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Joint ATLAS-CMS working group on optoelectronics for SLHC

Report from sub-group B
Optical Readout System Irradiation Guidelines

K.K. Gan
Department of Physics, The Ohio State University, Columbus, OH, USA
Karl Gill, Jan Troska, Francois Vasey
CERN, Geneva, Switzerland
Todd Huffman, Cigdem Issever, Tony Weidberg
Department of Physics, Oxford University, U.K.
Jingbo Ye
Department of Physics, Southern Methodist University
Pat Skubic, Rusty Boyd
Department of Physics and Astronomy, University of Oklahoma
Flera Rizatdinova
High Energy Physics Group, Oklahoma State University

Abstract

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1 Introduction

This document summarizes the agreement on irradiation guidelines between the ATLAS and CMS experiments for the optoelectronic readout system for detectors at the upgraded Large Hadron Collider (SLHC). Protocols about quality assurances will be published in a future document of the Joint ATLAS-CMS working group on optoelectronics for the SLHC. The components this document covers are summarized in Table I.

Table I: Components covered in this document.

Components	total dose and annealing	SEE	accelerated ageing	Effects of irradiation on long term reliability
Lasers	X	X	X	X
p-i-n diodes	X	X	X	X
Fibres	X			
Serializer and de-serializer chips	X	X	X	X

2 Radiation Environment at the SLHC

The devices located inside a detector at a SLHC experiment will be exposed to a very harsh radiation environment resulting in displacement damage and ionization damage in all susceptible parts. It is expected that parts located inside the detector will be inaccessible and therefore required to have high reliability.

The radiation environment is dominated by a pion flux centered at energies around 100 MeV, in addition to spallation neutrons having energy ~1 MeV nearer the surrounding calorimeters. Figure 1 shows the predicted Si total fluence as function of radius for CMS for an integrated luminosity of 500 fb^{-1}. For a radius of 30 cm CMS fluence values are $8.47\cdot10^{13}$ cm^{-2}. This number is agreeing within the errors with the ATLAS Si total fluence prediction, which is $10.67\cdot10^{13}$ cm^{-2} for a radius of 30 cm and an integrated luminosity of 500 fb^{-1} (corresponds to a dose of 52.51 kGy). These numbers do not include any safety factors.

Uncertainties in the particle fluences and doses mean that a safety factor was applied in order to evaluate the radiation tolerance of devices for the LHC. ATLAS and CMS assumed a safety factor of 1.5[1]. This value will be eventually refined based on the experience gained during LHC running.

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[1] Uncertainties assumed at the LHC: event generator ~20%; transport codes ~20%; displacement damage cross sections ~50% [Ian Dawnson].

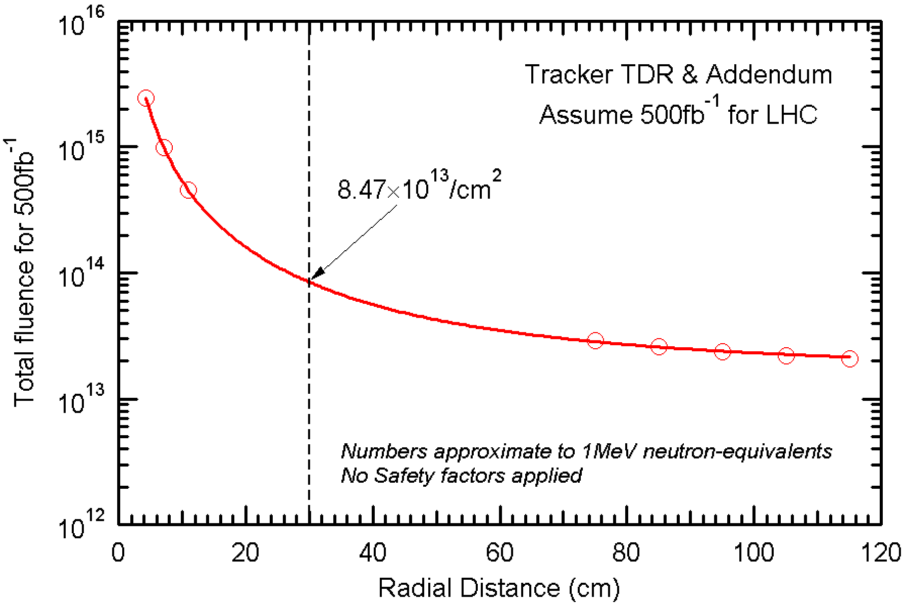

Figure 1: CMS Si total fluence for 500 fb^{-1} in 1 MeV neutron equivalents as function of radial distance. The are no safety factors applied [CMS TDR].

