Experiences with the ATLAS Pixel Detector Optolink and Researches for Future Links

J. Dopke[a], J.-F. Arguin[c], T. Flick[a], C. Gemme[d], G. Lenzen[a], P. Mättig[a], L. Masetti[b], J. Moss[e] , S. Sandvoss[a], S. Strandberg[c], C. Zeitnitz[a]

[a] University Wuppertal, Gaußstr. 20, 42119 Wuppertal, Germany
[b] Physikalisches Institut der Universität Bonn, Nussallee 12, 53115 Bonn, Germany
[c] Lawrence Berkeley National Laboratory, Physics Division, MS50B-6227, 1 Cyclotron Road, Berkeley, CA 94720, USA
[d] INFN Genova and Università di Genova, Dipartimento di Fisica, via Dodecaneso 33, 16146 Genova, Italy
[e] Ohio State University, 191 West Woodruff Ave, Columbus, OH 43210-1117, USA

jens.dopke@cern.ch

Abstract

The ATLAS Pixel detector has been installed in its final place into the ATLAS cavern in July 2007. After providing all the necessary connections, the final testing and commissioning has been performed before the first beam was circulated through the LHC in September 2008.

The connection between the 1744 detector modules and the readout electronics in the counting room is done via optical links, that have to be commissioned and tuned in order to be able to send commands to and receive data from the modules.

Tests for optical and electrical functionality of components during production and assembly sorted out failing parts. The commissioning work on the installed detector showed more than 97% of the system being functional.

The procedure of the commissioning work and observed issues on the system layout and function are discussed and brought into an outlook for future optical link designs.

I. The ATLAS Pixel Optical Readout

The optical readout of the ATLAS Pixel detector ([1], [2]) is a per module connection between the off-detector readout systems and the on-detector optical components, containing several custom made components both on- and off-detector ([3]). The off-detector components of the optical link are located on the Pixel Back of Crate (BOC) Cards, whilst the on-detector components make up the optoboards.

The 132 BOC cards are located in the Pixel readout crates in the counting room USA15, around 80m away from the detector itself. Each BOC card is paired to a Readout Driver (ROD, [4]) and interfaces it to the modules, and the readout buffers. The optical to electrical conversion is done on small plugins assembled to the BOC cards, the Tx- Plugins for the downlink and the Rx-Plugins for the uplink.

The optoboards are mounted to service panels in around 1m distance to the detector modules and connected to them electrically. Each optoboard is connected to 6 or 7 modules, which belong to a half stave in the barrel region or a sector in the disks. It serves one downlink to each module and one or two uplinks. The optoboards are mounted on service panels, which are mounted to the detector and form the patch panels nearest to the detector.

The downlink into the detector sends clock, trigger, command, and configuration signals (Timing, Trigger, and Control TTC) into the detector. The link is DC-balanced using a BiPhase Mark (BPM) encoding in order to send clock and data via a single line into the detector. This was found to be particularly useful, since the encoder only adds about 65 ns latency to the command stream, which is acceptable for the trigger latency. The receiving chip on-detector is the Digital Optical Receiver Integrated Circuit (DORIC), localized on the optoboards. The threshold for recognizing bits is automatically set to 50% of the incoming input signal by the receiver circuit. Afterwards the BPM signal is decoded into clock and data and sent to the pixel detector modules. The decoding is done per channel, such that each module receives individual clock and command. Inside the BPM encoder, each stream can be delayed individually in steps of 320ps. The individual phase shift with respect to the LHC Bunch crossing clock increases the efficiency for the detection of low charge hits.

The optical uplink is composed of an on-detector transmitter, the VDC (VCSEL Driver Circuit) driving a Vertical Cavity Surface Emitting Laser (VCSEL), and an off-detector receiver integrated circuit, the DRX. Data are sent as an NRZ stream to the off-detector electronics, thus no active decoding is needed. The signal is not DC-balanced, hence no automatic threshold adjustment can be performed here. Instead the threshold must be manually set between 0 and 255 uA. Phase adjustment of the returned data happens manually on the BOC, using PHOS4 integrated circuits (0 to 24 ns Phase adjustment with 1 ns step size).

