Optical links for HEP experiments

F. Jensen, C. Azevedo, L. Björkman, G. Cervelli, K. Gill, R. Grabit, and F. Vasey

CERN, Geneva (Switzerland)

Fredrik.Jensen@cern.ch

Abstract

Optical links for high-energy physics experiments present a unique set of challenges to the system designers. Presently optical links are being developed for several large-scale physics experiments. In particular the optical links under development for the tracker of the CMS experiment at CERN will be discussed. This paper focuses on the special system requirements encountered, and how these requirements can be met, using a mixture of commercial-off-the-shelf electro-optic devices and custom developments. The required component validation tests are also described in detail.

1. INTRODUCTION

Many modern high-energy physics (HEP) experiments exhibit an extremely large number of channels to be read out. The distributed nature of physics detectors also limit the possibility of multiplexing due to difficulties with long detector signal lines. The resulting large number of optical channels forces the use of commercial-off-the-shelf (COTS) components to reduce cost and development time of read-out systems. The high channel-count also makes the use of multi-way transmitter and receiver modules and fibre ribbon cables advantageous.

In certain HEP detector types, such as tracking detectors, a high channel count also leads to tight limits on space, mass and power dissipation. To meet these demands, compact low-mass components should be used as far as possible as well as low-power electronics.

High-energy physics experiments sometimes also involve high levels of radiation. In such cases rad-hard components have to be used for the part of the read-out chain exposed. Often this means that extensive radiation hardness tests have to be carried out. An additional environmental constraint present in certain detectors or sub-detectors is a high magnetic field, requiring the use of components with low magnetic susceptibility.

An important aspect of any HEP readout system is its reliability. The ever-increasing complexity of detectors, in combination with considerable induced radiation levels for some experiments make servicing more difficult and time-consuming. Detector lifetimes often exceed 10 years and the total cost of a HEP detector is high, thus to reduce the occurrence of unnecessary and expensive replacement of parts component reliability needs to be excellent. In most cases reliability tests are performed on opto-electronic components by the manufacturer, however it is important to note that this is done only on *un-irradiated* components. It is therefore important to ascertain the reliability of components also after they have been irradiated if the read-out system has to survive high radiation doses.

The performance requirements on HEP detector read-out systems vary considerably. Some detector readout systems currently being designed should support data-rates up to ~1Gb/s/link for tens of thousands of links whereas others have a need for only ~1Gb/s for a whole experiment. Even though commercial digital optical links exist that operate at these speeds, it is a challenge to adapt these technologies to physics detector read-out systems, in particular if a large number of links is required, as this has to be achieved at a very low cost and often in a harsh environment.

The CMS tracker optical links have to meet all of the environmental demands discussed above and will be described in the following section.

2. CMS TRACKER OPTICAL LINKS

The Compact Muon Solenoid (CMS) is one of four detectors being developed for the Large Hadron Collider (LHC) at CERN [1]. The CMS tracker is responsible for detecting particle tracks and momenta. This task will be achieved by a multilayered structure of silicon and gas microstrip detectors that will give a total of ~12×10^6 channels to be read out [2]. The data from the tracker will be time-multiplexed at a rate of 256:1 into ~50000 uni-directional *analogue* read-out links. In addition about ~2000 bi-directional digital links will distribute timing and control signals to and from the tracker.

The constraints and performance requirements on the CMS tracker optical links are listed in Table 1. The environmental demands on the CMS tracker links are severe with high radiation doses and magnetic fields. In addition the read-out system should have a high density with low power dissipation.

Table 1: CMS tracker optical link requirements

Typical requirement	*Possible solution*
High channel count (50000 links)	COTS/multiway modules/fibre ribbon cables
Space/mass/power limits	compact/low mass components/low power electronics
High radiation dose (100 kGy, 10^14 p/cm^2)	rad-hard components/radiation hardness validation
High magnetic field (4 Tesla)	non-magnetic packages/validation
Performance (40MSamples/s)	low-cost COTS/performance validation

The architecture of the CMS tracker analogue readout system is shown in Fig. 1. The ~50000 uni-directional links are based on edge-emitting laser transmitters and pin photodiode receivers operating at a wavelength of 1310nm. In every single-mode fibre, 256 electrical channels are time-multiplexed at a rate of 40MSamples/s. Two in-line patch-panels fan-in the fibres originating from the transmitters, first to a 12-way ribbon, and then to an 8-ribbon cable carrying 96 fibres away from the detector to the counting room. All system components situated inside the detector volume (drivers, lasers, fibres and connectors) must be non-magnetic, radiation resistant and reliable.