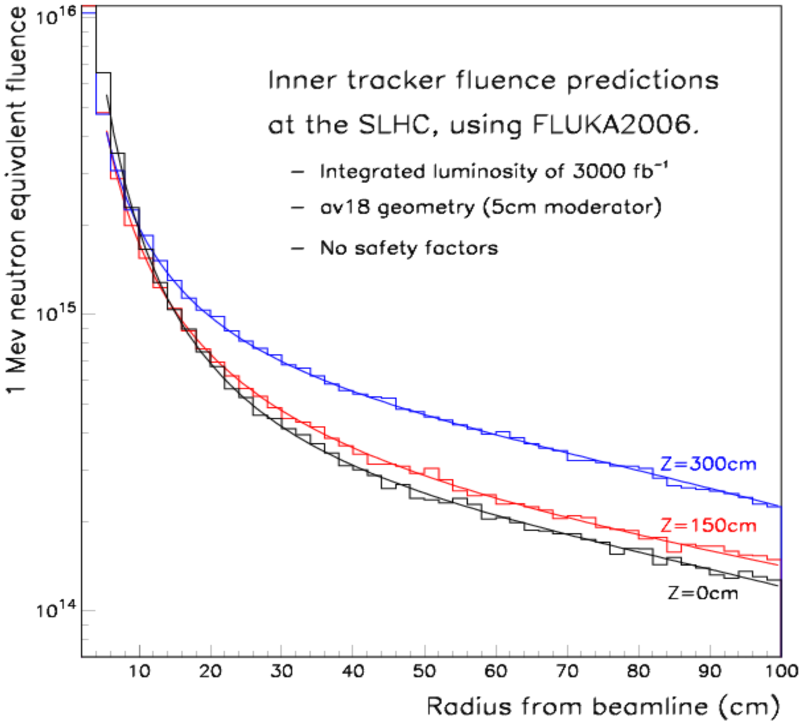

Figure 2: ATLAS Si total fluence for 3000 fb^{-1} in 1 MeV neutron-equivalents as function of radius from the beamline for different z positions for a geometry with 5 cm of neutron moderator lining on all the calorimeters [Ian Dawson]. There are no safety factors applied.

Detectors for the SLHC will be designed for 3000 fb^{-1}. Figure 2 shows the ATLAS predicted total fluence for the SLHC as function of radius and for different z values. The chosen detector geometry for Figure 2 has a 5 cm neutron moderator lining on the calorimeters in order to compensate for neutron moderation by the missing Transition Radiotion Tracker (TRT), which will be replaced by silicon detectors at the SLHC. The fluences at small radii (< 20 cm) are dominated by particles from interaction point and fluences at larger radii (70 – 80 cm) are dominated by neutron-albedo which are greatest near endcaps.

Table II shows total fluences for Si and GaAs for different radii for 3000 fb^{-1} where a safety factor of 1.5 was applied to the last columns of this table. These fluence estimations were derived from the study in [IM Gregor] which was used to estimate the LHC fluences for ATLAS.

	Radius [cm]	Si Fluence no safety factor applied	Si Fluence with safety factor 1.5	GaAs with safety factor 1.5
B-Layer	5.05	80.0E+14	120.0E+14	96.0E+15
1st Layer	8.85	30.0E+14	45.00E+14	31.8E+15
2nd Layer	12.25	16.0E+14	24.00E+14	13.8E+15
PP0	18.00	10.0E+14	15.00E+14	8.40E+15
SCT 1	29.90	6.40E+14	9.600E+14	4.08E+15
SCT 2	37.10	4.80E+14	7.200E+14	2.82E+15
SCT 3	44.30	4.00E+14	6.000E+14	2.16E+15
SCT 4	51.40	3.56E+14	5.340E+14	1.68E+15

Table II: Fluences in 1 MeV neutron equivalents per cm^2 for 3000 fb^{-1} for Si and GaAs based on [IM Gregor]. The first column for Si has no safety factor applied where as the second column for Si and the column for GaAs have safety factors of 1.5 applied to them.

Based on these predictions we recommend that components for the SLHC should be irradiated up to $15\cdot10^{14}$ 1MeV neutron equivalents/cm^{-2} corresponding to a dose 0.5 MGy.

3 Irradiation Programme

3.1 Samples and Sample Sizes

Poisson sampling curves are normally used to establish limits on the failure probability based on tests on a limited number of samples. For example, in a test using 10 devices where there are no failures, the upper limit on the probability of failure is 23% with 90% confidence level. To reduce the upper limit on the failure probability, more devices need to be tested. Table III summarizes the minimum sample size needed to establish an upper limit on the failure probability of less than 10% at the 90% confidence level for various number of failures[2].

Table III: Minimum sample needed to establish an upper limit on the failure probability of less than 10% at the 90% confidence level for various number of failures.

Failures	Sample
0	23
1	39
2	54

During the first exploratory tests on a given component, small numbers of samples, e.g. 5, could be used to avoid wasting money on potentially useless parts. However, solid conclusions cannot be established about the reliability or suitability of the devices that pass these first exploratory tests except that these devices are worthy of further, more detailed investigation.

In all tests, several unirradiated samples from the same lot should be kept as control samples, i.e. not irradiated or aged.

Table IV: Number of tested devices for the radiation tolerance evaluation of the ATLAS inner detector readout components for the LHC.

Devices	Test Type	Number of Tested Devices
VCSELs	First Tests	130
VCSELs	Test on production wafer[3]	20

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[2] These calculations assume that the numbers of failures follow Poisson statistics. However it is known that for some devices such as VCSELs, the distribution of the number of failures follow a Weibull law**[XX]**.

[3] All production devices came from the same wafer.

PIN diodes	First tests + production wafer tests[4]	96
Opto ASICs		
DORIC4A	First Tests	20
DORIC4A	Production wafer tests[5]	64
VDC	First Tests	9
VDC	Production wafer tests[6]	64

Table IV shows the number of tested devices for the ATLAS inner detector for the LHC.

Xx				

Table V: Number of tested devices for the radiation tolerance evaluation of the CMS inner detector readout components for the LHC.

For SEE test there is no special requirement on the test sample size in product identification and evaluation phase, although a sample size greater than 3 is recommended. In product batch testing phase for design and construction, a sample size of 10 from each batch with a control sample (those not put in irradiation) of 1 or 2 modules is required.

3.2 Failure Criteria

Device failures are defined such that a device fails to function according to the system operating specifications, either failing during the test, or having characteristics that are outside the specifications following extrapolation of the ageing data to the full ten-year lifetime of the links.