The optical fibres are a spliced combination of radiation hard and radiation tolerant fibres, bundled into 8-way ribbons. Only 6 or 7 channels of this connection are used, depending on which geometrical units are read out. The eighth connection is disabled by design on the optoboard, but is usable in the off-detector electronics.

ATLAS Pixel modules have two data outputs which can be set to work at different modes: 1x40, 1x80, 2x40 and 2x80 Mb/s. Depending on their physical location and the corresponding occupancy expected during runtime, the data is given to the optoboards at different bandwidth and on either one or two channels.

Depending on the detector occupancy, there are two flavours of optoboards with either 8 or 16 inputs, which are transmitted via either one or two ribbons to the same number of RX-Plugins.

The ROD, that receives the data from the BOC Card and builds an event fragment out of them, can only cope with 40 MBit/s inputs, therefore all 80 Mbit/s data streams are split into two 40 Mbit/s streams inside a logic built into the Pixel BOCs. This needs particular attention when adjusting signal phases.

II. Implications of the chosen Layout

The choice of the hardware was driven by the position in the setup and the accessibility during runtime, leading to different properties for on- and off-detector components:

A. On-Detector

The on-detector components ([5]), incorporated into the optoboard are inaccessible during runtime, therefore a lot of features were included to make them operable under harsh conditions and without user intervention.

The automatic threshold adjustment of the DORIC is meant to work from an average input current of 4000 uA down to less than 40 uA, thereby basically allowing any light input to drive the system in stable conditions. It cannot correct for wrong input duty cycles, which directly influences the output clock quality. These are adjusted on the signal itself by the sending instance, the BPM.

There is only one parameter for transmission, the laser forward current generated by the VDC. $V_{iset,}$ the voltage controlling the light output power of an optoboard, is adjusted for all 8 or 16 channels at a time via an external voltage set by the Detector Control System (DCS). Since the lasers have slightly different thresholds and the connection quality varies per channel, it is normally not possible to find an ideal setting for all channels. The best average tuning has to be chosen instead. Foreseeing possible degradation of the lasers due to irradiation, high power versions were chosen, which give a fibre coupled output power of 3mW peak in average, but might about 7mW peak amplitude for some channels (cf. [6]).

B. Off-Detector

The off-detector components are located in the ATLAS counting rooms. They can be accessed during the life time of the detector. The BOC cards and RODs are controlled via single board computers, of which one is installed in each readout crate. The optimization of the parameters for the optical link can be done remotely by performing and analysing tests for the installed detector and optical link.

The transmission parameters to be adjusted for each channel are the laser forward current, two different delays in the transmission line, coarse and fine, and the Mark-to-Space Ratio (MSR). The on-detector clock reconstruction is based on transitions of the incoming signal and thus depends on the mark-to-space ratio of the signal. If not tuned properly, two clock modes with different periods exist on detector (see Figure 1), one between rising and falling edge of the BPM stream and another one between falling and rising edge. The adjustment of the mark-to-space ratio influences the phase of the on-detector clocks. Adjusting the fine-delay of the signal influences the mark-to-space ratio, which needs to be taken into account, when tuning the system for optimal transmission parameters.

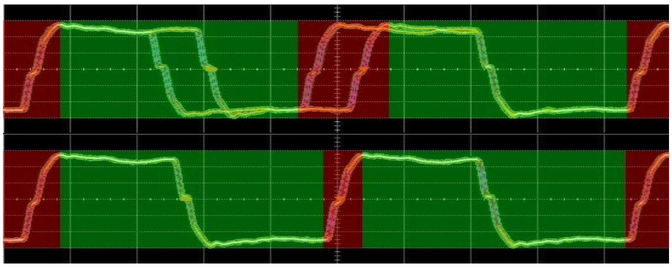

Figure 1: On-detector clock reconstructed from mistuned and tuned mark-to-space ratio

Reception parameters are the threshold applied to the incoming PiN current and the phase adjustment to the incoming signals, such that all received signals on a single BOC can be registered with a common clock.

The current response of the PiN diode has a characteristic slow component, generated by a low-field region inside the PiN volume, when fed with a light pulse. Therefore the signal response does not have perfectly steep edges and with higher signals, a higher noise floor is introduced. The DRX is only capable of applying a maximum threshold current of 255µA, which is typically over-steered with an input signal swing of about 2mA. This again translates into a fibre coupled light power of ~3mW reaching the PiN diode. Higher signals can lead to a situation in which the system is not able to reconstruct data, because the DRX input contains only of the noise floor.

