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The Versatile Link, A Common Project For Super-LHC

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ABSTRACT: A common project to develop a bi-directional, radiation tolerant, high speed (4.8 Gb/s) optical link for future high energy physics experiments is described. Due to be completed in 2012, it targets the upgrade programs of detectors installed at CERN's Large Hadron Collider (LHC). The development of radiation and magnetic field tolerant opto-electronic devices, fibre and connectors is described. Both Single-Mode and Multi-Mode versions of the system operating respectively at 850 nm and 1310 nm wavelength are proposed. First results at component and system level are presented, based mostly on commercially available devices.

KEYWORDS: Optical detector readout concepts, Radiation-hard electronics.

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1. Introduction

Radiation tolerant, high speed optoelectronic data transmission links are fundamental building blocks in today's large scale High Energy Physics (HEP) detectors, as exemplified by the four experiments currently under commissioning at the Large Hadron Collider (LHC), see for example [1,2,3,4]. New experiments or upgrades will impose even more stringent demands on these systems from the point of view of performance and radiation tolerance. This can already be seen from the developments underway for the Super Large Hadron Collider (SLHC) project, a proposed upgrade to the LHC aiming at increasing the luminosity of the machine by factor of 10 to 10^{35} $cm^{-2}s^{-1}$, and thus providing a better chance to see rare processes and improving statistically marginal measurements [5].

In the past, specific data transmission links have been independently developed by each LHC experiment for data acquisition (DAQ), detector control as well as trigger and timing distribution (TTC). This was justified by the different types of applications being targeted as well as by technological limitations preventing one single solution from fitting all requirements. However with today's maturity of optoelectronic and CMOS technologies it is possible to envisage the development of a general purpose optical link which can cover most transmission applications: a Versatile Link. Such an approach has the clear advantage of concentrating the development effort on one single project targeting an optical link whose final functionality will only result from the topology and configuration settings adopted.

The Versatile Link project concentrates on fast bi-directional digital optical data transmission at rates up to ~5 Gb/s with an emphasis on low power dissipation and low mass components. It targets operation in point-to-point or point-to-multipoint bidirectional [1] topologies and will most likely be made available in Multi-Mode (MM) and Single-Mode (SM) versions operating at 850 nm or 1310 nm wavelength respectively. This wavelength diversity is a possible answer to the desire of some experiments to retain compatibility with the fibre buried inside their detectors. The versatile link will have serial data interfaces and will be protocol-agnostic (within the limits set by the DC balance requirement on the data stream). The radiation resistance of its front-end will be qualified up to typical SLHC-tracker levels, i.e. $15 \cdot 10^{14}$ 1 MeV neutron equivalents/cm^2 (Si) corresponding to a dose of 500 kGy (Si) (with ~1.5 safety factor) [6].

Examples of Versatile Link applications could be a DAQ link implemented in a point-to-point (P2P) configuration while a TTC link could be built around a point-to-multipoint topology (PON), as shown in Figure 1 below.

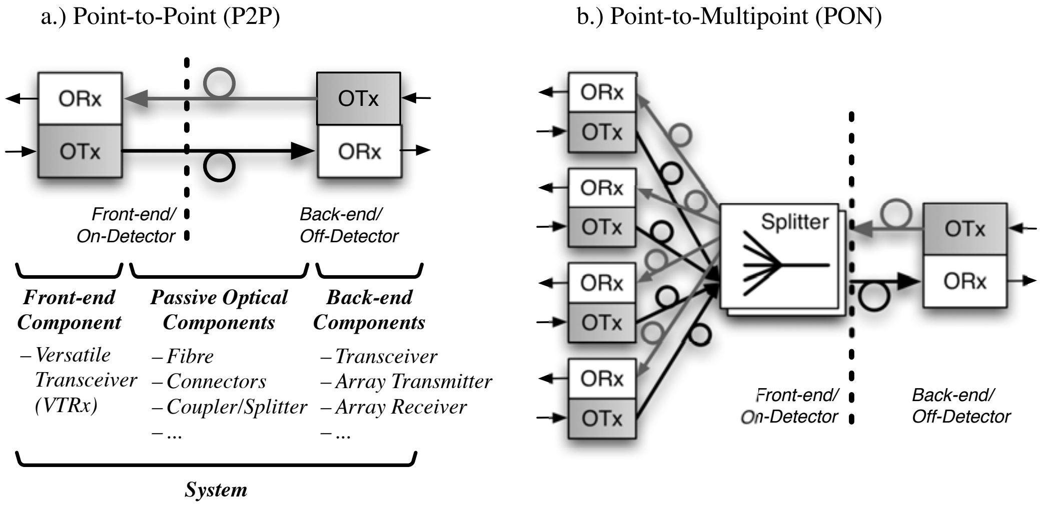

Figure 1. Different link topologies achieved with Versatile Link components. a) simple point-to-point architecture. b) point-to-multipoint tree, also referred to as Passive Optical Network. OTx and ORx are optical transmitters and receivers, usually combined in one transceiver module.

The proposed Versatile Link project is a complex one due to the many variants and options on offer. It poses several technological challenges and requires a development effort in optoelectronics, ASIC design and system integration. It will focus mainly on the development of the physical optical layer of the system but will also investigate different link architectures and topologies. It will develop and qualify active electro-optic components such as packaged laser transmitters and *p*-*i*-*n*-diode receivers, as well as validate passive components such as fibre, connectors and splitters. The ASIC design work associated with the transmit and receive functionality of the Versatile Link (laser driver and transimpedance amplifier) will be carried out in the framework of the Giga-Bit-Transceiver (GBT) project [7, 8].

[1] Bidirectionality is understood here in its most simple sense, as transfer of data in two directions over two fibres.

The project schedule is split into 3 phases, each lasting 18 months: proof of concept, feasibility demonstration and pre-production readiness. Project completion is due for the end of 2012.

As shown in Figure 1.a, the Versatile Link project is best described by breaking it down into system and components. In this paper we will first review components in section 2 and then describe system aspects in section 3.

2. Components

The Versatile Link components can be grouped into three categories: the front-end Versatile Transceiver (VTRx) located inside the detector volume, the back-end components in the off-detector counting room, and the passive optical fibre and connectors linking the two. Each component category is described in detail in subsections 2.1 to 2.3 below.

The VTRx – labelled ORx/OTx in Figure 1 – is the only component to be custom-developed for the Versatile Link project. It is used as the unique front-end module in all topologies: P2P as well as PON and combinations of the two.

