ (Non Return to Zero) code for the data links. This choice was made very early on while we were planning to use LEDs so there was need to minimize the bandwidth. This argument went away when we changed to VCSELs. However we continued to use NRZ code because it was claimed that this would simplify the on-detector electronics and we should do everything we can to minimize on-detector complexity. With hindsight we can now say that this argument was wrong. The use of a non-balanced code has created enormous difficulties in practice, as it requires very careful optimization of receiver thresholds. This would not be an issue for a small system but is very awkward for a system with 8000 links, as it takes a lot of time to understand the problems in the few problematic channels. Another problem with this non-balanced code is that we are very sensitive to a slow turn on of the VCSEL which occurs in 0.2% of the VCSELs. This of course would not be an issue in a system with a balanced code.

The TTC system uses a balanced code, BiPhase Mark encoding. This makes this system far easier to operate in practice the data links. My personal conclusion: **Always use balanced codes.** However there is no special argument for the use of the BiPhase Mark scheme as opposed to other balanced codes.

ATLAS Pixels

The pixel system of the ATLAS detector learned about the slow turn-on problem from the SCT and were able to reject the ~7% of the opto-boards with very slow turn-on VCSELs before the installation on the service panels. We concur with the SCT that we should avoid the use of unbalanced code.

8.2 Packaging

8.2.1 Laser

Pig-tail, vs Receptacle, Single vs Array

CMS

The low-mass, non-magnetic and radiation-resistant package selected by the CMS-tracker was produced by ST-Microwelectronics as a sub-assembly of larger, more complex modules. As expected, the most delicate point with the Edge Emitting laser was its alignment with the single mode fibre, which turned out to be the slowest and most difficult processing step at ST-Microelectronics and which also turned out to be the most frequent cause of laser failure. Apart from the fragile fibre interface, the lasers mounted on Si-submounts turned out to be robust, compact and lightweight, and no problems were reported to bond to their electrical connection pads. In the future, in light of the experience gained in CMS, and looking at the commercial developments of packaged lasers and pins for TRx modules, **a pig-tail-less laser packaged in a miniature Optical Sub-Assembly (OSA) would seem to be a better solution in terms of interfaces.**

At the front-end, only single channel components were used, as a modularity of at most 3 channels was imposed by the system architecture, a modularity which could not be easily and economically implemented with arrays. At the backend however, the choice of 12-way receiver and 4-way transceiver arrays turned out to be an excellent one and allowed the design and production of dense and rugged FED and FEC boards with no fibre routing on the PCB.

ATLAS SCT

At the front-end a custom low mass, radiation hard non-magnetic package was designed. It is a pig-tailed package with two data fibres and one TTC fibres. The packaging is based on 45 degree angle polished fibres to couple the light from the VCSEL to the fibre and from the fibre to the p-i-n diode. This opto-package was developed in Academia Sinica and the SCT production was carried out in Radientech, Taiwan. One problem with this type of opto-package was that a very small fractional light leakage created a significant signal in the silicon. Since the light signal is synchronous, this was a major problem and the light leakage had to be eliminated by a specially designed plastic cover and Al foil. The yield of the opto-packages was good. One issue with this approach is that the opto-packages are deep inside the detector and therefore quickly became inaccessible during detector integration.

The off-detector packaging is based on 12 way arrays of VCSELs and p-i-n diodes. The arrays are glued with a precision jig relative to MT guide pins to allow an MT-12 terminated ribbon to connect to the array. The basic concept worked well but it was decided that we needed a push-pull connection, so the mechanics of the BOC (the back of crate card) was adapted to allow ribbons with Infineon SMC shells over the MT-12s to connect to the arrays. There were problems with the yield initially as the alignment was not precise enough but eventually this was resolved and the scheme works quite well. This packaging was also developed by Academia Sinica and the production transferred to Radientech.

One problem that has emerged with this packaging is that the effective attenuation length of the light coupled from some of the VCSEL arrays is shorter than measured with LED sources. It is thought that this problem is due to coupling into the larger loss, higher transverse modes in the SIMM fibre.