III. Commissioning work

A. Installation and Testing

The electronics and fibres were extensively tested during production, where individual testing was possible. The full link was then commissioned on site by either communicating with the detector or with special tools, like loopback fibres and an Optical Time Domain Reflectometer (OTDR).

OTDR measurements have shown that most of the fibres are in good shape even though the installation conditions, e.g. time and space constraints, were not as good as in standard telecommunication fields.

Loopback fibres identified misaligned TX-Plugins and malfunctioning TTC channels. The I/C curves resulting from the loopback tests were recorded using low level software running directly on the crate (Example see Figure 2).

The complete Pixel detector package was tested including the operation of the optical link in a connectivity test at the surface and in the cavern. The correct connection and the capability to address each detector module has been tested and verified.

B. Tuning of Parameters

Tuning of all parameters is done via software from the Data Acquisition System (DAQ), as these can communicate with the modules, take data with the system, and control most of the transmission parameters directly via communication inside the readout crates. Only the optoboard light power is to be adjusted via DCS. Tuning V_{Iset}, RX-threshold and RX-delay is compulsory, since they are needed to reconstruct data returned from the pixel detector modules. For a complete tuning of the optical link all the parameters have to be addressed, which will be described in the next sections (see also [7]).

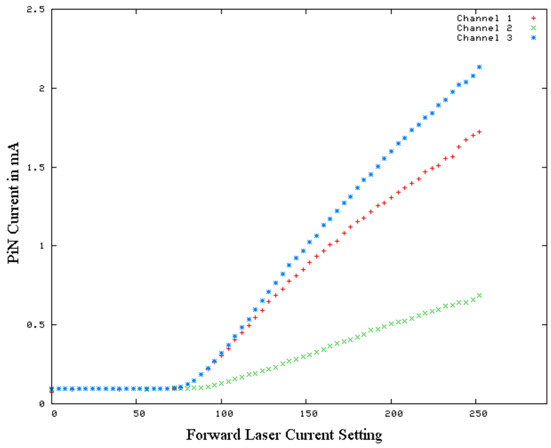

Figure 2: Loopback test result showing different increases in fibre coupled light power with increase of laser forward current setting.

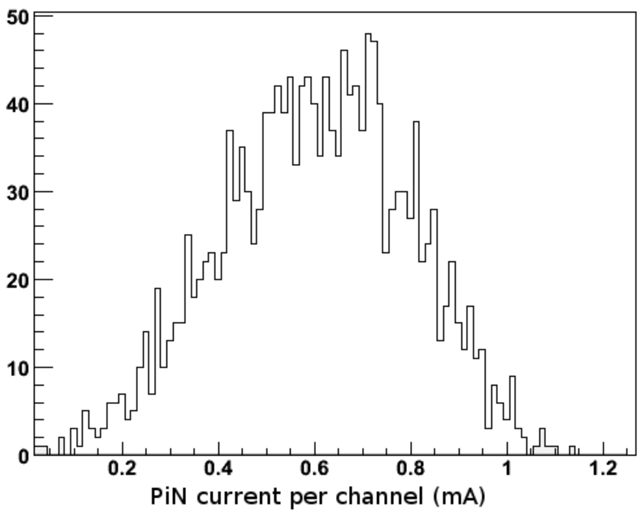

Figure 3: PiN currents produced by all TTC-lasers in use in the ATLAS pixel detector

Light power for the TTC lines should be adjusted to rise an average PiN current of 300µA per channel on the optoboard. The optoboard has only one supply line for the PiN voltage and can therefore only measure the total current produced by the active channels. The use of DAQ-DCS communication, to turn on each TX-Plugin laser channel individually, and to read the corresponding optoboard PiN current values makes the measurement particularly slow. Since the light power of the TTC links has proven to be operational even without tuning, all channels are set to a forward current of about 10mA, which produces a PiN current of about 3-4 mA total for all 6/7 channels used on the optoboard. Regular checks of the lasers fibre coupled power are performed in system, results can be seen in Figure 3.