The back-end components are situated outside the harsh detector environment. They are standard components selected to be compatible with the VTRx in the various architectures under study.

The optical fibres and connectors link front-end to back-end. They are commercial off-the-shelf passive components which need to be evaluated and compared. Besides functionality, environmental resistance and reliability, radiation resistance will also be investigated for the various technologies under study.

2.1 The Versatile Transceiver

The VTRx will be a bi-directional optical-to-electrical plus electrical-to-optical conversion module with an optical connector interface. It will be based upon a commercially standard transceiver, allowing us to work with an industrial partner with experience in the design and production of such modules. A necessary minimum of customization to allow the VTRx to be operated within the environment of a vertex and/or tracking detector at SLHC, will be carried out. In particular this means that the material of the VTRx will be minimized, avoiding the use of metals where possible, in order to yield a low-mass, low-volume module. Materials will be non magnetic and the internal components must be capable of operating in a magnetic field of 4 T, which for example precludes the use of ferrite beads in the laser bias network found in standard transceivers. The SLHC environment poses two additional challenges for the design and operation of the VTRx: radiation at the level of 1.5×10^{15} 1 MeV neutron equivalents (Si) / cm^2 and 500 kGy (Si) total dose; and low-temperatures that are likely to be in the range -10 to -40 °C. Finally, the VTRx will exist in two flavours: one version operating with MM fibre systems at 850 nm; the other operating with SM fibre systems at 1310 nm.

Work on prototyping the VTRx is being carried out on three major fronts that are described further below:

1. The packaging of the VTRx itself in order to enable it to be used in the HEP detector environment.
2. Functionality testing that ensures the performance targets are met.
3. Radiation testing, of both the components that make up the VTRx and the object as a whole, to guarantee device functionality within the radiation environment of SLHC.

2.1.1 Proof of Concept

Small form-factor bi-directional transceivers are available commercially in three families that cover data rates between 1 and 10 Gb/s: SFP, SFP+ and XFP as shown in Figure 2, where we also show the GBT chipset's target data rate of 4.8 Gb/s. We have evaluated samples of standard components of these families at both 850 nm and 1310 nm and concluded that the SFP+ module type is the best suited for customization in order to turn it into a VTRx [9].

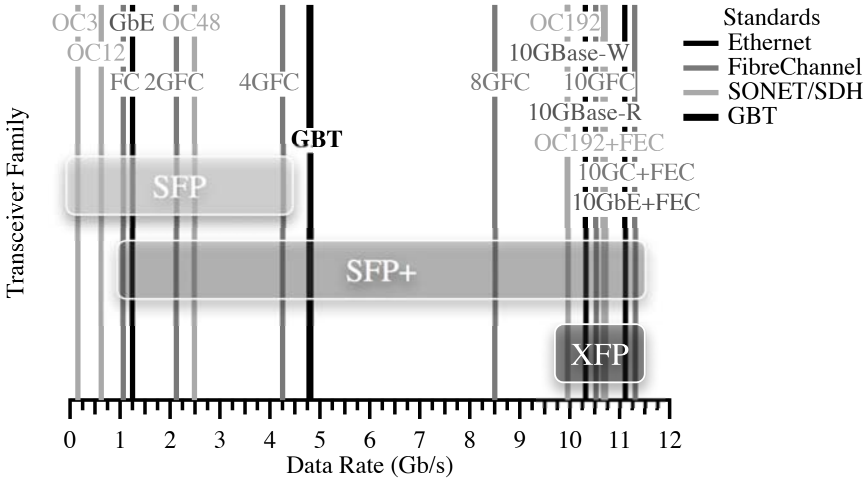

Figure 2. Data-rate standards and their coverage by three candidate transceiver module families (SFP, SFP+ & XFP). The SFP+ that covers the widest range (including the GBT target of 4.8 Gb/s) appears to be the best candidate for VTRx customization.

The steps needed to customize and qualify a modified VTRx for use in the HEP environment are under discussion. They will include the modification of the physical envelope and materials used to construct the transceiver as well as the specification of the internal components of the VTRx. A standard commercial transceiver of SFP+ type contains: a laser diode mounted in a Transmitter Optical Sub-Assembly (TOSA); a laser diode driver (LDD); a *p-i-n* photodiode mounted together with a Trans-Impedance Amplifier (TIA) in a Receiver Optical Sub-Assembly (ROSA); a Limiting Amplifier (LA); and a microcontroller for overall module control and diagnostics, as shown in Figure 3a. The VTRx (Figure 3b) will contain: a TOSA with a laser diode qualified for use in the HEP environment; a custom laser driver designed for this application in the framework of the GBT Project; and a ROSA containing a *p-i-n* photodiode qualified for use in the HEP environment and a custom TIA/LA circuit designed for this application, also in the framework of the GBT Project [7,8].

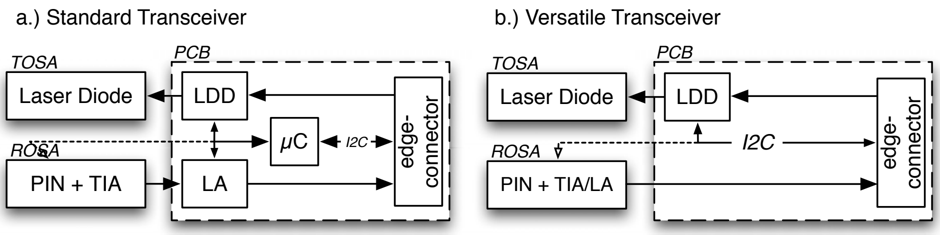

Figure 3. Block Diagram of standard and versatile transceivers showing internal components (LDD – Laser Diode Driver; LA – Limiting Amplifier; μC – Microcontroller; PIN – Photodiode; TIA – Transimpedance Amplifier; I2C – 2-wire bus protocol [10])

2.1.2 Functional Evaluation

The functional evaluation effort has concentrated on developing a set of test setups and methods for the characterization and future qualification of transceiver modules [9]. These test methods, that are shared across the evaluation procedures of all parts of the project, have been exercised by evaluating the range of optical transceiver modules depicted in Figure 2 and the results have led to the conclusion given above that the SFP+ family is the most promising for VTRx customization. Performance has been broken down into three areas: power consumption; evaluation of the transmitter; and evaluation of the receiver. These characteristics are measured across data rates from 1 to 10 Gb/s in order to establish the operating margins, even if the current target bit rate is that of the GBT Project (4.8 Gb/s). An example of the transmitter eye diagram obtained from a prototype SFP+ module supplied by a commercial manufacturer is shown in Figure 4. This example highlights a development for the 1310 nm variant of the VTRx based upon SM VCSELs emitting at 1310 nm. VCSEL-based transmitters would allow a reduction in power consumption as they require lower operating currents than edge-emitting laser diodes.