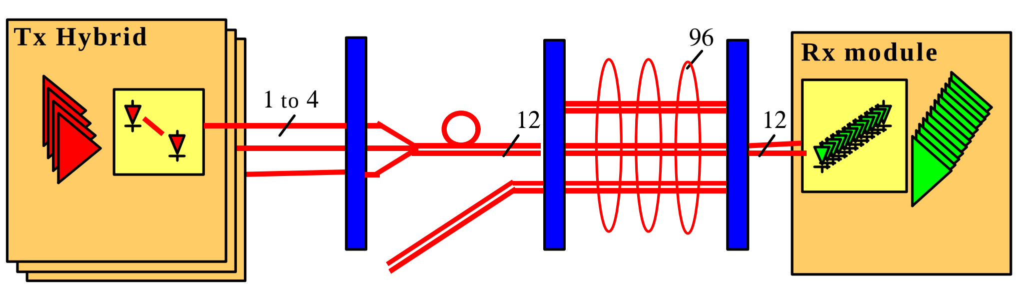


Figure 1: Block diagram of the analogue readout link

The analogue link requirements are summarised in Table 2. They are modest in comparison to what is typically achieved in other analogue distribution networks such as cable TV, but must be met at a very low cost, in a harsh environment, and for a large quantity of channels.

Table 2: CMS tracker performance optical link requirements

Characteristic	*Typical requirement*
Analogue coding scheme	Pulse Amplitude Modulation 40MSample/s
Peak SNR	48dB (250:1)
Integral linearity deviation	2 %
Bandwidth	100MHz
Settling time to 1%	18ns

The ~2000 bi-directional digital links (Fig. 2) used for control and timing distribution are based on almost identical components as the analogue readout system, since the small number of digital channels do not justify the effort of selecting and qualifying specific devices. The only differences between analogue and digital systems are the number of fibres per ribbon (8 compared to 12) and the fact that the receiver modules placed inside the detector need to be built with radiation resistant photodiodes and discriminating amplifiers.

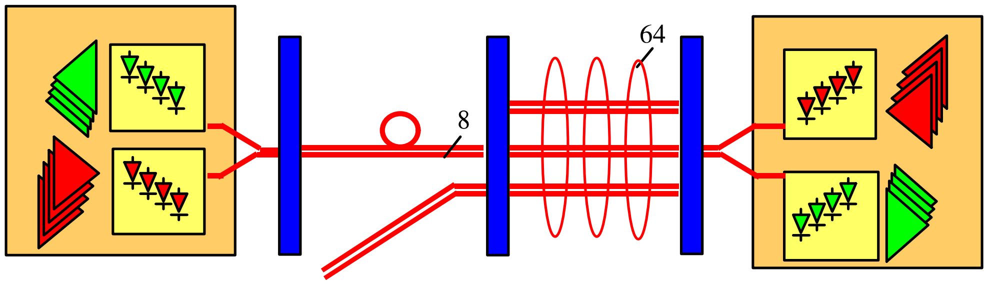


Figure 2: Block diagram of the digital control link

The digital link requirements are summarised in Table 3. The operation frequency will be 40Mb/s for the data and 40MHz for the clock channels. The development options, choices and component types selected to be used in the tracker optical data transfer system has been described elsewhere [3]. Results obtained with 4-channel prototype parallel analogue links have been reviewed in [4].

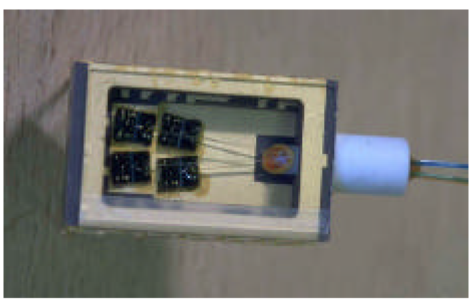
Table 3: CMS tracker digital optical link requirements

Characteristic	*Typical requirement*
Bit Rate	40Mb/s
Bit Error Rate	10^{-12}
Sensitivity	-30dBm
Bandwidth	100MHz
Jitter	<0.5ns