Any device failure should be analyzed post-mortem, in order to establish the cause of failure. Only failures that are intrinsic to the device-under-test will be counted in the statistics of the test. For example, failure of wire-bonds to the test-board will not be counted.

Irradiation tests are accelerated tests and an extrapolation of the measurements to the real environment will depend on the tests results. Annealing data will be necessary in order to be able to extrapolate results.

3.3 Evaluation of Devices under Test before Irradiation

Before an irradiation test the performance of to be tested devices should be measured. In case of lasers, p-i-n diodes and chips the devices should be run for an extended amount of time in the test setup which will be used to perform the irradiation test. Their performance should be measured during this run in periodic intervals. If possible the performance of the devices should be measured as function of temperature. In case one observes that the performance of the devices is strongly depending on temperature it is mandatory to measure the temperature during irradiation. Only burned in devices should be irradiated.

3.4 Laboratory Simulation of the Radiation Environment

In order to validate components for radiation hardness within a reasonable time we must carry out accelerated tests. If no dose rate dependency is observed, the effects expected over the lifetime of the components are then determined by extrapolation of the damage and annealing results from the tests to the conditions expected at a given location in the detector.

For radiation effects accelerated testing means using only a limited number of radiation sources with fluxes or dose rates well in excess of those expected in the detector. It also applies to measurements of annealing and wearout where these effects are normally thermally activated, thus the effects can be accelerated by increasing the temperature [see Section 3.6]. Finally only a very small percentage of the final numbers of devices are tested

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[4] All production devices came from the same wafer.

[5] 4 ASICs of each flavour from each wafer; 16 wafers in total.

[6] 4 ASICs of each flavour from each wafer; 16 wafers in total

and a given test may be limited in practical terms to no more than 20 for example due to the number of measurement channels or physical space available.

In the case of ionization damage testing, cobalt-60 gamma sources are the most suitable for irradiation of packaged devices, since the photons are penetrating and strong sources are available. X-ray sources are suitable only for tests of unpackaged chips. Accumulated effects are characterized in terms of the total dose received, which is measured using standard techniques, e.g. PAD dosimeters or by pre-calibrating the radiation source.

It should be noted that for displacement damage, the effects are often compared with reference to the non-ionizing energy loss (NIEL) of a given particle in a given material, which is then normalized using the NIEL of 1 MeV neutrons to relate the tests made to an equivalent fluence of 1 MeV neutrons. The number of defects created in the irradiated material is hypothesized to be proportional to the NIEL, which is also a function of the incident particle energy. Many calculations have been made of NIEL in common semiconductor materials such as silicon and gallium arsenide [Reference]. Some evidence for approximate NIEL scaling in GaAs Truelight VCSELs is seen in [Beringer, Teng].

Care is required when using NIEL to make judgments. It does not take into account any non-linear effects e.g. due to secondary device-level behavior such as responsivity or leakage current change in a photodiode due to field modification inside the active region. It does not account for annealing during irradiation. Also care is required for any extrapolation to complex devices like modern lasers where the laser diode internal structures is for example a very complex structures made of strained layers of GaAs/AlGaAs with engineered doping or a mixture of very thin layers of n- or p-doped InGaAsP and InP on an InP substrate, plus additional diode structures to confine the injected current to the active volume. In such devices it is not known exactly where the most important radiation damage occurs, i.e. whether in a given layer or at certain interfaces, or the characteristics of the defects. It is therefore not possible to predict or extrapolate the susceptibility of some types of devices using NIEL calculations and damage measured for example with one radiation source.

A wider experimental approach should be followed to determine the radiation tolerance of devices for SLHC dtetectors, ideally involving a sufficiently wide series of radiation damage and annealing and wearout tests with in-situ measurements made under different operating conditions, i.e. bias, temperature, on different types of candidate samples. A variety of radiation sources (24 GeV protons, 200 MeV pions, 1 MeV neutrons) should be used to test the effects of the most important parts of the spectrum expected in the detector.

Based on a detailed comparison of the damage and annealing data, the relative damage of the various sources for each type of component under the different operating conditions can be compared and extrapolations of the expected damage in SLHC conditions can be made. The validity for NIEL calculations for a given device can then also be checked.

3.5 Radiation Tolerance Validation

3.5.1 Fibres

Common wisdom exists regarding the procedures for testing optical fibres for use in various types of radiation environments. This section is meant to be an overview or summary of that wisdom which is largely collected from other sources.

3.5.1.1 Radiation Exposure of Optical Fibres

There seems to be no clear way to predict how radiation will damage optical fibre, consequently the procedures to date have involved actual exposure of test lengths of fibre identical to the production version to levels expected over the fibre’s lifetime.

Radiation exposure takes three forms:

1. Charged hadronic sources. Typically this involves protons from beams, but pions or charged kaons might also be used. This source produces bulk and ionizing damage.
2. Neutral hadronic sources, typically neutrons (but neutral kaons are possible though this author knows of no instance of their use only for radiation testing). This source produces bulk damage almost exclusively.
3. Gamma rays or electrons. This source produces Ionizing damage.

Optical fibres for data transmission are almost universally made of SiO2 (silica) which is doped with various elements to obtain the changes in refractive index for the propagation of optical signals. The common doping element considered at CMS and ATLAS is Ge. ATLAS has a bespoke fibre with a fluorine dopant. Past tests where there was Phosphorous dopant did not turn out well for even low-level radiation environments.

Past experience in tests at both experiments and in a wide range of nuclear and space-based applications indicate that, even in environments with a high level of hadronic radiation, it is the ionizing component of that radiation which effects the performance of optical fibres. This effect is through the creation of colour centres through the fibre reducing transmission efficiency. As a result, all fibres currently in use in the ATLAS and CMS detectors are either pure silica or doped with Ge and Fl.

