DEVELOPMENT OF RADIATION TOLERANT Gb/s OPTICAL LINKS FOR THE FRONT-END READOUT OF THE ATLAS LIQUID ARGON CALORIMETER

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Abstract

In the baseline readout solution for the ATLAS liquid argon calorimeter, approximately 1500 unidirectional Gigabit/s (Gb/s) fibre-optic links are used to transfer data from the calorimeter to receivers in data acquisition electronics situated up to 200 m away. In an architecture currently under study, 'G-Link' serialiser chips manufactured by Hewlett Packard are used to convert calorimeter data words into a 1.6 Gb/s serial data stream which is fed into a VCSEL (vertical cavity surface emitting laser diode) based emitter system operating at 850 nm. Graded index multimode optical fibres are used to couple the on-detector emitters to PIN-photodiodes located in receivers. In this note results from neutron irradiations of a complete G-Link based link demonstrator are presented along with results from neutron and ionising irradiations of potential link components (packaged VCSEL's and graded-index fibres).

1 INTRODUCTION

1.1 Link Architecture

Approximately 1500 unidirectional optical interconnects are required for the readout of the ATLAS liquid argon (LArg) calorimeter [1]. Each on-detector front-end board (FEB) is fed by 128 'raw' calorimeter channels which are processed and on receipt of a level-1 trigger accept readout over an optical interconnect. The interconnect must allow a throughput of 1.28 Gb/s (32 bits every 25 ns). The bit error rate (BER) of the interconnect must be better then 10^{-9} so the performance of the LArg data acquisition as a whole is not compromised. The interconnect architecture currently favoured is a single serial optical link per FEB as this reduces cost due to the fewer number of components required compared to a parallel link implementation. The link is based around commercial 'off-the-shelf' components. The emitting end of the link comprises of a Hewlett Packard G-Link serialiser chip connected to a VCSEL laser diode [2]. Graded index multimode (50/125) fibre is used to connect the emitters to off-detector receiver units which contain G-Link deserialising chips. This architecture is shown schematically in figure 1.

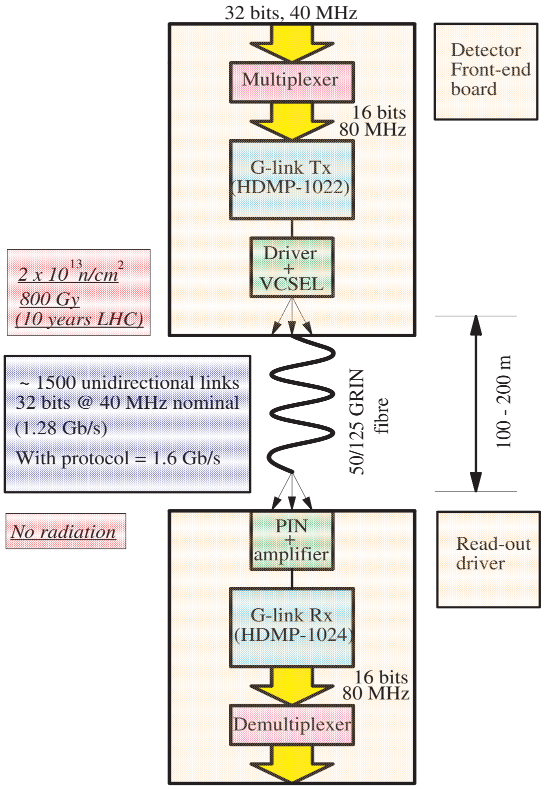

Figure 1: A schematic of the front-end readout links for the ATLAS LArg calorimeter.

1.2 Radiation Issues

Over 10 years of LHC running, the components at the emitting end of the link will be subject to high levels of both neutron (1.7×10^{13} n(1 MeV Si) cm^{-2}) and ionising (gamma) radiation (800 Gy). The receiving part of the link is not exposed to significant levels of radiation. Access to link components mounted on-detector would require a lengthy access into ATLAS and so it is important that the components operate reliably for 10 years in this hostile environment.

Components were irradiated with 6 MeV neutrons at the SARA cyclotron facility in Grenoble [3]. The neutrons are produced by impinging 20 MeV deuterons on a beryllium target. The components under irradiation are located approximately 30 cm from the target, behind a liquid nitrogen cryostat which is used for other tests. The activation of nickel foils was used to determine the absolute neutron fluence to an accuracy of around 15%. The typical neutron flux at SARA is approximately 5×10^{11} n cm^{-2} hr^{-1}, about 1500 greater than that expected in ATLAS.