3. COTS AND CUSTOM DEVELOPMENTS

Apart from the custom designed electronics for the laser-drivers [5] and photodiode-receivers [6], all optical link components to be used in the CMS tracker are based on Commercial-Off-The-Shelf products (COTS). Slight deviations from the standard manufacturing process are only allowed to meet specific functionality requirements such as low back-reflection (for analogue performance), or particular environmental constraints such as high magnetic field. For instance, whereas distributed feed-back (DFB) edge emitting lasers are known for their superior analogue performance, and even though pure silica core fibre is usually recommended for radiation sensitive applications, standard low-cost Fabry-Perot lasers and telecom-grade single mode fibre is specified for the CMS-tracker optical links. This development strategy has the advantage of minimising development and system cost, but dictates the launch of extensive validation programmes to confirm that as wide a range of COTS as possible can be used reliably in the CMS tracker environment.

The optical link COTS devices consist of semiconductor lasers and photodiodes, as well as optical fibre and connectors. The laser transmitters are based on fully commercial laser chips, however, as noted above, environmental considerations constrain the packaging of the die. In particular the packages should be nonmagnetic and have small mass as well as small size. In addition it might be advantageous in some cases to use multi-way components. Thus for the CMS tracker two main types of transmitter packages have been developed: one is a 4-way nonmagnetic, fully hermetic, hybrid DIL package shown in Fig. 3, the other type is a very compact 1-way package consisting of a sub-mount with a lid, also made of non-magnetic material. Two versions, from different manufacturers, of the 1-way package are shown in Fig. 3.



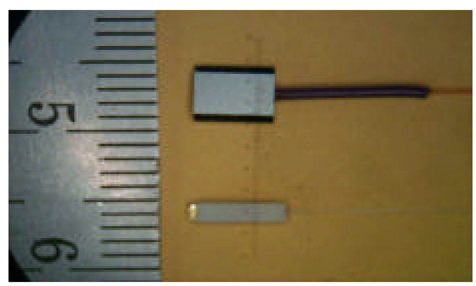


Figure 3: 4-way laser hybrid DIL laser package (left) and two version of 1-way submount-based laser package

The two types (multi-way DIL and 1-way submount with lid) of laser packages address different needs. Both are compact, but the DIL package is more resistant to handling and wear. On the other hand the 1-way submount-type minimises mass and space expenditure, but is also more sensitive to handling, and might require more care during installation and maintenance.

The fibres, intended for the CMS tracker links, are fully commercial telecom grade fibres. The radiation resistance of these fibres has been carefully checked and been found to be sufficient also for the high radiation levels encountered in the CMS tracker. Initially pure-silica core fibres were thought to be required as in general pure silica resist radiation better than standard Germanium-doped glass used in telecom fibres. It has been shown however that Ge-doped fibres are sufficiently radiation hard to be employed at the doses, dose-rates and temperatures foreseen to be present in the tracker environment [7]. Thus the fibre intended for the tracker is a fully commercial product. Space constraints again force custom development when it comes to cabling, as standard telecom and data-com cables do not have the required density, nor the required flexibility necessary for the tracker links. Fig. 4 shows examples of candidates of fibres, ribbon fibres and cables for the tracker links.

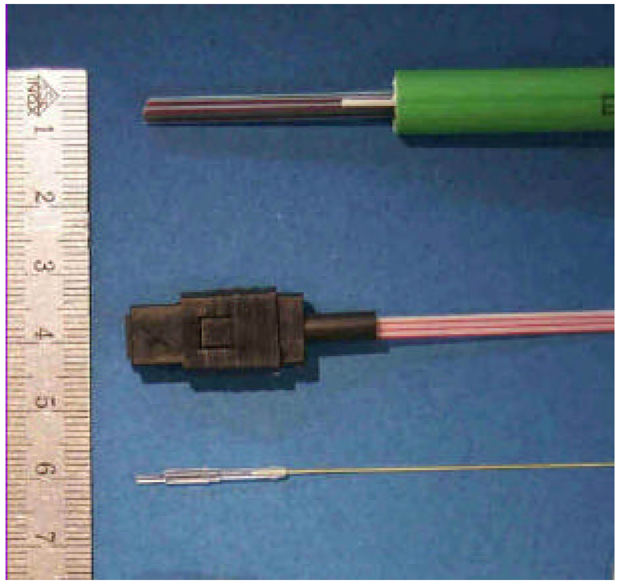


Figure 4: 96-way ribbon-fibre cable (top), 12-way ribbon-fibre with MPO-connector (middle) and single fibre with compact 1-way connector (bottom).