Sources of gamma rays, providing only ionizing radiation damage, are thus favoured for fibre tests. These sources are often from the decays of radioactive elements with Co60 being a popular source. Such exposures have the benefit of large luminous volumes which can accommodate many meters of fibre in the exposure chamber or target area. Gamma sources have another key benefit of being incapable of activating the test rig or the fibres themselves thus permitting easy transport off the radiation site after the proper contamination surveys.

Tests in a neutron source might point out problems with mechanical stability if high integrated doses can be obtained. There is also concern about the integrity of the fibre buffer and the mechanical stability of any cabling that will be subjected to high dose rates. These ancillary issues are reasons for neutron-source tests.

Recommendation: Tests for radiation tolerance at SLHC fluences can be performed in gamma sources alone. But the full integrity of the final cabling structure, including any sheathing, should be exposed to neutrons to check for mechanical stability problems.

3.5.1.2 Test procedure in gamma sources

Several elements are required for testing optical fibres for losses due to radiation damage. Below is a list of the more common elements.

Source: This is typically either a laser (VCSEL or edge emitting) or a Light Emitting Diode (LED). LED sources have the advantage that they can emit light over a broad range of wavelengths so damage can be broadly assessed. Lasers launch a high energy density of light down fibres which might aid bleaching or even annealing effects. Lasers can also provide a high loss tolerance so a longer length of fibre may withstand testing.

It is important that the source’s light output be independently monitored so that power fluctuations can be monitored during the test.

Detector(s): Typically these are p-i-n diodes if a test is being performed at high speed or Large Area Photodiodes (LAPD’s) if overall transmission is of interest. LAPD’s can experience temperature dependent effects that take some time to stabilise due to their large packaging and active area.

Test set-up: Below is a diagram of a suggested set-up for in-situ optical fibre testing.

The laser supplies light to a fibre splitter which then sends approximately 50% of the optical power down two fibres, the test and the control. (The exact percentage of light launched down the test or control fibres is largely irrelevant but the time-stability of this coupling is very important.)

The test fibre runs into the exposure volume where the length to be tested is coiled. The control fibre makes the same run, as near as possible, but does not coil in the radiation volume, rather it returns directly to the optical detector(s). Ideally there would be one optical detector with some mechanism of switching which fibre’s light output is being recorded on the same optical sensor. However, many sensors show excellent stability characteristics, so continuous monitoring on two different optical receivers might be desired. This is a description of a test system for a single fibre channel. It is always desirable to replicate this system over many channels to test ribbon fibres and to mitigate the effect of variations within fibre batches and optical coupling into and out of the fibre.

Important Considerations: As one can see by bending a bit of plastic located between crossed polarisers, stress causes changes in that medium’s optical properties. Several groups who have performed optical tests have also reported significant effects depending on the bending radius.[ref. NATO Docs. And H. Ooms] Consequently it is important to record the bend radius of the fibre spool during any tests. During any exposures it is recommended that the fibre be subjected to minimal stresses and indeed, even removed from any support if possible. All types of cables foreseen should be tested not only bare fibre (if it is foreseen to make jacketed cable). Coil size should reflect size available in radiation source and be such that it is within fibre bending spec and can be shown not to affect the results of the damage. Attention must be paid to the recommended minimum bend radius from the fibre manufacturer and also account for the likely bending that will be experienced in the final system [reference H. Ooms and M. van Uffelen private communication].

Exposure times and monitoring intervals will depend on the radiation rate of the source and the total dose desired.

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Figure 3: Test set-up for fibre exposure.

Table VI: Table of current fibre radiation test results at the LHC.

Experiment	Fibre Description	Dose received	Fibre length tested	Total loss measured
CMS			100m	10dB
ATLAS	Step-index, pure silica core, F cladding dopant	330 kGy and $1x10^{15}$ n(1 MeV Si)/cm^2	10m	0.05 dB/m
ATLAS	Graded Index, Ge Doped core	800 Gy(Si) & $2x10^{13}$ n/cm^2	10m	0.1 dB/m
ATLAS	Graded Index, Ge and P Doped core	4.9 kGy, $3x10^{12}$ n/cm^2	10m	>1 dB/m

3.5.2 Lasers

During early sample validation a small number of devices, e.g. 5 per test, from each supplier should be irradiated under a variety of conditions, e.g. with ideally different levels of radiation, with different radiation sources, with and without electrical bias, e.g. 3 parts biased at ‘normal levels’ and 2 others unbiased, and if possible at different temperatures, e.g. room temperature and the final intended operating temperature.

Samples should be packaged in the final form to facilitate mounting and testing and checking for any radiation damage effects to the packaging. The lasers should be irradiated with gamma rays and then neutrons [to full dosages in both cases?], up to the worst-case doses and fluences unless it is known how to extrapolate with good confidence to higher dose and fluence levels.

Once the dependence on radiation source, temperature, bias and time have been understood, later qualification tests on larger numbers of components can be made using only gamma and neutron sources at room temperature. In the later tests the sample sizes should be larger and sufficient to validate each wafer-lot of parts.

In-situ monitoring of the device output power vs current (L-I) and voltage vs current (V-I) characteristics should be made at periodic intervals before, during and after irradiation. The rates of degradation and annealing of the important parameters e.g. laser threshold current, and efficiency can therefore be determined. The rise and fall times of the devices at various currents should be measured before and after irradiation and also during the irradiation if possible. The ambient temperature should also be monitored during the irradiation.