ATLAS Pixels

The on-detector VCSEL and *p-i-n* optical packages for the ATLAS pixel optical link are similar to the off-detector packages described above but without the SMC shells.

p-i-n Diodes

CMS

p-i-n diodes in CMS are based on InGaAs material, in order to be sensitive at 1310 nm wavelength. We found during early test campaigns that only top-entry devices would feature adequate radiation resistance which made it impossible to procure the *p-i-n* diodes in the same package as the lasers (as ST-Microelectronics could only assemble bottom entry *p-i-n* diodes). An alternative product assembled in a ceramic carrier with a fibre pig-tail and a Kovar leadframe was finally selected. This difference in *p-i-n* and laser packaging made the optohybrid assembly process more complex than should have been. Even though the *p-i-n* diode fibre interface was much more rugged than the laser one, it is felt that **a pig-tail-less OSA package similar to the laser one would be preferable in the future**. At the backend, the choice of 12-way receiver and 4-way transceiver arrays turned out to be an excellent one and allowed the design and production of dense and rugged FED and FEC boards with no fibre routing on the PCB.

ATLAS SCT

The packaging for the ATLAS SCT *p-i-n* diodes is the same as for the laser (see section 8.2.1).

ATLAS Pixels

The on-detector VCSEL and *p-i-n* optical packages for the ATLAS pixel optical link are similar to the off-detector packages described above but without the SMC shells (see Section 2.3).

8.2.2 Connector

Size vs Handling, Cleaning, Splicing, buffer/sleeve quality, Index matching

CMS

The connectors selected by CMS were of the MU type for single fibre connections and of the MT12-type (angle polished) for ribbons. Both are well established standards and met the performance requirements with good margin. Difficulties were associated to the level of ruggedness of the selected connector shells: the choice of a short and compact “simplified MU” connector at the front-end resulted in difficulties when assembling the system as it could not be disconnected without a tool and could not be cleaned easily; the choice of a compact MFS connector at PP1 also resulted in difficulties in handling and cleaning. We confirmed during CMS tracker construction that connectors are critical elements of an optical system: in a system design optimization process, **compromising connector functionality, accessibility, cleanability or ruggedness in order to gain density may be a risky option. Also, cleaning and inspection tools must be made available (together with documented procedures) at the same time as the connectors are installed.**

ATLAS SCT

The SCT uses flat-polished MT-12 connectors at the patch panels near the detector and at the BOC in the counting room. For the multimode application we did not need the angle polished MTs. The basic MT-12 connectors worked well despite the connections in the pit having to be made in a not very clean environment. The connections were checked for continuity and we were able to spot a handful of cases of dirt on the connectors. These were quick to clean and fix. For the PPF0 patch panel at the edge of the disks, there was no access to use a conventional MT-12 spring clip, so we had to use Infineon SMC shells and adaptors. The main problem with this, is that Infineon withdrew this product and we could not buy any more parts. The Infineon SMCs were also used at the BOC end (see section 8.2.1).

Fusion splicing was used to connect the single fibres from the on-detector “harnesses” to the 12 way fibre ribbon. The single fibres were first ribbonised into a short length of 12 way ribbon and then a standard 12 way ribbon splice was made. An additional length of heat shrink was used to protect the fragile single fibres. This created more work for the manufacturer but was quite robust. Fusion splicing was also used successfully to repair one broken fibre ribbon at the end of the fibre cable and for a few cases for the ribbons on the endcap.

ATLAS Pixels

For the on-detector optical link of the ATLAS pixel detector, each optical package couples to a fibre ribbon terminated with an MT ferrule. A custom designed hosuing is used to secure the ferrule. The connector is fabricated with Peek for radiation hardness. The lock-in mechanism uses two small clips that must be handled with care. A special extraction tool is needed to extract the MT ferrule. We broke the clips on several opto-boards but they could be readily replaced. Overall, the connector is not as user friendly as a commercial product but it is acceptable given the space constraint.

The patch panel at PP1 is an expensive custom design with gas-tight seal to connect the fibre ribbons. Two patch panels are needed, one at each end of the detector. The panels were designed and fabricated by Ericsson. Due to the space constraint, connectors of MT16 style are used. This halves the number of MT connectors needed since each MT16 connector supports two rows of 8-channel ribbons. The extraction of an MT16 connector from the patch panel is somewhat difficult and requires a special tool.