The optimizing of the mark-to-space ratio is done by configuring the detector modules to send back half the incoming clock (20 MHz clock-like data signal). Now in the RX-path on the BOC the incoming positive pulse width can be measured by sampling the data with a 20 MHz clock and adjusting all possible phases between 0 and 49 ns. Flipping the BPM signal versus returned clock phase by sending a single one (without affecting any other parameters), the on-detector clock modes are exchanged so that the returned positive pulse width correspond to the other on-detector clock mode (see Figure 4). The ideal setting can now be found by adjusting the MSR to give the smallest difference between the two measured pulse widths (cf. Figure 5).

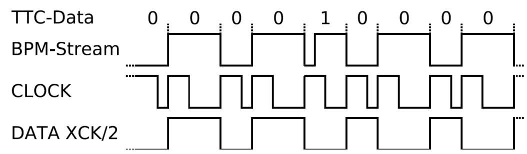

Figure 4: Flipping the phases between BPM stream and returned half clock

V_{Iset} tuning has to be performed for all channels connected to the same optoboard at the same time. Since low power channels prefer higher settings of V_{Iset}, while high power channels prefer lower ones due to the saturation effects in the RX PiN diodes, the recent tuning algorithms for V_{Iset} incorporate a measure for the quality of RX-threshold tuning at the corresponding V_{Iset}, which directly reflects the light power incoming to the RX-Plugin. The target is set to have an average threshold tuning of more than 200 uA, such that the output signals from the optoboard are reasonably high and stable, as the lasers are driven well above their threshold currents.

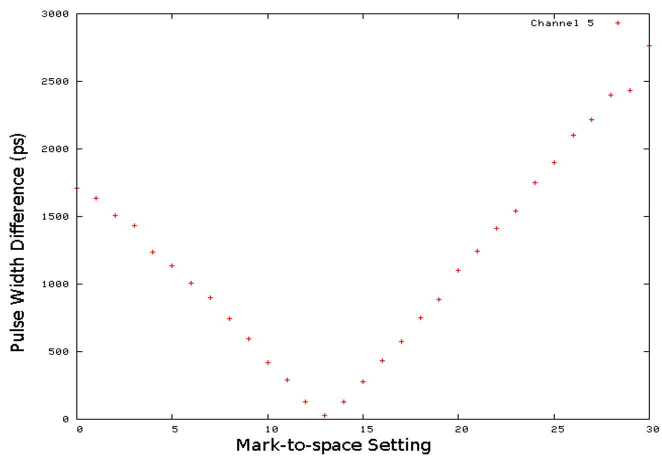

Figure 5: Resulting plot from Mark-to-Space Ratio tuning showing the difference between adjacent clock cycles on-detector - The ideal setting is the closest to zero difference.

RX-thresholds are tuned such that the range of delay settings, which can be used, is maximal, meaning the return bit width is equal to one clock cycle. This effectively gives a threshold below 50% of the returned signal size, since the lasers have a non-negligible turn-on time and the PiN-diodes response function gives signal edges a smaller slope. The intersection of rising and falling edges thus happens at thresholds lower than 50% of the signal size. In case a threshold is tuned to the maximum allowed setting and the signal is still wider than 27.5 ns it is counted as an overshoot for the tuning of V_{iset} causing it to be decreased.

RX delay is set such that the sampling point for registering data off-detector is about 5 ns before the edge transition from one bit to another. Signals have proven to be more stable after settling for a few ns, whereas right after the transition, the amplitude fluctuates, depending on the number of previously sent ones and zeros. (See Figure 6 - Transitions happen from right to left Time is invers to RX-delay)

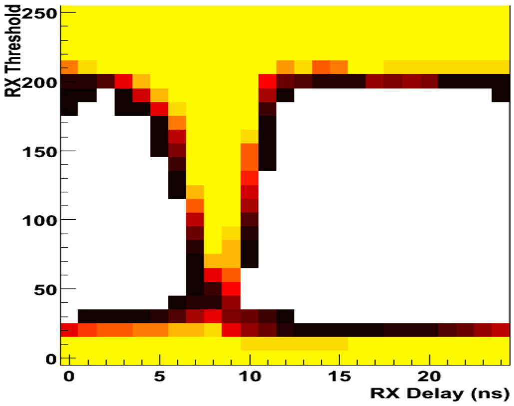

Figure 6: RX-delay versus RX-threshold (fast) BocScan, White regions received an expected number of one and zeros during the scan (Comparable to a single phase eyepattern)

TTC-delays have generally not been adjusted yet. They will optimize physics performance (see [8]) by shifting the timing of the Pixel detector to have a sampling window for one bunch crossing start right when the first charges arrive. The detector is slower in receiving low charges and thus might shift these into the next sampling cycle. The optimal setting is obtained when the timing window starts at the arrival time of the highest readable charge.