High density is required also on the receiving end of optical link systems with large number of channels. A 12-way analogue receiver chip has been custom developed for this reason. Custom development was necessary for the CMS-tracker optical links as there are no analogue receiver chips with sufficient density on the market. However relatively recent developments in data-com opto-electronic components have produced multi-way fast *digital* modules. The solution for the CMS tracker builds on these developments, as the receiver package used is intended for digital modules, thus reducing cost and development time for the tracker optical links. A commercial 12-way PIN-diode array is used in conjunction with the developed 12-way receiver chip. These components are then introduced in a modified version of a commercial 12-way digital receiver package (not shown). The package under consideration has the further advantage of having excellent heat conduction properties as well as providing high channel density in multi-way format.

4. COMPONENTS VALIDATION PROGRAM

The optical link COTS devices, as described in the preceding section, are targeted at the telecom market. Such telecom components are usually qualified for digital data transmission and for operation in standard (but nevertheless stringent) environmental conditions. Their use in an analogue system and in an environment like LHC must thus be carefully checked.

The component validation programme, devised to minimise the risk of using COTS in the CMS-tracker application, has three parts:

a) The in-system functionality tests must demonstrate that the telecom-grade components being evaluated meet the system-level requirements. For instance, standard Fabry-Perot lasers must be shown to satisfy the low noise requirements of an analogue readout system.
b) The environmental tests must subject the devices under evaluation to stress conditions not part of the standard telecom qualification programmes. For instance, telecom-grade single-mode fibre must be shown to be radiation-resistant, and component packages must be proven to be non-magnetic.
c) The reliability tests finally must ensure that environmentally stressed components (in particular irradiated devices) will have sufficient reliability to operate within specs during the lifetime of the experiment.

The validation programme described below in more detail is thus not simply a clone of standard telecom qualification procedures. It is an additional test, specifically matched to the operational and environmental requirements of the experiment. In this paper, we illustrate, as an example, the description of the validation-programme with results obtained with Fabry-Perot edge emitting lasers supplied by ITALTEL (Milano). Similar validation tests are being performed on all components considered for use in the CMS-tracker optical links.

4.1. In-system functionality tests

The in-system functionality tests evaluate the system performance with the device under test embedded in a reference analogue optical link. It is assumed that devices meeting the analogue link requirements will also be good candidates for the digital links. The investigated system parameters are dynamic range, linearity and pulse response. The measurement procedure is described in [8]. The results are compared with the system-level specifications and presented in a way that allows comparison between devices and manufacturers. Figure 5 shows, for example, the optical link static transfer characteristic measured with 20 laser transmitters of the same type. The output noise in the full system bandwidth is plotted in Fig. 6, normalised by the full-scale signal amplitude, as a function of link input voltage.

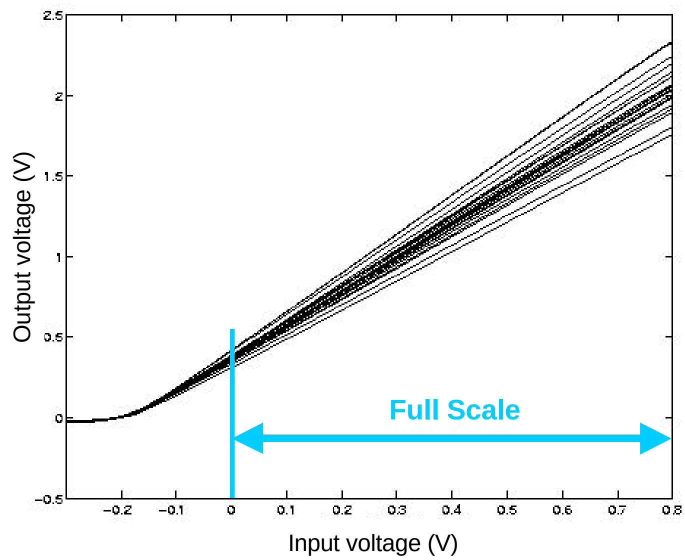


Figure 5: Output performance of the reference optical link versus input voltage, for the 20 laser transmitters under test.