8.3 Cables

CMS

All optical cables used in the CMS tracker were supplied by Ericsson. We had several difficulties with cable materials:

- For the single fibre tight buffer, the choice to use acryllate turned out to be wrong. The material was not properly qualified, was too soft and proved to be unstable under environmental temperature changes. The resulting buffer damage problems (and the particular case of buffer ruptures) affected production and quality control of lasers, *p-i-n* diodes and optohybrids in a significant way until the decision was eventually taken to switch from acryllate to polyethylene.
- For the ribbon cable, the selected zero halogen material turned out to be shrinking under extreme temperature stress. The learning curve to understand how to handle these long assemblies was very slow and had to be repeated with all manufacturers handling this cable.
- For the multi-ribbon cable, the choice of a ribbon stack in a loose tube design was imposed by the tight bend radius constraint (8cm). Cable cavity dimensions and packaging/handling procedures required a long development time to stabilize.

In summary, optical cables are not as simple as they seem. They must be thoroughly tested and qualified before and after being produced. **Optical cables must be tested in conditions identical to the ones they will experience during operation, installation and also manufacturing. The lengths tested must be similar to the ones of the final objects** as long assemblies can behave in a significantly different way than short ones.

ATLAS SCT

The fibre cable used by the SCT was produced by Fujikura. It was installed and all the fibres were tested with an LED source and apart from the one broken ribbon (see section 8.2.2), everything appeared to be perfect. However when we started to operate the SCT we discovered that the currents in the on-detector p-i-n diodes was significantly lower than expected (see section 8.2.1). Part of the problem was connected to the fibre cable. The extra attenuation seen in the fibres in the installed cables was not seen in identical fibre in a spare cable. This result was confirmed by OTDR measurements. This observation strongly supports the conclusion that optical cables must be tested “in conditions identical to the ones they will experience during operation…”.

ATLAS Pixels

For the ATLAS pixel detector, the radiation-hard fibres produced by Fujikura were ribbonised by Ericsson. The radiation tolerant GRIN fibres were also spliced to the radiation hard SIMM fibre by Ericsson. The same vendor was also responsible for the connector termination, fusion splicing, and ruggedization.

8.4 Optohybrid

Uni vs bi-directional, Single vs Multiway, flavours, pig-tail strain relief, electrical connector.

CMS

The CMS optohybrid concept turned out to be a very effective way to interface the front-end electronics to the cabling system. The selected NAIS electrical connectors are good and very reliable and only few optohybrid connection failures were reported. One difficulty occurred because of the nature of the laser and *p-i-n* diode mounting techniques. The laser needs to be glued and bonded while the *p-i-n* diode needs to be soldered. These are manual steps that could not be well integrated in the manufacturing process flow, knowing that the fibre pig-tails cannot sustain temperatures in excess of 80 degrees. Moreover, the fibre pig-tails are not very robust, as the implemented strain relief on the opto-hybrid is not effective in axial stress conditions. These tails turn the optohybrid into a rather fragile and cumbersome object which needs to be handled with care. Moreover, the many different pig-tail lengths required by the various subdetectors to avoid excess slack transform the optohybrid into a multi-flavor object requiring careful stock management. In the future, we would recommend the **optohybrid to have both electrical and optical connector interfaces, making automated assembly and full electrical testing possible, and decoupling active from passive components stock management.**

ATLAS SCT

The SCT barrel used an integrated optical and electrical harness. The opto-package was mounted on a Cu/Kapton flex circuit. 16 different flavours of this flex circuit were required. There were many different lengths of low mass tapes and fibres, so that overall there were 46 harness flavours. This made production very difficult and it made it impractical to produce any completed spares. Instead spare sub-assemblies were produced and they were turned into complete harnesses on demand. This created some delays. Since this integrated harness was a very large and complicated structure, it was very hard to achieve a high yield. Another major disadvantage of this scheme was that it was difficult to handle the excess length of fibre during assembly and integration.

The SCT Endcaps used a slightly more modular design with separate optical and electrical harnesses. The opto-package was mounted on a PCB with an 8 pin connector to allow it to be connected directly to the SCT Endcap module. This resulted in only 7 flavours being required and therefore greatly simplified production.

The conclusions from the SCT experience support the proposal to have electrical and optical connector interfaces on the optohybrid.

ATLAS Pixels

The opto-hybrids (opto-boards) of the ATLAS pixel detector contain both optical and electrical connections. The custom design connectors on each opto-board allow the fibre ribbons to be detached. The pig-tail-less opto-boards are therefore easy to produce, test, and install. The yield is over 90%. The opto-boards use BeO as the substrate for heat management. Two flavours of BeO boards were ordered, one for the inner barrel layer, and the other for the two outer barrel layers and disks. The latter BeO boards were fabricated into two different flavours depending on the placement of the VCSEL optical package at one of the two locations due to the mechanical constraint of the patch panels.