The gamma irradiations were performed with ^{60}Co facilities at BNL, Brookhaven (only fibre) and Karolinska Hospital, Stockholm (fibre and VCSEL's). As the ^{60}Co source decays it emits two gamma rays at energies of 1.17 MeV and 1.33 MeV. Polymer-alanine dosimeters were used to measure the total ionising dose received by the components under test to an accuracy of around 4%. Solid state detectors were used to cross-check the result. The dose rate delivered at BNL (Karolinska) is approximately 200 (80) Gy hr^{-1}, about 10^4 (4000) greater than that expected in ATLAS.

2 IRRADIATION STUDIES

2.1 Demonstrator Link

Overview

A set of demonstrator links based around the G-Link chipset have been constructed and the emitting end of the link irradiated with neutrons. Both emitter and receiver boards do not have the optics mounted directly. Instead, there is a socket following the industry standard for transceiver modules. This allows a variety of different optical solutions to be easily evaluated - such as a driver circuit (if necessary) coupled to the VCSEL's described in section 2.2. The receiver board also features an Altera PLD to allow some processing of the G-Link outputs. During the tests described in the remainder of this note, industry standard VCSEL-based Gb/s transceiver modules have been used. As the links are unidirectional only half a transceiver is used at either end of the link. Due to this partial use, it is unlikely that such transceivers will be a final solution for ATLAS. However, in a demonstrator link they are very suitable for gaining experience with the irradiation of Gb/s link components.

G-Link Chipset

The G-Link chipset enables parallel data loaded into the transmitter to be delivered to the receiver over a serial channel. The chipset is particular attractive as it hides the complexities of encoding, multiplexing (transmitter) and clock extraction, demultiplexing and decoding (receiver) from the user. Furthermore, frame synchronisation and DC balance are maintained automatically. The G-Link protocol attaches a 4 bit control word to every 16 bit data word sent over the link, making a 20 bit frame, as shown in figure 2. The control word denotes the data type being sent (control, data or fill frame) and contains a 'master transition' which the receiver uses for frequency locking. The chipset is run

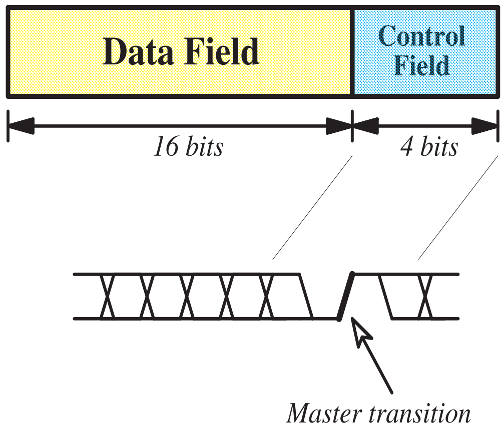

Figure 2: The structure of a G-Link data frame. A 16 bit data word is followed by a 4 bit control word containing a master transition which the receiver uses for frequency locking.

in the 'double frame mode' which, with the addition of external (de)multiplexing elements, allows a 32 bit data word (40 bit frame) to be sent as two separate 20 bit frame segments. Data inputs to the chip are TTL and the serial Gb/s output is PECL. The (de)multiplexing elements are standard ATLAS components, used by many subdetectors, and not expected to present any additional radiation tolerance issues. The monolithic silicon bipolar G-Link chipset is based on a masked 'sea of gates' architecture using 25 GHz transistors.

Transceiver Modules

The transceiver modules contain a 850 nm VCSEL emitter and driver packaged together with a PIN-diode based receiver and amplifier and discriminator. Optical connections are made with push-fit 'SC' connectors. The modules accept PECL inputs and so can be directly coupled to the output of the G-Link. Three varieties of transceiver have been tested : Hewlett Packard, Honeywell HFM2450 and Methode MDX-19-4-1. The Hewlett Packard and Honeywell transceivers use silicon bipolar laser drivers whereas the Methode driver is based on discrete components.

Testing Procedure

The neutron irradiations have two aspects. Firstly, the components on the emitting end of the link must survive the total neutron fluence expected after 10 years of LHC running without any effect on the performance of the link - total dose studies. Secondly, the radiation induced bit error rate in the link must be acceptable - single event studies. During irradiation all components were biased and approximately 70 m of fibre joined the emitter to the receiver.