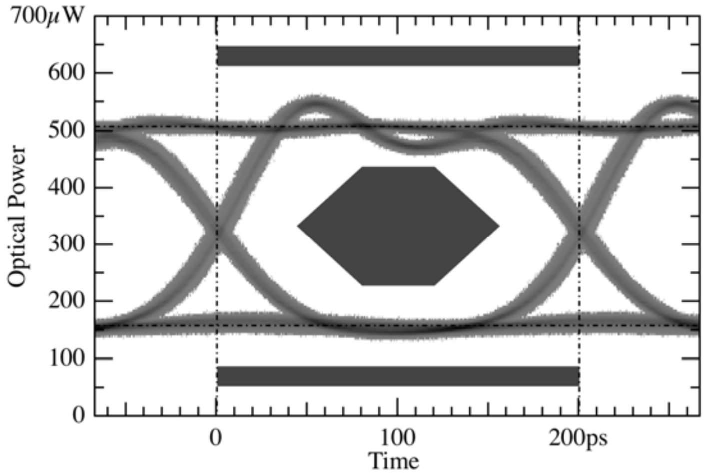

Figure 4. Transmitter Optical Eye Diagram taken at 5 Gb/s from a prototype SFP+ based upon a 1310 nm SM VCSEL.

Another aspect for the customization of the VTRx relates to the need to operate in a magnetic field. Commercial transceiver modules use laser bias-T configurations that are based upon ferrite beads, which cannot operate in even low magnetic fields due to saturation of the ferrite material. We have demonstrated that several ceramic-core wire-wound chip inductors with properly chosen values can produce a reasonable bias-T configuration for use in the VTRx as shown by the transmitter eye diagram in Figure 5.

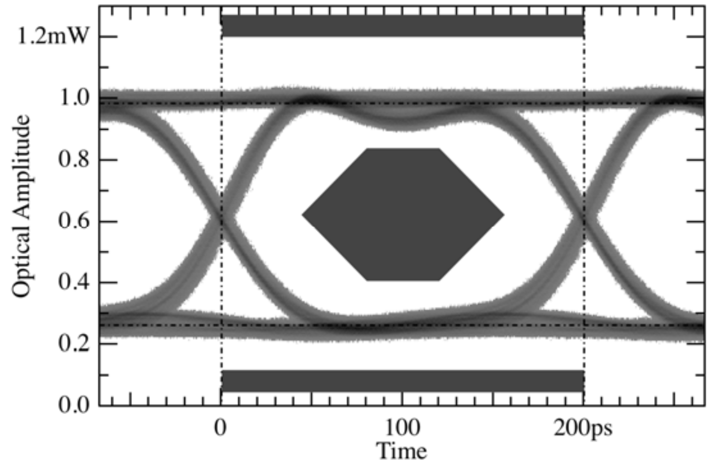

Figure 5. Transmitter Optical Eye Diagram taken at 5 Gb/s from a laser driver test board fitted with a magnetic field tolerant bias-T and 850 nm MM VCSEL.

The testing of commercially available modules using the test methods that have been developed is leading to the drafting of specifications for the VTRx based upon the results obtained and our past experience. These specifications will become available in the course of 2009.

2.1.3 Radiation Testing

A single-event upset (SEU) study has been carried out with 60 MeV protons at PSI, Villigen, Switzerland [11] to determine the extent of the need for forward error correction in the optical links transmitting data from the counting room to the detectors. Photodiode-based receivers are known [12,13,14] from the literature to be sensitive to SEU as the photodiodes themselves can act like particle detectors. Our test aimed to survey a large range of commercially available *p-i-n* photodiodes as well as *p-i-n* photodiodes integrated with a TIA in the same package (ROSA). We tested 23 devices from 12 manufacturers at 1.5, 2.0 and 2.5 Gb/s using a custom FPGA-based Bit Error Rate Tester (BERT) that was able to time-stamp error events in order to carry out more complex error analysis offline. MM devices and SM devices were tested at 850 nm and 1310 nm wavelength respectively.

An overview of the results for the worst-case grazing incidence proton beam is shown in Figure 6. The overall trend for all devices is very similar, even if several orders of magnitude separate the response of different devices. The smallest active diameter device performs best, while the inclusion of the TIA within the package does not affect the SEU rate significantly for devices of the same active diameter. In terms of error statistics, we observed that the combinations of photodiode and TIA (mounted either in the ROSA close to the *p-i-n* diode or slightly further away on the test board) produce error bursts. For the *p-i-n*-only devices these bursts are generally less than 10 successive bits long while they can be hundreds of bits long in the case of the ROSAs. In the former case we believe the effect to be due to the TIA response to a sudden large SEU-induced signal while the average signal level is much lower. In the latter case it appears to be due to upsets of nodes within the TIA itself. These results show on the one hand that Forward Error Correction (FEC) is mandatory for such links to maintain 10^{-12} Bit Error Rate (BER) within an SLHC Tracking environment, and also indicate that careful design of the TIA in the framework of the GBT project might go a long way to mitigating burst errors due to SEU. The reader is directed to [15,16] for a complete presentation and discussion of the results obtained.

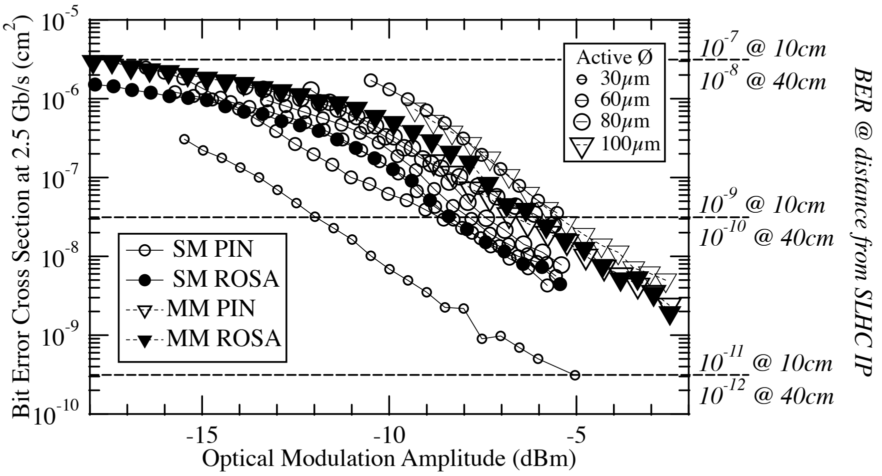

Figure 6. Overview – in the form of measured bit error cross section – of SEU results for one of each of the different device types tested at 2.5 Gb/s. The right-hand side shows the approximate equivalent BER at various distances from an SLHC Interaction Point (IP). Optical Modulation Amplitude is measured in dBm[2].