8.5 Electronics

Die vs package, soldering, inspection

CMS

All chips mounted on CMS optohybrids were packaged. This turned out to be a good choice in terms of handleability and robustness. However, difficulties occurred when packaging companies changed and subtle differences in the package caused the optohybrid layout to fail. In general, it was found that the LPCC packages used were difficult to inspect. In the future, we would recommend the **package choice to be made in close collaboration with the hybrid designers.**

ATLAS SCT

The SCT used bare die chips for the on-detector packages. These chips were wire bonded to the Cu/Kapton flex (barrel) or PCB (Endcap). The fragile wire bonds were protected by the plastic covers required to avoid light leakage. This seemed to work very well. The chips used for the off-detector opto-electronics were packaged. A 64 pin LCC package was used for one chip and this had no problems. A 100 pin QFP was used for the other off-detector opto-electronic chip. This required a special tool to be developed to form and cut the leads. The tool needed very careful adjustments each time a new batch of QFPs was received as the dimensions changed slightly. **The SCT experience shows that if necessary, bare die can be used.**

ATLAS Pixels

The opto-boards of ATLAS pixel detector were populated with bare die chips. Each optical package is served by a pair of 4-channel chips. The wire bonds are protected with encapsulant. The encapsulant of the two chips are connected due to the close proximity imposed by the space constraint. Consequently we must stack a second layer on both chips whenever we peel off the encapsulant due to a bad chip.

8.6 Architecture

8.6.1 Readout

From single to ribbon, redundancy

CMS

The decision in the CMS tracker to have the opto-hybrids located very close to the front-end modules was driven by the analog nature of the signal which could not be transferred electrically over long distances. This turned out to be a good choice and resulted in a very quiet readout system. The first breakpoint in the optical system (so called distributed patch panel) was at the single fibre level: optohybrids had relatively long pig-tails in some cases necessitating careful slack management. They were connected (never spliced) to the ribbon fanouts thus remaining fully independent and detachable from each other. The ribbon fanouts with simplified MU connectors turned out to be rather fragile assemblies and the edge channels (1 and 12) were quite susceptible to mishandling (kinks in the loose tubes protecting the single fibres). At the second breakpoint (PP1), compact MFS connectors were used and the ribbon sheath had to be removed to meet the tight space and density constraints. This made the assemblies fragile and vulnerable at the precise location where slack needed to be taken up. In the future, we would recommend to **use ruggedized cables throughout the system, even in the case of space constraints**, and spend time working on thin ruggedization schemes instead of loosing time during installation.

No redundancy is available in the CMS tracker readout system.

ATLAS SCT

The SCT decided to use opto-packages very close to the front end modules because of worries about grounding and electrical pick up from high speed signals. Fusion splicing was used to join single fibres to ribbons. While the splicing was successful, the resulting large and fragile objects were very difficult to manufacture with a high yield and could not be removed from the structure once cooling loops were installed. 900 um black furcation tubing was used for the single fibres to prevent light leaks. However this tubing provided very little protection for the fibres and there were many problems during assembly.

The SCT system had some redundancy for both the data and the TTC links. This redundancy was designed to allow for some low failure rate during operation. It is now being used to deal with channels damaged during assembly (broken fibres or VCSELs damaged by ESD). A better alternative to this level of redundancy would be to locate the opto-electronics at the edge of the structure such that they could be replaced if they failed during detector integration. This would also allow for ruggedized cables to connect to the on-detector opto-electronics. The key conclusion from the SCT experience is **that we should avoid burying delicate fibres and optoelectronics in completely inaccessible regions of the detector.**

ATLAS Pixels

The ATLAS pixel detector uses only fibre ribbons that are much less fragile than single fibres. The opto-boards are located near the disk sectors by using micro twisted-pair cables for the transmission of electrical signals between the opto-boards and pixel modules. The cables decouple and simplify the design, production, installation of the opto-boards and pixel modules. The location also allows the replacement of defective opto-boards and electrical and optical cables (including rerouting to bypass defective links) until quite late in the detector integration. The rerouting is necessary since there is no redundancy in the links. The use of the micro twisted cables is one of the advantageous features of the pixel design and should be preserved in SLHC if possible.

8.6.2 Control

Separate control from readout channels?