A figure of merit describing the performance of a link is traditionally given by the bit error rate. Performing industry standard bit error rate tests at Gb/s speeds requires the use of expensive equipment which is often not optimised for the transfer of 32 bit data words. Moreover, only a single link can be tested at once, which is not ideal for irradiation studies when larger sample sizes are desirable. A purpose built bit error rate tester is under construction for testing LArg links but was not available at the time of the irradiations. For the tests described in this note a simpler approach was followed. Before and after (up to a week afterwards due to a 'cool down' period) an irradiation, the integrity of a single link could be assessed using a logic analyser comparing received data to a reference table. The single link limitation and large dead-time of this method makes it unsuitable for irradiation tests. A simpler scheme, using the G-Link's inbuilt error detecting functionality, is therefore used. The G-Link receiver provides an error flag which is generated internally from a check of the control field in the transmitted frame. The control field check is sensitive to illegal control words (not all 2^4 combinations are allowed) and deviations from a strict alternation of the master transition bit. The data word is not checked. There is also a 'link-down' indicator which is asserted when the G-link cannot identify a frame to lock on to. It is important to understand the frequency of this type of error during irradiation as the G-link error recovery procedure takes a minimum of 128 frames (1.6 μs) to recover the link.

With no radiation present, both tests indicated no errors during many days of operation.

Total Dose Studies

Total dose studies were made in three separate tests, as summarised in table 1. In the first and last tests, the G-Link chips were coupled to transceiver modules. In the second test, the link was run at 160 Mb/s over 15 m copper links. This is discussed further in the next section. In all cases the G-Link chips survived the irradiation with no errors being indicated during the two test procedures described above (using fresh transceivers). Note that G_{1-4} survived a 30 year LHC equivalent irradiation. The only transceiver modules not to suffer damage during irradiation were those supplied by Methode. A post-irradiation 'autopsy' on the Honeywell transceivers revealed that the laser driver had failed but the VCSEL still functioned within specifications when coupled to a fresh driver. The Methode transceiver had a driver comprised of discrete components. For technical reasons, the HP transceiver could not be easily tested after dissection.

Test	G-Link	Optics	G_n status	Optics status
1	G_1	HW_1	OK	Dead
(10	G_2	HW_2	OK	Dead
years	G_3	HP_1	OK	Erratic
equiv.)	G_4	M_1	OK	OK
2	G_1	Cu	OK	n/a
(20	G_2	Cu	OK	n/a
years	G_3	Cu	OK	n/a
equiv.)	G_4	Cu	OK	n/a
3	G_1	M_2	OK	OK
(10	G_5	M_3	OK	OK
years	G_6	M_4	OK	OK
equiv.)	G_7	M_5	OK	OK

Table 1: Summary of G-Link (G_n) demonstrator link irradiations. G-Links G_{1-4} and G_{5-7} come from different batches. Transceivers are denoted by : HW_n, Honeywell; HP_n, Hewlett Packard; M_n, Methode. Test 2 used copper (Cu) links, with the link running at 160 Mb/s.

Single Event Studies

Four complete links equipped with Methode transceivers were used to investigate single event effects during a neutron irradiation. During irradiation, the link-down time was estimated by monitoring the G-link error flag and link-down indicator. The distribution of the link-down times can be seen in figure 3. The sharp peak around zero (12.5 ns)

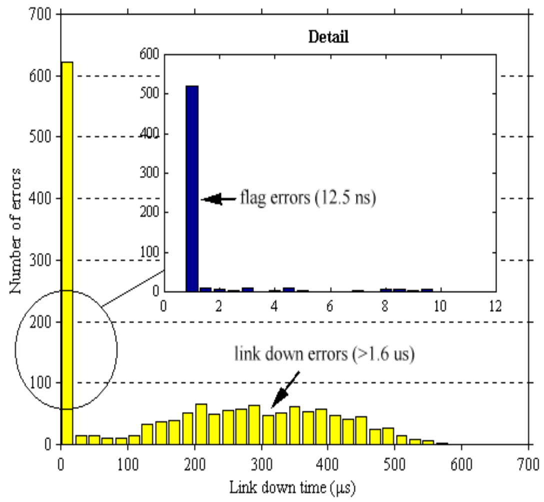

Figure 3: The distribution of the link-down time measured during neutron irradiation for a link comprising G-link chips and Methode transceivers.

is composed solely of error flag errors. The rest of the entries (all >1.6 μs) occur when the G-link asserts the link-down indicator after loosing frame lock. Note that a single link-down event lasting 300μs corresponds to the loss of 24 000 20 bit frames, which is clearly unacceptable. In order to maintain a bit error rate of $\mathcal{O}(10^{-9})$, approximately one such 300μs link-down event can be tolerated every 100 hours.