Total fluence and dose tests are planned for 2009 in order to survey the radiation-hardness of candidate lasers and photodiodes for use in the VTRx. These tests will aim to assess the relative suitability of different device types that are commercially available and could be used in the ROSA and TOSA that will be included in the VTRx.

2.2 The Back-End Components

Off-detector elements will not be subject to the special requirements of radiation and magnetic field tolerance that must be met for front-end components. As a result, the off-detector or back-end components are to be selected from the best candidates identified which are commercially available. The back-end components must be evaluated to ensure that they meet the overall requirements of the system to be configured. In particular, any selected components must be capable of operating successfully with the VTRx discussed above. The activities to support the back-end component selection include a survey of existing components, laboratory testing of selected sets of available components, documentation of a detailed test plan, and the preparation of a production matrix to serve as guidance for a following production phase for SLHC.

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[2] $Power[dBm] = 10 \times \log_{10}\left(\frac{Power[W]}{1mW}\right)$

2.2.1 Candidate Component Types

Components which will be considered candidates for possible use as back-end components in the SLHC will be selected from mature devices which are commercially available from well-established vendors of the relevant technologies. Evaluation of relevant back-end components will include:

1. P2P transceivers
2. Array transmitters and receivers
3. High power optical transmitters
4. PON transceivers

P2P transceivers are used to implement the simplest form of network, the point-to-point network in which simplex links are terminated by a transmitter at one end and a receiver at the other end (see Figure 1.a). Transceivers include both of these components in a single package. Devices are available which operate utilizing MM transmission at 850 nm over distances on the order of a few hundred metres. For longer transmission distances or higher data rates, devices which operate utilizing SM transmission at 1310 nm are also commercially available. Representative samples of both families of devices will be studied, the goal being to test transceivers capable of 10 Gb/s operation in SFP+ packages. Figure 7 illustrates a representative example of such a device including a commercially available transceiver evaluation board used in testing.

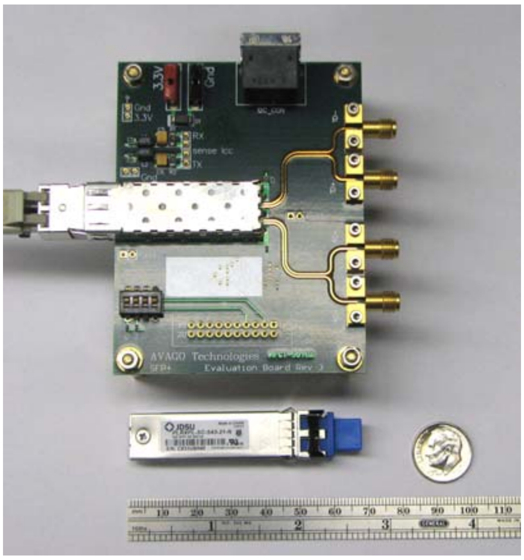

Figure 7. SFP+ package optical transceiver along with evaluation platform printed circuit board (PCB)

Array transmitters and receivers (also known as parallel optics) offer a higher degree of integration than is available using P2P components. The use of these components can increase the channel density of the readout electronics with a commensurate concentration of data. They may also reduce costs by reducing the number of individually packaged components. Devices are currently available operating at 6.25 Gb/s in each of 12 channels for distances up to 100 metres or 5 Gb/s in each of 12 channels over distances up to 150 metres. Both SM and MM devices will be evaluated.

PON transceivers are needed to implement point-to-multipoint network topologies such as illustrated in Figure 1.b. This approach reduces the number of required transceivers and optical fibres in parts of the network by the use of passive optical splitters and combiners.

The performance characteristics which are measured may be useful in defining the specific topology which will work best for the SLHC data networks.

2.2.2 Back-End Component Testing

While the BER is the most common performance measure associated with optical links, other optical and electrical measurements are needed to assess signal quality and may be useful for understanding BER measurements or even to initiate corrective or preventative maintenance actions [17]. Therefore, each of the candidate versions of back-end components will be tested with a suite of standard tests. The approach to testing the components would be based on well established practices drawn from industry (see section 2.1.2). The performance of these tests will make use of standard test components being developed for the project (see section 2.3). For a list of tests to be performed, refer to Table 1.

Table 1. Back-end component tests

Transmitter Tests	**Receiver Tests**
Optical modulation amplitude (OMA)	Receiver sensitivity
Extinction ratio	Electrical output levels
Optical eye closure	Electrical eye closure
Average transmitted power	N/A
Rise and fall times	Rise and fall times
Jitter characterization	Jitter characterization
Transmit mask compliance and mask margin	Receive mask compliance and mask margin
Transmitter latency	Receiver latency

Figure 8 illustrates data gathered for one of the tests (OMA). The data illustrates the location of peaks in two histograms (one for logic ‘1’ at higher transmitted power and one for logic ‘0’ at lower transmitted power) in the transmission of a pseudo-random bit stream at 5 Gb/s. The separation in the peaks is used to measure the OMA. Compatibility tests of these back-end components must also be performed to verify that they operate with the custom front-end components (the VTRx devices) being developed.