The CMS tracker control system is entirely separated from the readout system. It was designed and developed well after the readout system and was thus less discussed and tested. It is based on redundant control rings, which are optical between the Front End Controller (FEC) backend boards and the Digital Opto Hybrids (DOH) at the frontend, and electrical from Control & Communication Unit (CCU) Module to CCU Module. Each CCU module distributes clock and control signals electrically to several front end modules. These digital lines as well as the CCU and DOH modules were found to generate noise into the readout system in several cases, and had to be shielded appropriately. In the future, we would recommend to **design the readout and control systems in**

parallel, and to take great care in carefully shielding the digital electronics and electrical distribution cables.

ATLAS SCT

The SCT TTC distribution is optical from the BOC to the on-detector opto-package. The same problems arise from this architecture as for the data links (see section 8.6.1).

ATLAS Pixels

The TTC distributions of the ATLAS pixel detector is also optical from the BOC to the on-detector opto-package. However, the architecture of this link is identical to the data link, simplifying the design of the system.

8.7 Dark fibre, Spare cables

Ribbon fill factor, cable fill factor, spare fibres vs accessibility

CMS

The fraction of dark fibre in the CMS tracker optical system is approximately 20%. This includes unused fibres in ribbons, unused ribbons in multi-ribbon cables and dark cables. Dark cables (not connected at the front-end or back-end) are installed (one in every sector) to cover possible problems during cabling or commissioning. Despite its reassuring elegance, the dark fibre concept has not yet been much used in reality: if a problem with an optical fibre at the front-end is discovered during initial cabling, then the problem is immediately fixed or the ribbon is changed; after tracker installation, the distributed (front-end) patch panel is not accessible anymore, and the dark fibres become useless until the next major maintenance. In conclusion, dark fibres are only useful in phases when a) the patch panels are accessible (allowing re-routing) and b) the cabling channels are not accessible (making replacement impossible). Conditions a) and b) were only met in very few exceptional cases up to this day.

ATLAS SCT

The SCT has no dark fibre in the barrel and 2% in the Endcap. However this dark fibre has no functionality. During cable installation one fibre ribbon was damaged and it was repaired by fusion splicing a new MT-12 pig-tail to the end of the ribbon. Two spare fibre cables were produced in the event of a catastrophic failure of one or two cables but in the end they were not required**. From the SCT experience of installing and connecting the fibre cables for the barrel, there is no strong argument yet for having dark fibres in cables or installing spare fibre cables.**

ATLAS Pixels

The fraction of dark fibre in the ATLAS pixel detector is ~20% because the number of pixel modules in a stave and disk sector does not have a modularity of 8, each stave contain 13 modules and each disk sector contains 6 modules. This is a waste of resource (space and money) and should be avoided in the future if possible. There are a few spare fibre ribbons between the opto-boards and PP1. Some of the spare ribbons were utilised due to breakage of the ribbons or ceramic guide pins in the MT connectors during the installation or testing. There are 4 spare cables (8 ribbons/cable) in the 84 cables between PP1 and the counting room and some of the ribbons in the cables are also spares, resulting in a total of 19% spare ribbons. A total of four ribbons in three cables were damaged during the installation.

8.8 System capacity

Granularity, bandwidth usage

CMS

With one fibre per two APV front-end chips, the CMS tracker readout is very distributed, and the fibre capacity is not well used. At an average trigger rate of 100kHz, the analog system transports 128x2x100’000= 25.6MSamples/s on average, excluding headers and trailers. Assuming a resolution of 8 bits per sample, the average link equivalent digital throughput is around 250Mbits/s, with peaks at 320Mbits/s. In view of the high optical system cost and of the effort required to install such a large quantity of optical fibres, **a future system will have to be more bandwidth efficient.**

ATLAS SCT

The SCT system used 12000 fibre channels to transfer data at very low bandwidth (40 Mbits/s). It is not practical or affordable to scale this up to an SLHC detector, therefore the SCT conclusion agrees completely with the

CMS one about bandwidth efficiency.

ATLAS Pixels

The ATLAS pixel detector contains 5,000 fibre channels (including dark/spare fibres) but transfers data from each pixel module at 80 Mbits/s by using both edges of the 40 MHz clock. For the inner barrel layer, two links are used to transfer data from each module due to the higher hit occupancy.