The majority of this data was taken at a SARA deuteron beam current of 5 μA which corresponds to a neutron dose rate approximately 1500 that expected in ATLAS. At 5 μA there was approximately 1.5 (1) link-down (error-flag) error recorded per minute. To estimate the error rate at ATLAS-like dose rates, some data was also taken at lower beam currents. The error rate was observed to drop rapidly with beam current, but insufficient beam time was available to allow any robust conclusions to be drawn.

Future tests will be dedicated to low dose-rate studies and improved monitoring of the G-Link error flags will allow the link integrity at ATLAS-like dose rates to be determined. As single event type errors were also observed in the low speed test with copper links (see total dose section), it would be instructive to separate the G-Link and transceiver in a high speed test. As it is impossible to do this with copper links, there is a development under way to drive VCSEL's directly from the G-Link.

2.2 Packaged VCSEL's

Nine Honeywell HFE4080-321 and nine Mitel 1A440 VCSEL's were irradiated with both neutrons and gammas [5]. The VCSEL chips were housed in TO-46 packages encapsulated into metal ST assemblies to allow simple fibre connections. The Honeywell VCSEL's were equipped with plastic lenses to facilitate efficient fibre coupling, the Mitel VCSEL's had a flat window. The active VCSEL chips are approximately cubic with sides of length 500 μm. Similar VCSEL's are used in the transceiver units discussed in section 2.1. During the irradiations the aim was to investigate radiation induced attenuation of the VCSEL's light output and possible changes in the VCSEL's threshold current. As such, the tests purely investigated the DC (time averaged) characteristics of the VCSEL's. Each VCSEL was equipped with a fibre which was routed away from the radiation beams to a PIN-based receiver unit [4] connected to an ADC mounted inside a PC. During irradiation, the VCSEL's were biased above threshold. At periodic intervals the bias current was varied between 0 mA and 10 mA and the corresponding light output recorded. After the irradiation period was over the VCSEL's remained biased to check for any evidence of annealing effects. The total neutron fluence received by the VCSEL's was measured to be $(2.1\pm0.4)\times10^{13}$ n(1 MeV Si) cm^{-2}, corresponding to 10 years of LHC running, and the total ionising dose was (5.1 ± 0.2) kGy, corresponding to 66 years of LHC running.

Figure 4 shows the relative attenuation in the light output from a Honeywell VCSEL as a function of the time during neutron irradiation. The vertical lines denote the start and end of the irradiation period. This plot is typical for all the Honeywell VCSEL's tested and compatible behaviour is seen for all the Mitel VCSEL's. Figure 5 shows the corresponding results from a gamma irradiation. The neutron (gamma) irradiation reduces the light output by about 10% (5%) for 10 year LHC equivalent exposures. After the neutron irradiation a few days of annealing restores the light output to pre-irradiation levels. No such annealing behaviour is observed after the gamma irradiation. The threshold current for either type of VCSEL did not move significantly during either type of irradiation.

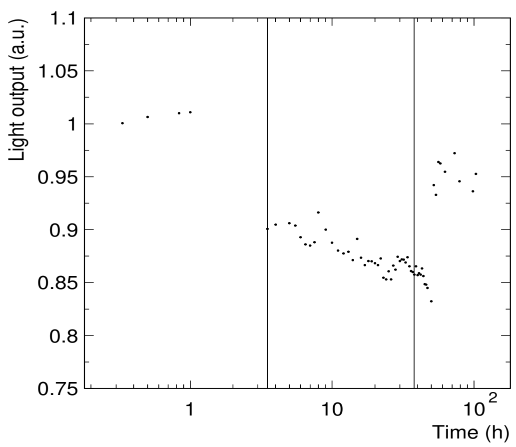

Figure 4: Relative attenuation of the light output from a Honeywell VCSEL as a function of the time during a neutron irradiation. The vertical lines indicate the start and end of the irradiation period. Note the annealing behaviour after the irradiation is completed.

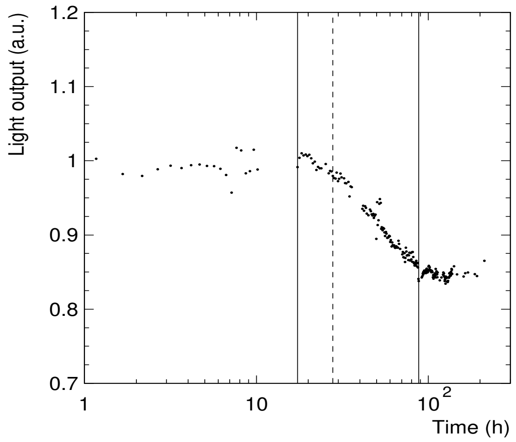

Figure 5: Relative attenuation of the light output from a Mitel VCSEL as a function of the time during a gamma irradiation. The vertical lines indicate the start and end of the irradiation period. Note the absence of annealing after the irradiation is completed. The dotted line denotes a 10 year LHC equivalent dose.