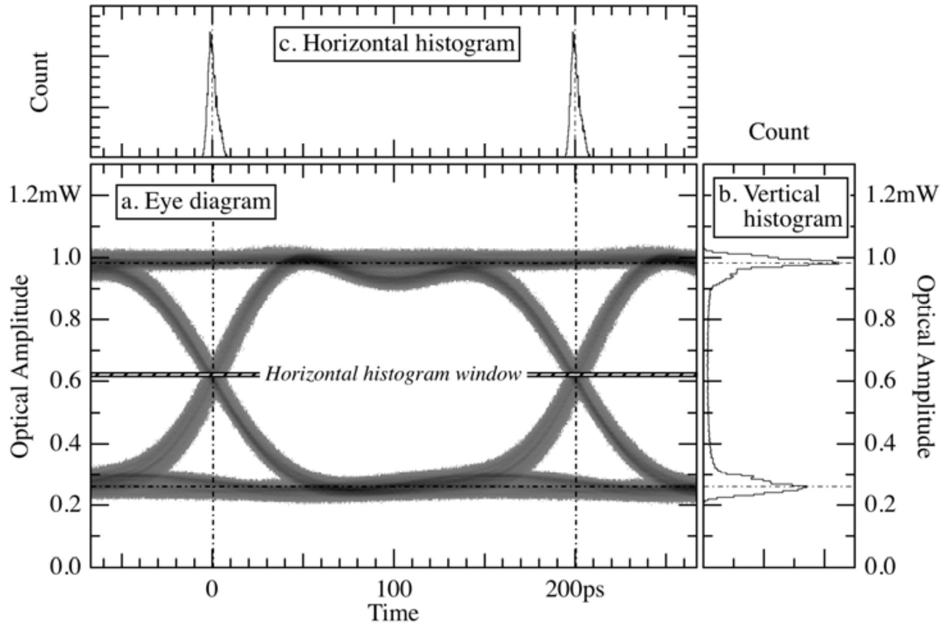

Figure 8. Histograms extracted from the transmitter eye diagram for the purposes of measuring the performance (see section 2.1.2).

Component reliability is an important property that must be considered. There may be restricted opportunities to service faulty or failed components so the transmitters and receivers need to be suitably robust for extended operation in the SLHC. In addition to the reliability of the individual components, the reliability of the packaged and mounted component assemblies must be verified. This is also important if there are not sufficient numbers of spare components and assemblies available for replacement over the expected lifetime of the project. While mature commercially available products should have reliability data available from vendors, there may be a need to perform further reliability testing of components. For example, to verify the operation of components and assemblies in specific rack mounted environments, such testing may be performed. In these cases, the tests will be based on experience gained from the industry for the specific components but may be performed in specific test setups to mimic the expected operation as closely as possible. Industry standard or commonly accepted reliability test methods will be researched, and, if necessary, included in the set of standard test procedures such as documented in [18]. Consultations with vendors and industry representatives on quality control procedures will help to ensure that the components are correctly stored, handled, and operated.

Based on the information gathered from testing, component documentation, and vendor due diligence, a production matrix can be compiled for use in a production phase of the SLHC. This matrix would serve as guidance for final component selection by providing a view of such details as component costs and availability, test results, and other information relevant to the procurement and use of the candidates.

2.3 Passive Optical Components

The passive optical components which will be required for the Versatile Link are fibres, connectors and fibre couplers that may be needed to implement the various topologies under investigation. The fibres will also require protective jacketing around individual fibres (for inside the active volume of the detector) and multi-fibre cables for the longer run from the detector to the counting rooms.

Since systems based on MM transmission at 850 nm and SM at 1310 nm are being developed, suitable variants of the passive components need to be identified for both wavelengths. For the fibres, this implies that Graded Index (GRIN) fibres for use at 850 nm and SM fibres for use at 1310 nm will be considered. The main tests that will be performed will be to verify the radiation tolerance for the expected SLHC doses (up to 500 kGy(Si) [6]). Other studies will look at mechanical properties of fibres, in order to understand reliability issues, particularly after irradiation. The components will be evaluated under realistic environmental conditions. The optical bandwidth of irradiated fibres will also be evaluated.

The programme for the evaluation of radiation tolerance of the passive optical components has started and the status and plans will be described in the following three sub-sections. To minimise risks during production, two sources for each component type will be identified.

2.3.1 Fibres

The bandwidth for the fibres should be sufficient for data transfer at a rate of 5-10 Gb/s over lengths of up to 150 m. A commercial SM fibre[3] has already been tested with a gamma source to the expected doses and has shown very encouraging performance [19]. Another possibility for SM fibre is to use the same fibre currently used for the LHC machine, which has already been demonstrated to have excellent radiation tolerance [20]. One commercial[4] and one prototype GRIN fibre[5] have also been tested to SLHC doses with good results [19]. This prototype fibre is expected to become commercially available during 2009. As the fibres show important annealing with time and light (photo-bleaching) the tests were all active in which the performance of the fibres was monitored during the irradiation and realistic light levels have been used. Extensive studies of the dose rate effects for the GRIN fibre[4] were performed showing that the damage for a given total dose increased with dose rate as anticipated. The expected radiation induced attenuation for the commercial GRIN fibre[4] has been very conservatively evaluated for a specific route to the ATLAS counting room for a realistic SLHC scenario and found to be acceptable for warm operation with an estimated total radiation induced absorption of 0.41±0.05 dB [19]. This fibre has the required bandwidth and will therefore be used as a reference for future tests. In addition the bandwidth of the irradiated fibres will be evaluated. Attempts to find other sources of radiation tolerant GRIN fibre are being pursued.

Significant annealing has been observed with all tested fibres and this is expected to be slower at lower temperatures. Thus far all the existing tests have been performed at room temperature or higher and further studies are needed before these fibres can be qualified for low temperature operation (-40 to -10 C) as would be required if they were to be operated inside SLHC silicon trackers.

Mechanical performance tests of unirradiated fibres have started and will be repeated on irradiated samples. The aim is to determine if the mechanical reliability is degraded by

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[3] Corning SMF-28
[4] Corning Infinicor SX+
[5] Draka-RHP-1.

irradiation. These tests involve tensile strength measurements using a pull test machine. This is a destructive test, as the breaking point is used to determine the strength of the fibre at a given strain rate. Some example data for the applied force as function of fibre extension of the SMF-28 fibre are shown in Figure 9. The uniform transfer of force from the tensile machine to the fibre is essential for obtaining good measurements. A good quality of the force transfer can be assessed by inspecting the plot of measured force versus extension of the fibre. The force should increase linearly as function of extension and should not show any irregular shapes. Different pull speeds can be used to perform a reliability analysis [21].