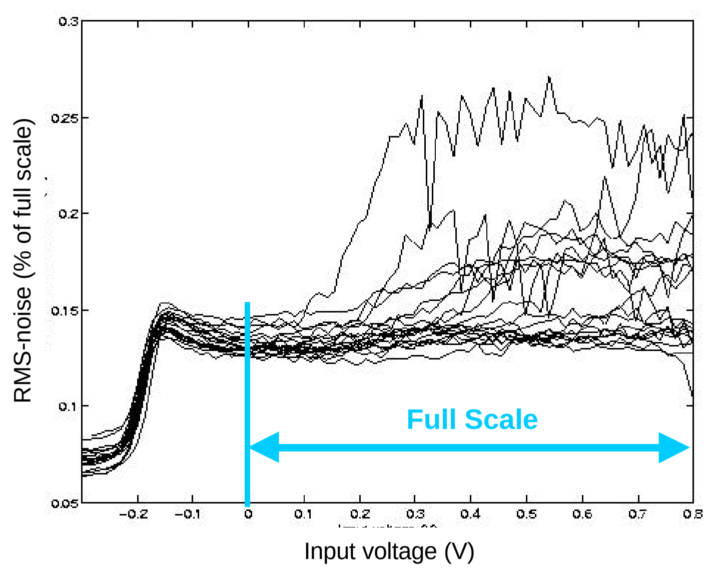


Figure 6: Noise performance of the reference optical link versus input voltage, for the 20 laser transmitters under test.

These plots can be reduced to 1 point per device as shown in Fig. 7, where deviation from linearity and noise are computed, and normalised to a chosen fraction of the full scale signal [9]. Integral deviation from linearity and peak signal to noise ratio can thus be quickly evaluated for any device operating in a given range. For instance, assuming an input voltage full scale of 800mV, one can quickly asses that in the first quarter of the operating range (i.e. 200mV input), a peak signal to noise ratio better than 140:1 and a linearity deviation of less than 0.6% are typically obtained with the tested devices. In the full operating range (i.e. 800mV), the peak signal to noise ratio of the same devices is greater than 300:1 for a linearity deviation of less than 1%.

The pulse response of the system is dictated by the custom designed transmitting and receiving electronics. It shows little dependence on the COTS under test. Typical rise time values are of the order of 3ns. The in-system test results for laser transmitters shown above indicate that the investigated devices meet the CMS-tracker analogue link requirements, despite the fact they were developed as digital transmitters for telecom applications

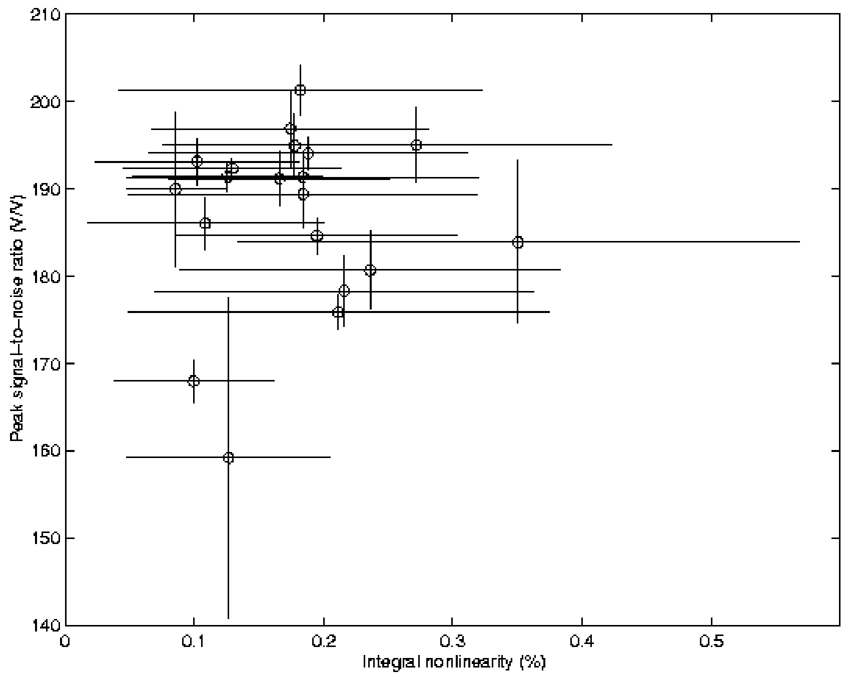


Figure 7: Peak signal to rms noise ratio versus integral non-linearity in a 200mV input range (one quarter of link full scale) for the 20 lasers characterised in Fig. 5 and 6. For each device, the mean value and standard deviation in the considered range are shown.