2.3 Multimode Fibre

Two 10 m long pieces of commercial off-the-shelf fibre have been irradiated with neutrons and gammas. The fibres were not chosen for any particular reason, but rather to be representative of commercially graded index fibre. Due to the speed of the link, graded index fibre with a small core size is needed to ensure dispersion does not compromise the performance of the link. The first fibre is a piece of 50/125 germanium doped silica core 8-way fibre ribbon supplied by Acome. The second piece is a duplex patch cord supplied by Alcoa-Fujikura and designed for use with the transceiver modules described in section 2.1.

The fibres were arranged in coils to maximise the amount of fibre in the radiation beam. A 850 nm VCSEL emitter was used to send light through the fibres and a calibrated optical multimeter used to measure the received amount of light. The emitter was monitored during the irradiation to check that the output power remained constant. Figure 6 (7) shows the induced attenuation during the neutron (gamma) irradiation. The induced attenuation in the

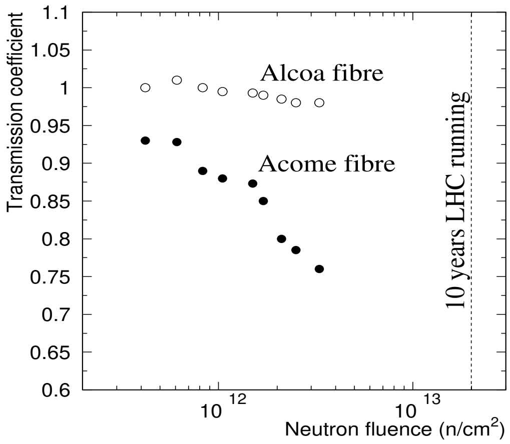

Figure 6: Neutron induced attenuation in 10 m lengths of two varieties of commercial graded-index fibre. The dotted line allows an extrapolation to the expected attenuation after 10 years of LHC running.

two fibres after a 10 year LHC equivalent dose is significantly different after both the neutron and gamma irradiations. The Alcoa-Fujikura fibre exhibits extremely good neutron and gamma radiation tolerance whereas the Acome fibre fails catastrophically during gamma irradiation.

3 SUMMARY

A serial optical link running at 1.6 Gb/s and based around the G-Link chipset and commercial VCSEL/PIN-diode transceiver units has been developed. The link fulfills the specifications of the readout links required for the ATLAS LArg calorimeter and runs error-free in the laboratory for many days. Initial results on the neutron tolerance of the link are presented. The link satisfies total dose requirements if Methode transceivers are used, but further tests are needed to fully understand single event effects. In particular, a better understanding of errors induced by a loss

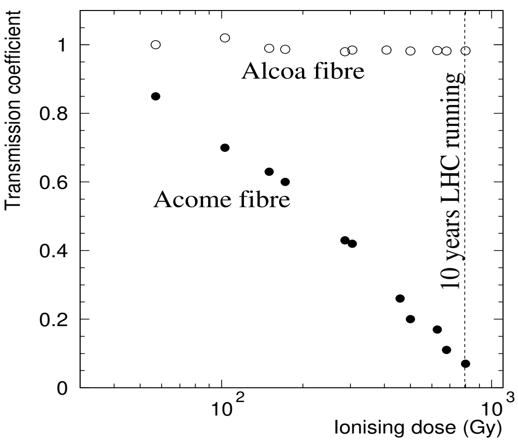

Figure 7: Gamma induced attenuation in 10 m lengths of two varieties of commercial graded-index fibre. The dotted line allows an extrapolation to the expected attenuation after 10 years of LHC running.

of frame lock which can result in a mean link-down time of 300 μs is needed. Results from the neutron and gamma irradiation of packaged VCSEL emitters and multimode fibre are also presented. Both brands of VCSEL are sufficiently radiation tolerant for use in LArg links. The radiation tolerance of the two off-the-shelf graded-index fibres tested differed greatly. One of the fibres would be suitable for use with LArg links. The reason for the marked difference in behaviour between the fibres is under investigation.

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