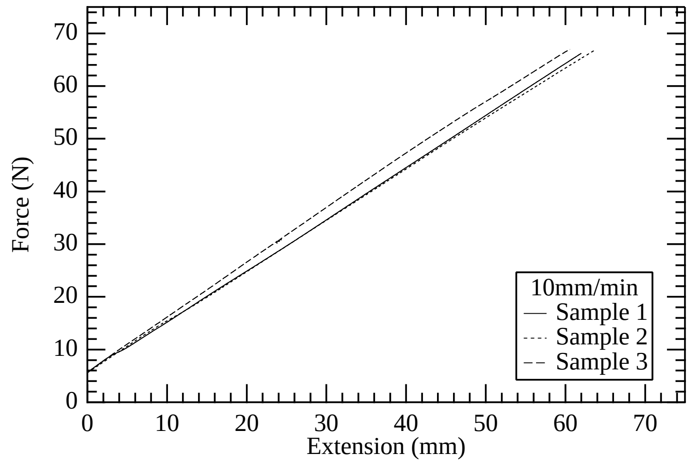

Figure 9. Pull force versus extension (transfer function) for 3 samples of 50 cm lengths of unirradiated SMF-28 fibre at a pull speed of 10 mm/ minute. The ends of the curves indicate the breaking points. The fibre was preloaded with 500 MPa before the dynamic test started.

2.3.2 Fibre Couplers and Connectors.

The first radiation tests with fused taper couplers have given very good results for both GRIN and SM fibres as the damage is consistent with that expected from the lengths of fibre used in the devices. However the first radiation tests with a SM Planar Lightwave Curicuit (PLC) coupler showed significant sensitivity to radiation and further investigations on this type of coupler are necessary. Other versions of PLC couplers will be surveyed to determine if more radiation tolerant devices are available.

The LC connector[6] has been identified as the most suitable small form factor connector for single fibres for both SM and MM systems. The first radiation tests have given very encouraging results, although more work is still needed to understand all the systematics in the measurements. The fibre plant may involve the use of multi-way fibre ribbons, therefore the radiation tolerance of multi-way connectors like the MT-12[7] will be evaluated.

2.3.3 Fibre Cabling

The Versatile Link will use individual fibres, therefore protective jacketing will be required. The longer runs of fibres from the detector to the counting rooms will require the use of multi-

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[6] LC : Lucent Connector
[7] MT: Mechanically Transferrable

fibre cables or equivalent protection systems. The radiation tolerance of these cables and jacketing will need to be evaluated. Since the concern will be about changes in mechanical strength, it will be necessary to test with both ionising and non-ionising sources. A comparison of mechanical strengths will be performed before and after irradiation.

3. System

In this section we discuss system level tests for the Versatile Link. While component level evaluations focus on characterizing the optical transceivers, the fibre, the connectors and the splitters, system level measurements emphasise parameters that are relevant to data transmission over the link. As depicted in Figure 1, the basic configuration of the Versatile Link is point-to-point. Based on this a point-to-multipoint topology may also be configured. In this section we only discuss the P2P system evaluation, and leave the PON to later investigations when we have a better understanding of the P2P configuration. The parameters to be measured are adopted mostly from industrial standards, with considerations for application specific needs in HEP, such as the time critical TTC signal and data transmissions to and from the detector front-end. Special evaluation criteria and test procedures need to be established and are one of the system-level tasks in the Versatile Link project.

In a P2P serial digital optical link system, signal integrity is checked at several test points (marked as TP1 to TP4 in Figure 10). The electrical signals at TP1 and TP4 interface the Versatile Link to up/down stream electronics. They follow the Current Mode Logic (CML) digital signal standard usually used for back-end components, and the specific levels adopted in the GBT ASIC development for front-end components. The BER is measured by comparing information from TP4 with that at TP1. Overall link induced latency and jitter can also be measured. These are especially important for time critical information transmitted over the link (like TTC signals for instance). By introducing a variable optical attenuator (VOA) in the fibre channel, the overall optical power budget for the system can be measured or verified.

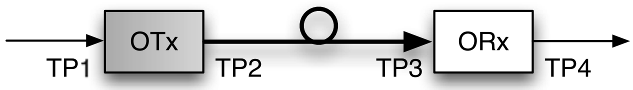

Figure 10. A typical P2P serial digital link system. Signals are checked at test points TP1 to TP4. TP1 and TP2 are at the input and the output of the optical transmitter OTx. TP3 and TP4 are at the input and the output of the optical receiver ORx.

In addition to the component level tests described in the previous section, we will evaluate the Versatile Link performance at room temperature and at system operating temperatures, for example at -40 to -10C in the inner tracker case. The fibre length used in the tests will be a multiple of 50 m with connectors to simulate patch panels in the actual fibre plant. The data transmission rate will be either set at 4.8 Gb/s (the GBT nominal speed) or a measurement parameter. The tests will be conducted at 850 nm over MM fibre or at 1310 nm over SM fibre, using the components identified to be used in the Versatile Link. One of the tests, the BER measurement, will be carried out by either an FPGA-based BERT or by a commercial BERT (with a bit error testing range from 0.5 to 12.5 Gb/s) with a bit stream that is either pseudo random or simulates the coding scheme of the GBT ASIC. In this way we will take advantage of the commercial BERT to go up to the full speed range specified for the SPF+ standard and will also develop and verify an FPGA-based BERT, a portable platform that will be conveniently used in several setups for user evaluation tests or irradiation tests.

A list of some of the system level measurements we plan to carry out follows:

1. BER as a function of introduced optical attenuation (translated as OMA at TP3) with 150 m total fibre length. The attenuation is introduced with a VOA inserted between two 50 m fibre cords, and the data rate is set at 4.8 Gb/s. Due to practical reasons, the measurement will stop if the BER is lower than 10^{-14}.
2. Jitter analysis as a function of attenuation at TP1 and TP4 at 4.8 Gb/s and with 150 m fibre. The total system introduced jitter is defined as the jitter at TP4 subtracted from that at TP1,
3. Eye diagrams measured at TP3 and TP4 at 4.8 Gb/s and 150 m total fibre length. From this measurement we will extract the signal rise and fall times. We will also perform the standard eye mask test and measure the eye margin by finding the largest eye mask before the eye mask test fails.
4. Maximum data rate (defined as the BER at 10^{-12}) with a 150 m total fibre length. Eye diagrams at TP3 and TP4 will be measured at this maximum data rate.
5. Maximum fibre length (defined as the BER at 10^{-12}), checked at 4.8 Gb/s with an increment of 200 m fibre cord up to 1000 m in total length. Eye diagrams at TP3 and TP4 will be measured at the maximum fibre length or with a 1000 m fibre.
6. System latency (the signal propagation time from TP1 to TP4) at 4.8 Gb/s and with 150 m fibre.