8.9 Environmental Resistance

8.9.1 Radiation

CMS

Fibre, lasers and pin-diodes have been systematically validated for radiation resistance at the preform and wafer level. Over 15 wafers and 12 preforms were qualified during production and released for use in CMS, resulting in an unprecedented number of test devices and test runs (over 1200 lasers were tested as part of the advance radiation validation program). No significant performance deviation or failures were ever observed during an irradiation test, indicating that: a) the observed radiation induced effects are of a generic nature and do not depend on random process variations or uncontrolled features, b) the level of process control is very high for the selected components. In the future, one might envisage building on this positive experience and **limiting the radiation validation effort during production.**

ATLAS SCT

The SCT tested the radiation hardness of samples from all fibre performs and found very small losses and no significant variations. Samples of the front end ASICs were tested from each wafer and no variation was seen. The VCSELs (pin-diodes) were all produced from one wafer. So one test of a sample of VCSELs (*p-i-n* diodes) was sufficient to verify the radiation hardness. The results were very uniform.

ATLAS Pixels

The optical link group of the ATLAS pixel detector tested the radiation hardness of the front-end ASICs and VCSELs/*p-i-n*s. The ASICs were initially fabricated using the 0.8 μm DMILL technology but suffered significant radiation degradation. We transferred the design to the 0.25 μm CMOS technology and observed no significant degradation after irradiation. For the VCSELs and *p-i-n*s, some degradation was observed but the VCSELs could be annealed by operating with high drive current.

8.9.2 Magnetic Field

CMS

A large effort was made to limit the amount of magnetic material present in the CMS tracker optical system. All purchased in-detector components were specified to be non-magnetic, which required in particular the customization of all optical connectors (springs and alignment pins). This strict requirement caused several difficulties during qualification but could eventually be met, except for the Kovar leadframe of the *p-i-n* photodiode which had to be accepted as is. It was however found that other subsystems did not apply this requirement strictly and used for instance standard connectors. In the future, we would recommend to **clarify the requirement for non-magnetic components and possibly revise its degree of application.**

ATLAS SCT

The SCT used non-magnetic materials for all the opto-electronics. This created a significant cost in money and effort. Special non-magnetic guide pins and MT spring clips and springs for the Infineon SMCs had to be produced. Also custom non-magnetic pin-holder plates for the Infineon SMCs had to be produced in-house.

ATLAS Pixels

No magnetic materials were used.

8.9.3 Mechanical

CMS

The environmental tests which caused most difficulties in CMS were the mechanical ones: repeated mate-demate tests, tensile stress tests etc… This is surprising as these tests are well documented in several standards, and are routine in all quality assurance labs. Difficulties were in fact only met with products which had not been fully qualified commercially or which had to be modified to meet some CMS-specific requirements. The lesson to be learned here is to **refrain from using non fully-qualified products**, even if they are advertised to perfectly meet the specific requirements or seem to be only a minor deviation from a standard product. In cases where a non-qualified product must be used, qualification tests must be imposed on the supplier and systematically cross checked by the user.

ATLAS SCT

The standard MT-12 connectors have proved to be very reliable. There were problems with the Infineon SMC housings, related to the non-standard way they were used, although these problems were resolved successfully. Insufficient thought went into how to install and test the cables and this led to problems (see section 4.3.3).

ATLAS Pixels

The standard MT connectors are reliable. However the clips of a few MT housings broke and needed to be replaced as noted in Section 8.2.2

8.10 Reliability and Quality

8.10.1 Qualification

Specifications, validation and qualification, cots vs custom, norms and standards

CMS

Components qualification was found to be crucial to the success of the CMS tracker optical link project. It was performed early, was based on established standards (Bellcore generic requirements in most cases) or written documents (for CMS-specific tests) and had been discussed with the supplier beforehand. Only one component passed qualification in the first run: the backend multi-channel receiver module (NGK). All others had to implement modifications to their process and resubmit. In one case, qualification took as long as one year: multi-channel MFS connector (Diamond). Once qualified, production quality was in general found to be good and stable. In the future, we would recommend to **include a reasonable qualification phase in the project schedule (i.e. 6 months).**

ATLAS SCT

The SCT qualification was based on written documents agreed by the working group and the manufacturer as most of the tests were quite specific to SCT operation. There were some tests that should have been performed that were missed and this was not realized until it was too late. Insufficient time was allowed for the qualification period and not all the problems were fixed before the production started, which made the production very difficult. **It is essential that the QA covers the full range of operation required during data taking.**