Bandwidth adoptions are done inside the BOC. After switching the decoding mode from simple forward 40 Mb/s to demultiplexing (80/160 Mb/s), all that needs to be done is readjusting the signal delay, to be on average 3ns less, because the decoding introduces an extra 3ns delay inside the BOCs integrated logic

IV. *Environment Control*

The optoboards are cooled via the same evaporative cooling system used for the modules of the Pixel detector. This cooling provides an operation temperature of about 5°C measured on the optoboards. The lasers used on the optoboards are optimized for an operation temperature of 20°C and some of them give no more light output when operated at temperatures much lower than that (measurements during production showed basically no light output at -25°C). Therefore a heating system was added, to heat the optoboards up to a programmable temperature.

Operating the optoboards without this cooling system still gives reasonable output for most optoboards, when operated with a 50% link occupancy as is used for tuning the system (half-clock return signal from the module). Switching to calibration scans that have a lower link occupancy, the average light output power drops due to the local induced heat inside the lasers not being high enough. Hence the tuning of the link succeeds, but leaves the system in a state unusable with lower link occupancies. This problem is called Slow turn-on , because the light power level increases during operation of the laser and heats the device. To avoid loosing the first bits the heaters are used to heat up the lasers to a higher temperature and therefore keeping them in a more stable operating condition.

A.Production Issues

When operating the system during commissioning of the ATLAS Pixel detector in its final position (installed inside of ATLAS and connected to the final readout system) single TTC channels started failing by not transmitting any light. This behaviour was shown to be compatible with ESD damage during early production of the TX-Plugins. The ones that were damaged by ESD died after a limited operation time, sometimes up to some month.

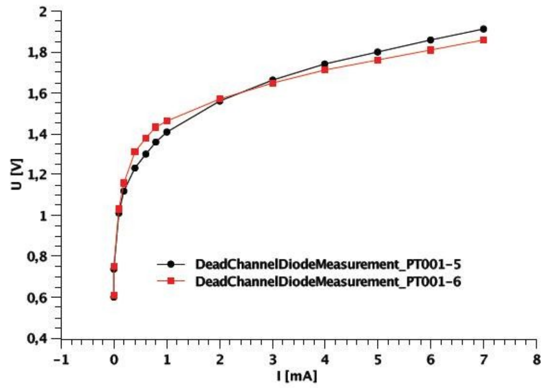

Figure 7: IV characteristics of a functional (red) and an ESD affected channel (black) of a Pixel TX-Plugin

The ESD damage cannot be tracked down in the system, as the only hint before losing light output power is a change in the IV-characteristics of the laser diodes: the knee voltage of the affected laser drops slightly whilst the slope beyond threshold rises. An example curve is shown in Figure 7.

A new batch of Tx-Plugins is been produced under stricter precautions against ESD. The intensive handling, which is necessary during the production of the plugins, is a point of high risk in the production procedure and must be controlled intensively.

V. Research for Future Links

The experiences, which have been made in the production and the operation of the present optical link, should be introduced into a design of a new optical link for the next generation detectors. Many points hidden in the details can be improved and make the life for the experts and operators of the optical links easier and more convenient. We want to describe some of them in this last chapter.

A. Layout Improvements

The layout of the optical transmission path can be improved by some modifications on both ends. The TTC link sending from the counting room to the detector is working very robust and stable, This suggests to include some of the features of the TTC link into the data link.

A DC-balanced transmission, as it is implemented in the present TTC path is to be part of the next optical data path as well, since it gives the possibility to automatically set up the input threshold as well as the phases of the signals. Instead of measuring the phase of on-detector clocks by scanning in order to get timing information, one could have the phase be measured by the system all the time, hence delivering stability information. This would solve two basic tune steps, the adjustment of the receive threshold for recognizing the incoming data and the generation of one or two clocks to register the data correctly before passing it to further parts of the readout system.