In addition to the above in-lab tests, tests with the VTRx and 20 m fibre under irradiation will be carried out to study the system level performance with the front-end components together with fibre and connectors inside a radiation environment. In these tests the system will operate at 4.8 Gb/s with a 150 m fibre at room temperature. The BER will be measured as a function of received radiation such as Total Ionizing Dose (TID), neutron fluence for Non Ionizing Energy Loss (NIEL) and particle flux for Single Event Upset (SEU). This set of tests is one of the main reasons for developing the FPGA based BERT mentioned above. Part of validating this FPGA-based BERT is reported below.

To conduct the above mentioned system level tests as well as for some component level tests mentioned in the previous sections, we developed the SFP+ carrier board shown in Figure 11. Tests of this carrier board with a commercial SFP+ optical transceiver module operating at 850 nm and 10 Gb/s have been performed. Preliminary results shown in Figure 12 confirm that the eyes at TP4 are wide open up to 10 Gb/s.

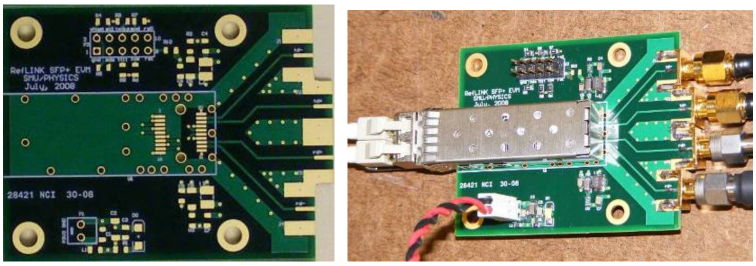

Figure 11. The SFP+ carrier board. Shown on the left is the PCB, on the right is the loaded board.

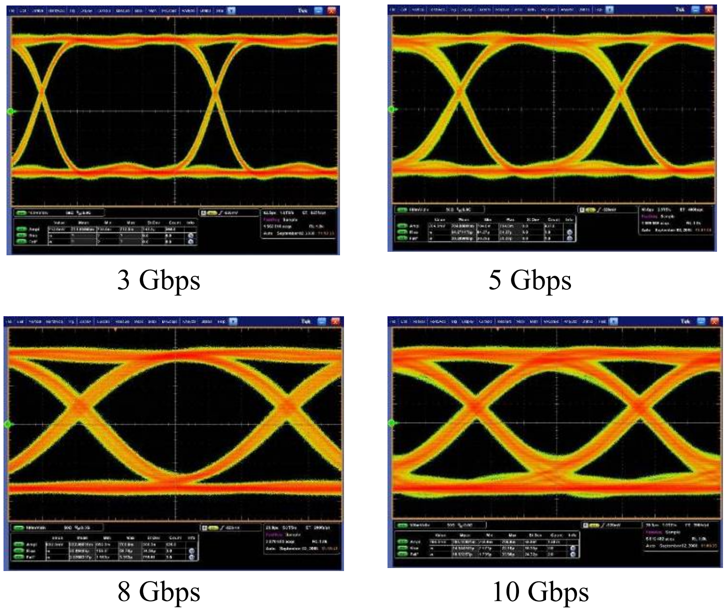

Figure 12. Eye diagrams at TP4 at 3, 5, 8 and 10 Gb/s with a commercial SFP+ module (850 nm VCSEL) and a short looped back fibre.

The BER of the SFP+ module assembled on its carrier board (with a short fibre looping back from the transmitter to the receiver) has been measured to be better than 3×10^{-14} at 10 Gb/s. During a BER measurement, by changing the phase between the clock and the data in the error detector unit of the BERT, a "bathtub" scan can be performed. Such a bathtub at 5 Gb/s data rate is shown in Figure 13. The bathtub scan provides more precise information on horizontal eye opening. than an eye diagram.

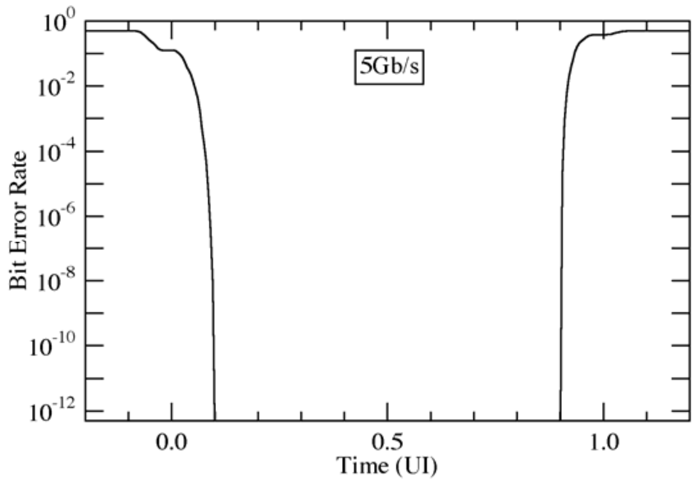

Figure 13. Bit error rate bathtub curve measured at 5 Gb/s.

Using the 12.5 Gb/s commercial BERT and the FPGA-based BERT (development based on an FPGA evaluation board), we performed a comparison between the FPGA-based BERT and the commercial BERT, and between our SFP+ carrier board and the SFP+ evaluation board from from a commercial source. The results of these comparative measurements are shown in Figure 14. From these we see that the FPGA-based BERT and our SFP+ carrier board function the same as their commercial counter parts. For practical reasons only the FPGA-based BERT will be used in irradiation tests.

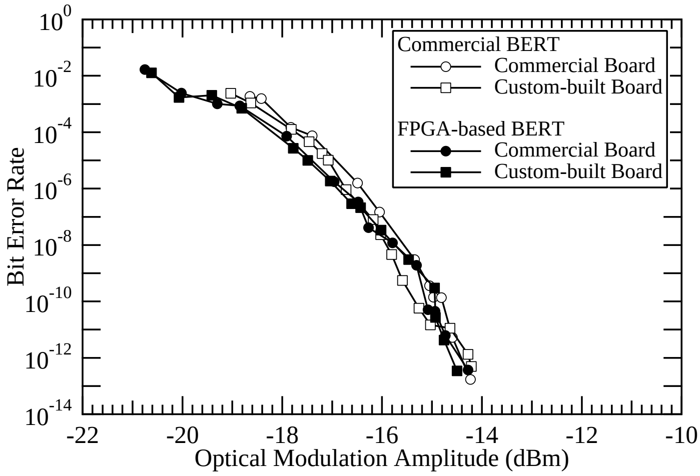

Figure 14. The BER as a function of OMA at the receiver ORx's input with various setups.