ATLAS Pixels

The qualification for the optical link of the ATLAS pixel detector was also based on written documents agreed by the working group. However, the test system for the qualification was not based on the final system components/software, resulting in the rejection of some opto-boards during the final qualification test on the patch panels. In particular, we were not able to find any VCSEL with slow turn-on after being informed of this issue by the SCT. The slow turn-on VCSELs were eventually identified with the production fibre ribbon which had bevelled finish on the MT connector, allowing the fibres to be pushed closer to the VCSEL array. Another problem that was discovered with the tests of the final prototype (after the opto-baord production was completed) was that the operating environment was much cooler than anticipated, resulting in low optical power for some arrays. Heaters were retrofitted on the opto-boards to raise the operating temperature of the optoboards to ~ 20ºC. A bypass capacitor for the current source that control the current in the VCSEL array was also retrofitted on each opto-board after the system test revealed that the system with the long electrical cables was much noisier than the QA test system. The capacitor was not installed initially due to the concern that the capacitor might leak after irradiation, rendering the opto-board inoperable. **In the future, production should start ideally after a system test has been performed with all final components and software.**

8.10.2 Production Supervision

Quality follow up, process change requests

CMS

Production quality was checked on a sampling basis for each production lot. Acceptance reports were systematically sent to the manufacturers, informing them of test results and recommendations, and keeping their attention focused on the quality of deliveries. In general, we found that production ramp-up and ramp-down time was underestimated. The throughput estimates provided by the manufacturers were peak values which had to be extended by 3-6 months for ramp-up and as much for ramp-down. In the future, we recommend to **include production ramp-up and ramp-down time in the schedule**. An excellent relationship with the manufacturer is crucial during production, and allows for tight supervision. Process change requests were handled in a very formal way to avoid any disturbance to the production flow and had to be followed by a product requalification. All quality and production related documents were stored in EDMS.

ATLAS SCT

The production quality was checked by SCT QA for all delivered products. Regular video meetings with the manufacturer were essential to give feedback, discuss problems and agree on solutions. The manufacturer achieved the promised peak production rate but it took many months to achieve this rate.

ATLAS Pixels

The Pixel opto-boards were fabricated essentially at two locations, allowing independent verification of any report encountered at one site. Quality and production related documents were stored in EDMS.

8.10.3 Components Tracking

Labeling, data base, archiving

CMS

A component labeling scheme was introduced very early on for the CMS-tracker optical system. This allowed to tag with CMS labels all components being produced and to easily and unambiguously collect the production test data into the CMS tracker database. In a second step, these labels will make it possible to link into a virtual chain all components connected together. This concept was however weakened by the fact that several independent databases were implemented at different levels, and different labeling conventions were adopted by CMS over time. In the future, we could benefit from a **more centralized management of labeling and database issues**.

ATLAS SCT

The SCT database was used for component labeling which worked ok. Initially we had planned to use the SCT DB for tracking the quality of the links through the production chain. In the end the manufacturer had so many problems and we were under such intense schedule pressure that only pass fail information was stored in the DB. This meant we could not look for deterioration of devices during the production. In future a DB should be used to allow full tracking of the performance of all the active components.

ATLAS Pixels

The opto-board QA information of one production site was posted on the web. This allows readily access to the information. In addition, a summary of most of the failed boards is also posted on the web, allowing the failure analysis. Some of the information is also stored in the pixel DB.

8.10.4 Reliability

CMS

Long term reliability of components was assessed during production as part of the CMS tracker optical system qualification program. Two out of 15 laser wafers were recalled on the basis of an accelerated ageing test indicating a ten-fold faster wearout than typically measured for comparable wafers. In depth analysis indicated that the accelerating factors might have been underestimated and that the two rejected laser wafers might in fact have been perfectly safe for use in CMS. Data from CMS tracker test runs show no sign of pending reliability issues.

ATLAS SCT

Long term reliability of the on-detector VCSELs, p-i-n diodes and ASICs were evaluated after irradiation to the maximum expected fluences and doses. All the on-detector VCSELs (p-i-n diodes) were produced from one wafer. Samples from these wafers were irradiated and then accelerated aging tests were performed. Similar tests were performed for samples of the ASICs from each of the wafers used for the production. No failures were seen in any of the accelerated aging tests and lower limits were estimated for the lifetimes which were better than the SCT specifications. We have however seen failures of a few of the VCSELs and we believe that this was due to ESD at the manufacturer**. In future we should verify the reliability of production batches by operating them for long periods under realistic operating conditions.**

ATLAS Pixels

For the optical links of the ATLAS pixel detector, long term reliability test of the on-detector VCSEL and *p-i-n* arrays was inadequate. Only three VCSEL arrays were subjected to an elevated temperature test for about three weeks. About 7% of the VCSEL arrays developed a common series resistance of several Ohms or greater. A QA to detect this was developed to identify this problem and suspect arrays were rejected just before installation on the patch panel. This problem might have been identified with a test using a larger sample over a longer time period.