The thermal resistance of at least one device must be measured. If measurements suggest that the device will be significantly heated internally during the radiation, e.g. by running at higher currents whilst measuring large damage effects, then the laser spectrum should also be measured during the irradiation on at least one device in the same test. This allows the thermal effects to be separated from the radiation damage effects.

3.5.3 P-i-n Diodes

In-situ monitoring of the dark current vs voltage and photocurrent vs incident optical power characteristics, ideally at different voltages, should be made at periodic intervals before, during and after irradiation. The rates of degradation and annealing of the important parameters, e.g. leakage current and responsivity can therefore be determined under final operating conditions. The rise and fall times vs voltage and photocurrent should be measured before and after irradiation and also during the irradiation if possible.

3.5.4 Serializer and Deserializer Chips

TID tests can be performed with gamma (from Co-60) or X-rays. Chips under tests need to be powered with the supplying current monitored as a function of total dose, if possible as a function of dose rate as well. PCBs designed specially for irradiation tests should also provide the possibility to monitor supply current to the analog and digital part of the chip. Dose rate needs to be planned in a way that dose rate effect can be studied with different dose rate steps. Irradiation facilities usually provide the dosimetry. A full scale of characterization measurements (discussed in the section above) of the serializer or deserializer and of the system with them need to carried out before and immediately after the irradiation, and periodically after the irradiation should annealing effects are expected.

If the TID effect is dose rate depending, and the annealing depends on other stimulus like high temperature or UV light, more studies will be need to understand the causes of the TID effects in order to draw conclusions on whether this component is radiation resistant in real operational environment. If low dose rate effect is expected, then a low dose rate safety factor needs to be applied.

3.5.5 LLD

3.5.6 Trans-impedance amplifier (TIA)

3.5.7 Optical Transmitter (OTx) and Receiver(ORx) Subassemblies

This section describes the irradiation test guidelines and evaluation criteria on optical transmitter subassemblies (OTx) and optical receiver subassemblies (ORx).

OTx usually consists of a laser driver chip, a current source circuit (if not inside the driver chip) and a laser (VCSEL or Edge Emitter). ORx usually consists of a PIN diode, a trans-impedance amplifier (TIA) and a limiting amplifier. The tests of lasers and PID diodes are discussed elsewhere. In this document, only the total ionizing dose (TID) effect and single event upset (SEU) tests of the OTx and ORx subassemblies are discussed.

OTx and ORx can be packaged in various ways, in either a commercial or a customer package. Packaging material may affect the way a test is set up and conducted. Irradiation source should be chosen in such a way that radiation can reach all active parts (laser, driver, PID diode, TIA, etc) that are inside the package. The laser and PID diode packaging often also serves as fiber coupling alignment guide to the laser and to PID diode. Deformation of this packaging material under irradiation may affect the performance of the optical system hence change the test results.

For the OTx and ORx modules TID tests can be performed with gamma (from Co-60) or X-rays. Modules under tests need to be powered with the supplying current monitored as a function of total accumulated dose, if possible as a function of dose rate as well. Modules designed specially for irradiation tests should also provide the possibility to monitor supply current to each active component (driver chip, VCSEL, TIA, etc). Dose rate needs to be planned in a way that dose rate effect can be studied with different dose rate steps. Irradiation facilities usually provide the dosimetry. A full scale of characterization measurements (discussed in the section above) of the OTx or ORx need to carried out before and immediately after the irradiation, and periodically after the irradiation should annealing effects are expected.

If the TID effect is dose rate depending, and the annealing depends on other stimulus like high temperature or UV light, more studies will be need to understand the causes of the TID effects in order to draw conclusions on whether this component (OTx or ORx) is radiation resistant in real operational environment. If low dose rate effect is expected, then a low dose rate safety factor needs to be applied.

3.6 Single Event Effects Tests

3.6.1 Seriliazer and Deseriliazer Chips

Serializer chips consist of a PLL based clock unit, a parallel data encoding (framing) and serializing unit, a high speed electrical output driver (usually LVDS). Deserializer chips have a clock-data-recovery (CDR) unit, a serial data de-serializing and decoding (de-framing) unit. In this section, the single event upset (SEU) tests on the serializer and deserializer chips are discussed.

3.6.1.1 Signal quality

A block diagram of an optical link is shown in Figure 4. Test points are defined to measure the signal quality at 5 locations in the link. TP1 is the electrical output signal from the serializer and the input to the OTx. TP2 is the optical output of the OTx, usually tested with a short fiber. TP3 is the optical input signal to the ORx, or the output of the optical fiber that is the full length in the application. TP4 is the electrical output of the ORx and the input to the deserializer. PT5 is the electrical output signal of the deserializer. In this document, only signals at TP1 and TP5 are of concern. We assume valid inputs to the serializer and to the deserializer (TP4). When the transmission rates are at industrial standards, there are IEEE documents describe the tests and evaluation criteria at TP1 to TP4 for a physical layer optical link implementation (example: the IEEE 802.3z standards for gigabit Ethernet transmission at 1.25 Gbps).

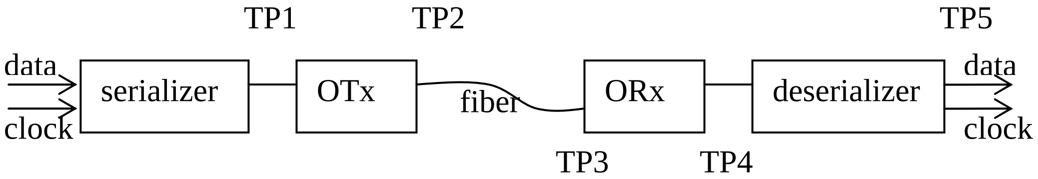

Figure 4: Block diagram of an optical link. Test points are defined as TP1: before OTx; TP2: the output of OTx, usually tested with a short section of fiber; TP3: the input to ORx, or the output of the fiber that is the full length in the application; TP4: the output of the ORx and input to the deserializer. Signals at TP1 and TP4 are electrical (usually LVDS). Signals at TP2 and TP4 are optical. Oscilloscopes with optical input are needed to measure signals at these two points.