The setup being developed for the system level tests will also be used to bench mark the commercial SFP+ transceivers discussed in section 2.2 and to confirm their compatibility with the VTRx discussed in section 2.1.

4. Summary

A common project to develop a bi-directional, radiation tolerant, high speed (4.8 Gb/s) optical link for future high energy physics experiments has been described. Due to be completed in 2012, it is part of the upgrade programs for detectors installed at CERN's Large Hadron Collider (LHC).

A radiation and magnetic field tolerant versatile transceiver has been described, based on the SFP+ module standard. First functional evaluation and single event upset test results of commercial modules have been presented. Optical fibre, splitters and connectors are also under investigation. Some functional and environmental resistance properties have already been evaluated and have been discussed. Setups and methods for testing backend components and system have been reviewed, demonstrating that the necessary tools and techniques are now available to carry out this development.

After completion of the project proof-of-concept phase in late 2009, feasibility will be demonstrated by assembling into a chain all components foreseen to be used in the system and confirming their inter-operability.

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References

[1] N. J. Buchanan et al., *Design and implementation of the Front End Board for the readout of the ATLAS liquid argon calorimeters*, 2008 JINST **3** P03004.

[2] J. Troska, G.Cervelli, F. Faccio, K. Gill, R. Grabit, A.M. Sandvik, F.Vasey and A. Zanet, *Optical Readout and Control Systems for the CMS Tracker*, IEEE Transactions on Nuclear Science, Vol 50 No4, pp1067-72, 2003.

[3] A. Abdesselam et al., *The optical links of the ATLAS SemiConductor Tracker*, 2007 JINST 2 P09003.

[4] K.E. Arms, K.K. Gan, P. Jackson et al., ATLAS pixel opto-electronics, Nucl. Instrum. Methods Phys. Res A, Vol 554, Issue 1-3, pp458-468, 2005.

[5] N. Hessey, *Overview and Electronics Needs of ATLAS and CMS High Luminosity Upgrades*, Proceedings of the Topical Workshop on Electronics For Particle Physics TWEPP-08, CERN-2008-0028, pp.323-7, 2008.

[6] Joint ATLAS-CMS working group on optoelectronics for SLHC. Report from sub-group B, https://edms.cern.ch/document/882783/2.6.

[7] P. Moreira, A. Marchioro, K. Kloukinas, *The GBT, a proposed architecture for multi-Gb/s data transmission in high energy physics*, proceedings of the Topical Workshop on Electronics for Particle Physics TWEPP-07, CERN-2007-07, pp332-6, 2007.

[8] The GBT project home-page: https://espace.cern.ch/GBT-Project/default.aspx

[9] L. Amaral, Jan Troska, Alberto Jimenez Pacheco, Stefanos Dris, Daniel Ricci, Christophe Sigaud and Francois Vasey, *Evaluation of Multi-Gbps Optical Transceivers for Use in Future HEP Experiments*, Proceedings of the Topical Workshop on Electronics For Particle Physics TWEPP-2008, CERN-2008-0028, pp.151-155, 2008.

[10] Inter-IC (I2C) Bus Specification, available at: http://www.semiconductors.philips.com/acrobat_download/literature/9398/39340011.pdf

[11] W. Hajdas, A. Zehnder, L. Adams, and B. Nickson, *The proton irradiation facility at the Paul Scherrer institute*, Nucl. Instrum. Methods Phys. Res. B, vol. 113, p. 54, 1996.

[12] P. W. Marshall, P. T. Wiley, R. N. Prusia, G. D. Rash, H. Kim, and K. A. LaBel, *Proton-induced BitError Studies in a 10Gb/s Fiber Optic Link*, IEEE Trans. Nucl. Sci., Vol. 51, No. 5, pp. 2736–39, 2004.

[13] P. W. Marshall, C. J. Dale, and K. A. LaBel, *Space Radiation Effects in High Performance Fiber Optic Data Links for Satellite Data Management,* IEEE Trans. Nucl. Sci., Vol. 43, No. 2, pp. 645–53, 1996.

[14] F. Faccio, G. Berger, K. Gill, M. Huhtinen, A. Marchioro, P. Moreira, and F. Vasey *Single-Event Upset Tests of an 80-Mb/s Optical Re-ceiver,* IEEE Trans. Nucl. Sci., Vol. 48, No. 5, pp.1700-1707, 2001.

[15] Jan Troska, Alberto Jimenez Pacheco, Luis Amaral, Stefanos Dris, Daniel Ricci, Christophe Sigaud, Francois Vasey and Paschalis Vichoudis, *Single-Event Upsets in Photodiodes for Multi-Gb/s Data Transmission*, Proceedings of the Topical Workshop on Electronics For Particle Physics TWEPP-2008, CERN-2008-0028, pp.161-166, 2008.

[16] Alberto Jimenez Pacheco, Jan Troska, Luis Amaral, Stefanos Dris, Daniel Ricci, Christophe Sigaud, Francois Vasey and Paschalis Vichoudis, *Single-Event Upsets in Photorecievers for Multi-Gb/s Data Transmission*, Accepted for Publication in IEEE Trans. Nucl. Sci.

[17] R. Ramaswami, K. N. Sivarajan, *Optical Networks: A Practical Perspective*, Morgan Kaufman p. 509, 2002.

[18] C. Yang, T. Liu, C. Xiang, J. Ye, *Lifetime Test for Optical Transmitters in the ATLAS Liquid Argon Calorimeter Readout System*, available at http://cdsweb.cern.ch/record/955111.

[19] B. Arvidsson et al, *The Radiation Tolerance of Specific Optical Fibres Exposed to 650 kGy(Si) of Ionizing Radiation*, accepted for publication in JINST.

[20] T. Wijnands et al, *Optical Absorption in Commercial Single Mode Optical Fibers in a High Energy Physics Radiation Field*, Nuclear Science, IEEE Transactions on Publication Date: Aug. 2008, Volume: 55, Issue: 4, Part 1, pages 2216-2222.

[21] Willem Griffioen, *Optical Fiber Mechanical Reliability*, Eindhoven University of Technology, ISBN 90-386-0494-7, PhD Thesis, 1995