This means of course that on the off-detector side as well as on the on-detector part the components of the link have to be revised to include the wished features,

Packaging has already been a major design aspect in the recent optical link, and will be for the next one. As could be seen from features like the slow turn-on, the thermal behaviour is not fully under control. Thus packaging needs to get a higher thermal conductance and the behaviour of lasers needs to be carefully checked whilst setting up components for the next optical link. The adoption of the operating temperature to the one, which is the best for operating the lasers, is crucial. For this the requirements of packaging, board design, and material choosing is to be conciliated. Important tests of the system under the real conditions which will appear in the final detector place are very important and should be enforced to take place as early as possible.

B. (Electrical) Features to be added

The ESD failures seen during commissioning of the recent link are the result of a post-mortem analysis showing a difference for different lasers. A control mechanism inside the system does not exist and the sanity status of the separate components can only be determined by judging the complete transmission chain behaviour. Features inside the individual components or on the cards where they are located can help to investigate the status and sanity of the single parts.

Embedding a possibility to measure IV curves of the used lasers in-situ would give a handle on recognizing a possibly damaged laser before it dies and estimating needs for replacements. Since the lasers are localized on off-detector boards which can serve an additional circuit to be able to measure this kind of parameters, it is worth to include this feature. The on-detector situation is different due to the space limitations. An external measurement circuit will not be introduced, but including an ADC which controls voltages and currents might be possible inside a chip itself.

Another feature to be introduced is the possibility of checking the correct data transmission. In the present design, the TTC signals can only be transmitted in encoded form. A data check needs therefore always a decoding part. On top of a only data or only clock transmission mode a possibility to loop back the signal for test purposes at several places would be very useful. To check the data before the electrical to optical conversion or after the optical transmission by sending it directly back can help to debug and qualify the data transmission quality in situ.

The last point is to increase the transmission speed of the link, which opens many possibilities. Either to include the data of several modules into one stream or to include error checking encodings into the data to be able to judge only on the transmitted bits and bytes.

To be able to meet the requirements for a solid data transmission in faster machines as the LHC is and transferring more data in shorter time, the future optical links have to include higher speed components and operate at higher frequencies than the machine frequency. It is to be study in time if there are disturbing effects on the data taking and performance of the detector and accelerator machine.

All in all the present Pixel detector optical link is a good basis to develop transmission systems for future detectors and the commissioning and operation has given and will give a good reference for further developments.

VI. Acknowledgements

Our thanks is to the community who developed, produced, tested, installed and commissioned the Pixel detector. Many people contributed to the work which is described in short was in this paper. Without the help of a large group of people the successful start of operation of the detector and its optical data transmission system would not have been possible.

VII. References

[1] The ATLAS collaboration 2008, The ATLAS Experiment at the CERN Large Hadron Collider, JINST to be published

[2] G Aad et al 2008, ATLAS pixel detector electronics and sensors, JINST 3 P07007 doi: 10.1088/1748-0221/3/07/P07007

[3] T Flick et al 2006, Optical readout in a multi-module system test for the ATLAS pixel detector, Nucl. Instrum. Meth. A 565 85

[4] T Vickey 2006, A read-out driver for silicon detectors in ATLAS 12th Workshop on Electronics for LHC and Future Experiments, Valencia Spain, 2006 http://cdsweb.cern.ch/record/1027436

[5] K K Gan et al 2007, Optical link of the ATLAS pixel detector Nucl. Instrum. and Meth. A 570 292

[6] S Nderitu 2007 Atlas pixel opto-board production and optolink simulation studies PhD thesis, WUB-DIS 2007-03 University of Wuppertal.

[7] Jens Dopke 2007, Studies for automated tuning of the quality of the Back-of-Crate card for the ATLAS Pixel detector, Diplomarbeit, University Wuppertal, WU D 07-02

[8| T Flick, P Gerlach, K Reeves and P Mättig 2007, ATLAS pixel detector timing optimisation with the Back-of-crate Card of the optical pixel readout system JINST 2 P04