In high speed serial data transmission, the clock is encoded in the serial bit stream. The CDR in the deserializer recovers the high speed clock and uses it in the de-multiplexing of the serial bit stream back to the parallel data. Hence the jitter in the serial bit stream is crucial for the link to work properly.

For a serializer, the only signal that is measured is its electrical output at TP1. This signal is usually differential (usually LVDS). An oscilloscope (real-time or sampling) triggered by the input clock (often called the frame clock) is used to measure this signal. When random (or pseudorandom) data pattern is used as the input to the serializer, this measurement shows the eye diagram. From this eye diagram, the following items are to be measured and checked against the design specifications.

1. The waveform’s signal level or amplitude.
2. The rise and fall times of the waveform.
3. The jitter in this bit stream and the jitter transform function of the serializer. A detailed discussion about the jitter measurements can be found in the sub.c document.

For a deserializer, with a valid input at TP4, output parallel data at TP5 are to be checked against the design specifications. The input at TP4 can be generated with a serial bit error rate tester (BERT), or by a serializer in the reference link (refer to sub.c document).

1. The output waveform’s signal level or amplitude.
2. The rise and fall times of the waveform.
3. The jitter in each data bit triggered by the recovered frame clock from the deserializer.
4. The skew between each data bit.
5. The timing diagram (phase relationship) of the data bits and the recovered frame clock.

6. The jitter of the recovered frame clock.

As a link system, the most important characteristic parameters are the bit error rate (BER) and the jitter tolerance on the input frame clock (sometimes called the jitter budget). The BER and the jitter tolerance are correlated. The measurements of these two parameters are detailed in sub.c document. The evaluation criteria on the BER and the jitter tolerance depend on the user requirement of the data transmission, on whether error detection and correction schemes implemented at higher level of the data transmission, and on the conditions of the electronics system in which the link is working.

3.6.1.2 SEU tests

SEU tests are carried out with protons above 60 MeV. SEU cross section as a function of the linear energy transfer (LET), measured with heavy ions, is (not relevant to HEP experiments) not required. To avoid mixing the SEU with TID effect, the proton flux needs to be kept low (< 10^6 proton/cm^2/sec.)

SEU tests on the serializer and deserializer are to be performed with a complete link operated at the design data rate during the irradiation tests. Electrical connection between the transmitter and receiver is recommended. Dynamic data, either a simulation of the actual event format or pseudo-random, are to be sent through the link and the BER is recorded as a function of the flux. Different flux steps need to be used in the test to study possible flux effects. Radiation induced BER is assumed to be proportional to flux so linear extrapolation is used to predict radiation induced BER in real operational environment. The accepted BER depends on the detector and physics requirements.

BER may also be affected by the incident angle of the proton to the chips under tests. It is recommended to perform the BER measurements at normal and grazing incidence.
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A detailed discussion about how to construct a setup for the BER measurement with boards of the reference link can be found in sub.c document.

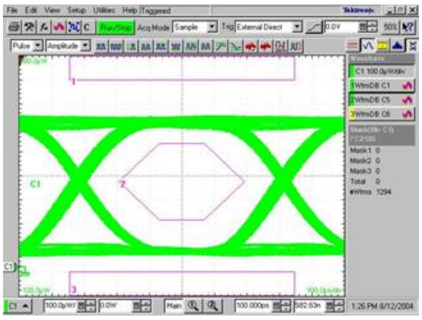
3.6.2 OTx and ORx Modules

In this section, the SEU tests on the OTx and ORx modules are discussed.

3.6.2.1 Signal quality:

For OTx, the signal quality measurements include output optical power, the eye mask test, the jitter measurement and the bit error rate (BER) measurement. For the ORx, these measurements include the sensitivity to the input optical power, the jitter and the BER. Since after the limiting amplifier, the signal amplitude in an eye diagram no long represents the input signal strength, there is no eye mask test, but eye diagram is usually still measured to monitor the electrical output signal waveform and to extract jitter information.

OTx Eye mask tests at industrial standard transmission rates are defined by IEEE documents (example: 1000BASE-SX in IEEE 802.3z standards for gigabit Ethernet transmission over fiber optic operating in multi-mode and 850 nm wavelength). In applications where custom data rates are used, a proposed definition of the eye mask is shown in Figure 5. The mask is defined 20% above the low level (usually logical 0) and 20% below the high level (usually logical 1) in the vertical axis (usually the voltage or optical power); 20% within the crossing points in the horizontal axis (the time). Most sampling oscilloscopes provide the possibility for users to define a user eye mask. A clean clock, usually the reference clock to the optical serializer is used as the trigger to the oscilloscope for the eye diagram measurement. If any dots are found within this eye mask, they may cause bit errors and the eye mask test fails.



Acq Mode Sample

Trig External Direct

0.0V

50%

C1 100.0µW/div

1 WfmDB C1

2 WfmDB C5

3 WfmDB C6

Mask1 0

Mask2 0

Mask3 0

Total 0

#Wfms 1294

100.0µW 0.0W

100.000ps 582.83n

1:26 PM 8/12/2004

Figure 5: A typical eye diagram with an eye mask defined 20% within the eye as shown as the red hexagon. Limits on over and under shoots are also marked with the red rectangles above and below the green eye diagram.