8.11 Installation

8.11.1 Active Components

CMS

Optical links are distributed systems whose active transmitting and receiving components may be physically separated, and may be assembled on boards built by different groups with different project timescales. The need for simple and mobile test systems should thus not be underestimated during the construction phase when one end of the link may be undergoing assembly while the other one is not yet assembled. This is especially true in the case of large collaborations where several groups may be working in parallel. The CMS tracker was constructed by more than 15 groups across the world, each one needing optical readout and test kits. In the future, **the requirement for advance test systems during construction should be taken into account in the project plan, budget and schedule.**

ATLAS SCT

The SCT links production was spread over fewer institutes, so the type of problems described for CMS did not arise.

ATLAS Pixels

The pixel links are smaller and its production was spread over even fewer institutions.

8.11.2 Cables

Length estimation, slack take up, protection, strain relieves

CMS

Cable installation is ongoing in CMS. The effort linked to managing 60’000 optical fibres (~750 cables) is enormous and certainly had never been properly accounted for. It is estimated that approximately 10MY of effort are being invested in preparing and supervising the optical cabling job. In any future system, it is highly recommended to **either reuse the existing infrastructure, or reduce the quantity of fibres by efficiently using the available capacity.**

ATLAS SCT

The SCT only required 144 readout cables but this was still a much larger job than anticipated. The length estimates turned out to be rather imprecise and the 7m contingency was insufficient as some cables were too short. However we were able to reallocate the locations of the racks to overcome this problem. In future more care should be taken in evaluating fibre cable lengths. The SCT cable experience confirms the above conclusion that we should **reduce the quantity of fibres by efficiently using the available capacity.**

ATLAS Pixels

There are 84 cables for the pixel detector and hence the cable installation job is manageable.

8.11.3 Patch Panels

CMS

The PP1 patch panel design work for the CMS tracker optical system was started very early as the available volume clearly constrained the connector choice. The selected multi-way MFS connector was the densest available on the market and eventually met the compactness requirement. It had however never been fully qualified as in-line connector, and underwent several adjustments during qualification to reach the desired level of performance. It was found much later that the envelope given to optical connections at PP1 could in fact have been relaxed to the point where more conventional connectors could have been used, resulting in a more rugged and simpler system. In the future, **any move towards a non-standard solution should be critically reviewed before being endorsed and alternative solutions should be sought.**

ATLAS SCT

The SCT barrel patch panel PPB1 was based on MT-12 connectors held in a custom “comb”. The big problem was that there was no room to lose any excess length of fibre, which resulted in fibre bending exceeding the minimum safe bend radius. The patch panel at the end of the disks PPF0 was based on MT-12s inside Infineon SMC shells. Here the big problem is that the Infineon SMCs became obsolete during SCT assembly.

In future there should be clean connector breaks at the end of the barrels/disks.

ATLAS Pixels

The first patch panels are located at the endcaps and this is where the optical cables originate. The second patch panels are located 3 m away. The excess cable length between the two patch panels are quite manageable. Between the second patch panels and the counting room is ~ 70 m cables and most of the excess length are managed in the counting room.

8.12 Performance monitoring

CMS

The analogue nature of the CMS readout link allows for easy monitoring of the transmitter operating point and link power budget. Automatic monitoring routines have been written and embedded into the CMSSW framework. They will provide a homogeneous assessment of the link performance across the 3 CMS tracker sub-detectors.

Spare fibre channels have been optically looped back at the front-end to enable monitoring from the back-end the darkening of the fibre under irradiation.

ATLAS SCT

The digital nature of the SCT link makes long term monitoring of the performance slightly more difficult. Nevertheless a simple scheme for performing scans of the receiver threshold allows a quick way to determine the performance of the data link. The results of these scans will be saved and this allows for a simple analysis of the long term performance. The TTC link performance can be simply monitored by measuring the currents in the on-detector p-i-n diodes.

ATLAS Pixels

The optical link of the pixel detector will be monitored with a similar procedure.