Limits on over and under shoots are usually also checked through the eye mask test. Signals with over and/or under shoots will not cause bit errors, but indicate maladapted circuits in the design.

A block diagram of an optical link is shown in Figure 4. In high speed serial data transmission, the clock is encoded in the serial bit stream and the clock-data-recovery-unit (CDR) in the deserializer recovers the high speed clock and use it in the de-multiplexing of parallel data. Hence the jitter in the serial bit stream is crucial for the link to work properly.

Jitter introduced by OTx is measured as the difference of jitter at TP2 and TP1 in the serial bit stream. Jitter introduced by ORx then difference of TP4 and TP3. Total jitter can be extracted from a histogram of the crossing point in the eye diagram. There are two jitter components that need to be measured, the random jitter and the deterministic jitter. Pseudorandom bit stream (PABS) is used for the jitter test. A more detailed document about how to measure these two jitter components is posted at http://www.physics.smu.edu/~scalise/SMUpreprints/SMU-HEP-04-10.pdf. One may also use a commercially available jitter analyzing package such TDS7BUPJA3 package for TDS7000B, Tektronix, to extract the information on different jitter components.

Bit error rate (BER) needs to be measured on the OTx and ORx in a link system or with a bit error tester (BERT). For the ORx, BER needs to be measured at full optical power from the OTx and attenuated optical power to the sensitivity limit of the ORx in its specification or data sheet. BER is system parameter that affected by many factors including the jitter in the system, the optical power margin in the system, and SEU if the system is placed in radiation environment. One needs to clearly define these parameters when conducting a BER measurement.

For OTx, its output optical power should also be measured. There are three optical power levels that need to be measured for the OTx: the average power, the high power (usually logic 1) and the low power (usually logic 0). The difference from the high power to the low power defines the optical margin to the ORx. In industry, the ratio of the high power to the low power used to be defined for this power margin and is called the extinction ratio (ER). Later the power difference is used instead of ER to define this margin. We will use the power difference in our tests of the OTx.

For ORx, the smallest power difference from the input optical high power to the low power that an ORx can still function (at a given BER, usually 10^{-12}) is defined as its sensitivity. By attenuating the optical power from the OTx to the ORx, one measures this parameter and the attenuation introduced is the optical power margin one has in the system. The sensitivity of an ORx is not only a component parameter, but also a system parameter. When more than one ORx is used in the same PCB, system noise and cross talks may also affect the sensitivity of each ORx. At component level, a commonly accepted sensitivity for 850 nm applications is -17 dBm. Commercial product usually reach -21 dBm.

3.6.2.2 SEU tests:

SEU tests are carried out with protons above 60 MeV. SEU cross section as a function of the linear energy transfer (LET), measured with heavy ions, is (not relevant to HEP experiments) not required. To avoid mixing the SEU with TID effect, the proton flux needs to be kept low (< 10^6 proton/cm^2/sec.)

SEU tests on the OTx and ORx are to be performed with a complete link operated at the design data rate during the irradiation tests (see the test procedure discussed in subgroup C). Dynamic data, either a simulation of the actual event format or pseudo-random, are to be sent through the link and the BER is recorded as a function of the flux. Different flux steps need to be used in the test to study possible flux effects. Radiation induced BER is assumed to be proportional to flux so linear extrapolation is used to predict radiation induced BER in real operational environment, unless this assumption is found not true in the tests with different flux steps.

BER may also be affected by the incident angle of the proton to the active components inside the OTx or ORx. It is recommended to perform the BER measurement at normal and grazing incidence.

There are three types of BER: the single bit flip, the multi-bit error in one data word, usually due to a bit error in the link system that is within the framing of the parallel data and that results in an invalid frame for the deserializer to decode, and the bit errors from the link frame loss. Only type one error can be corrected with error correction schemes imbedded in the data transmission. In the tests for OTx and ORx, we decide to use 8B/10B encoding scheme in the serializer so that test results on these three types of errors can be compared. More detailed discussion about these BER types and their measurement methods can be found in the subgroup C document. The accepted BER depends on the detector and physics requirements.

It is recommended that one performs a reliability test, or at least a life test on the OTx and ORx modules after they pass the TID and the NIEL test. Radiation effects should not greatly affect the expected reliability and the life time of the OTx and ORx.

3.7 Effects of Irradiation on Ageing and Long Term Reliability Tests

For qualification of devices that are being seriously considered for the final system at least 20 irradiated and at least 20 unirradiated devices per wafer-lot should be passed through a thermally accelerated ageing step.

The devices will be operated at least 80°C for at least 1000 hours to determine the rate of long-term wearout degradation. The inclusion of both irradiated and unirradiated samples allows a control of any possible degradation mechanisms that are due to radiation damage.

Failure criteria should be defined with respect to operating specifications. It is also useful to use the failure criteria recommended by Bellcore [1], e.g. > 50% change in operating current, in order to be able to make comparisons with other or manufacturers' tests.

Wearout failure mechanisms are normally assumed to be temperature dependent, being thermally activated following the Arrhenius law [Ref]. In any case where the activation energies for wearout failure and random failure of the lasers are not known a value of 0.4 eV will be assumed, following Bellcore recommendations.

3.7.1 Lasers

In-situ monitoring of the device output power vs current (L-I) and voltage vs current (V-I) characteristics should be made at periodic intervals during ageing. The rise and fall times at various currents should be also measured. In between measurement cycles, the lasers should be biased at a current representing the maximum that is expected to be used in the final application.

If the laser is inoperable at 80°C, e.g. due to thermal rollover, then the temperature can be reduced briefly to a reference value, e.g. 20°C, for the measurement at periodic intervals. If thermal resistance measurements suggest that a laser diode will be significantly heated internally during the test this additional heating should be taken into account when extrapolating the wearout or lifetime to other temperatures or biasing conditions.

3.7.2 Photodiodes

In-situ monitoring of the dark current vs voltage and photocurrent vs incident optical power characteristics, ideally at different voltages, should be made at periodic intervals during ageing. The rise and fall times vs voltage and photocurrent should also be monitored.

3.7.3 Fibres?

4 References

CMS Tracker Optical Links Quality Assurance Manual, by K. Gill, J. Troska, F. Vasey.

ATLAS Standard Radiation Test Methods, *Sub-part of ATC-TE-QA-001.*

“Irradiation Studies of Multimode Optical Fibres for use in ATLAS front-end Links.”, by G. Mahout, M. Pearce, J. Troska, A. R. Weidberg, J. Ye, *et al*. Nucl. Inst. Meth. A 446, (2000) 426-434.

“Radiation effects in commercial off-the-shelf single-mode optical fibres”; by J. Troska, J. Batten, K. Gill, F. Vasey; for *“Photonics for Space Environments VI”, San Diego, 22nd July 1998.* Reference contains several absorption curves vs. exposure.

“Radiation Effects Data on Commercially Available Optical Fiber: Database Summary”, *by M. N. Ott,* NASA Goddard Space Flight Center. An extensive list of fibres and their losses is presented in this document.

[XX] P.K Teng, et al., Radiation Hardness and Lifetime Studies of VCSELs for the ATLAS Semiconductor Tracker, Nucl. Inst. Meth. A 497 (2003) 294-304.

An example of a reactor exposure facility is detailed in: “SCK-CEN Gamma Irradiation Facilities for Radiation Tolerance Assessment”, *by A. F. Ferandez, H. Ooms, B. Brichard, M. Coeck, S. Coenen, F. Berghmans, and M. Decreton.*

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1. “Fibre Optic Data Links Reliability Qualification and Lot-to-Lot Controls,” GR-2903-CORE, 1995; “Generic Reliability Assurance Requirements for Opto-Electronics Devices used in Telecommunications Equipment,” GR-486-CORE, Issue 1, 1998.

[1] IM. Gregor, Optical Links for ATLAS Pixel Detector,Thesis, WUB DIS 2001-03, 2001, Wuppertal

1] J. Beringer et al., Radiation Hardness Lifetime Studies of LEDs and VCSELs for the Optical Readout of the ATLAS SCT, Nucl. Instr. Met. A435 (1999) 375.
[2] P.K. Teng et al., Radiation hardness and lifetime studies of the VCSELs for the ATLAS semiconductor tracker, Nucl. Instr. Meth. A497 (2003) 294.

5 Appendix A: Radiation Sources

The list of radiation sources were taken from http://atlas.web.cern.ch/Atlas/GROUPS/FRONTEND/radhard.htm#Radiation%20Facilities.

Table has to be inserted

6 Appendix B: NIEL Values

For Si NIEL values see: *A. Vasilescu (INPE Bucharest) and G. Lindstroem (University of Hamburg), Displacement damage in silicon, on-line compilation* at http://sesam.desy.de/members/gunnar/Si-dfuncs.html.

For GaAs NIEL values see XXXX

7 Appendix C: Irradiation Checklist

General administration	Details involving test facility	Test/Instrumentation preparation
Personnel paperwork: medical certificate, dosimetry paperwork (radiation passport) Foresee personal dosimeters at source facility Local contact details (phone, fax, e-mail) Obtain quote(s) Launch order for irradiation (or series of tests) Confirm schedule and access to source Confirm length of annealing period Confirm storage space Confirm office space Equipment shipping/transport papers Plan travel: Car rental and/or flights Car insurance if own car used Accommodation (local recommendation?) CERN Travel requests + ordre de mission CERN EDH official leave request	Define source flux/dose-rate requirements Confirm source flux/dose-rate profile Confirm useful test volume Determine if test volume is cooled or not and if temp/humidity are controlled and/or monitored. Check if dosimetry provided Confirm level of flux/dose away from source Collect dosimeters (if needed) Confirm mechanical support and interfaces if any present already in source Confirm cabling passages	Define cabling and connection maps Define remaining mechanical structure Define cooling method Integrate PT100 or similar thermal sensors Prepare PCBs Prepare mechanical supports Prepare cables (electrical optical) plus spares Prepare short-circuit connections to avoid ESD before/after test and during handling Set-up in lab with final mechanics, instruments and cabling Develop and test software drivers and overall measurement software Develop and test analysis routines Prepare transport packaging Prepare tools and other spare parts Make final soak test in lab before packing

8 Appendix D: History of the Document

Version/date	Comment
1.0/26.07.2007	This document was discussed at the Proposal B Meeting on the 27.07.07: http://indico.cern.ch/getFile.py/access?resId=1&materialId=0&confId=19327
2.0/08.08.2007	Comments of the Proposal B Meeting on the 27.07.07 were implemented. See minutes for details: http://indico.cern.ch/getFile.py/access?resId=1&materialId=0&confId=19327
2.1/15.08.2007	Added section about evaluation of DUT before irradiation.
2.2/27.08.2007	Comments from the Proposal B Meeting on the 17.08.2007 implemented. See http://indico.cern.ch/conferenceDisplay.py?confId=20018.
2.3/03.09.2007	Work on the structure of the document and took out QA out of the title in section 3.