4.2. Environmental tests

In the environmental evaluation procedure, the front-end components are tested for resistance to magnetic field and radiation. It is assumed that other usual qualification tests such as temperature cycling, vibration, etc. will have been performed by the manufacturers as part of the standard telecom qualification programmes.

The magnetic field resistance test is a simple mechanical test whereby the force exerted by the field on the device under evaluation is estimated.

The irradiation tests monitor in-situ the changes in the device performance resulting from radiation damage and subsequent annealing. They are carried out at room temperature with the devices operated under typical bias conditions. Both neutron and gamma irradiations are performed. Figure 8 compares the threshold currents of 30 irradiated lasers to pre-irradiation values. The devices were irradiated with neutrons at room temperature to a total fluence of the same order of magnitude (2.5 to 6 x10^{14}n/cm^2) as the maximum expected hadron fluence (pions, neutrons, protons etc. combined) in the CMS tracker over 10 years of operation. The irradiated samples were stored, electrically shorted, at room temperature for up to 15 months. Based on our earlier studies [10], we estimate that 30% of the initial radiation damage in the lasers annealed during this period.

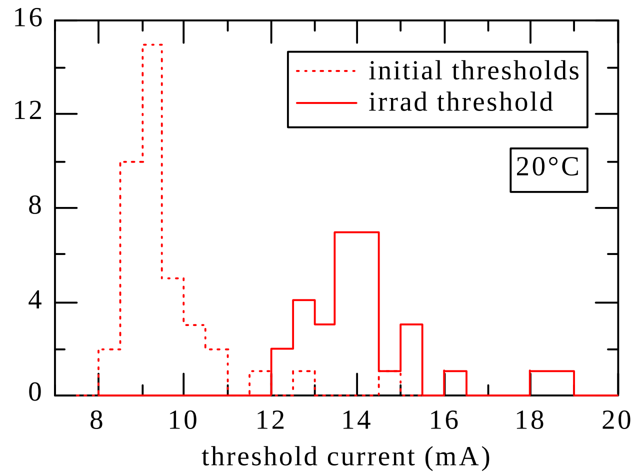


Figure 8. Threshold currents for the irradiated lasers. Data shown are the pre-irradiation values (30 plus 10 reference samples) and those measured after irradiation and annealing (30 samples).

A thorough discussion of the radiation damage effects for this particular type of laser can be found elsewhere for tests carried out using neutrons and other radiation sources [11]. Test results have also been published for optical fibre [7], connectors [12] and pin photodiodes [13].

4.3. Reliability tests

Manufacturer-qualified, telecom-grade COTS are known to be highly reliable. However, it is not known if radiation damage will influence this reliability. Component reliability is often categorised into three domains: early, mid-life, and old age failure, each with several different mechanisms [14] that contribute to the failure rate.

Early failures (sometimes termed ‘infant mortality’) are usually intrinsic to the device and are eliminated by a burn-in, or purge-test, inducing weak devices to fail before the components are employed in the field.

The mid-life failures can be subdivided into two parts, the first being simply due to the tails of the early and long-term failure distributions. The remaining failures are collectively grouped together as ‘sudden’ or ‘random’ failures, which are catastrophic failures often triggered by external factors such as electrical or mechanical shocks, depending upon the operating environment.

Long-term failures are usually dominated by ‘wearout’. For the optical link components inside the CMS tracker the most important wearout failure modes are likely to be resulting from a combination of radiation damage and intrinsic wearout degradation.

Ageing tests of irradiated components have been performed on semiconductor lasers and photodiodes, as well as optical connectors. As example, we show in Fig. 9 ageing test results obtained with 30 neutron-irradiated and 10 unirradiated lasers. The laser threshold current versus time is plotted for all the devices tested. At 80°C (20°C) the unirradiated devices have initial threshold currents of 21-31mA (8-11mA) and the irradiated devices have values of 28-55mA (12-19mA), this larger variation being mainly due to the different neutron fluences received by the various devices. Overall, the rates of wearout degradation of the laser threshold currents are very small, <0.4mA/1000hours in the unirradiated devices. For the irradiated devices, annealing of the radiation damage is the main effect. Only a few of the irradiated devices show increases in threshold current. The device labelled A, which has the most degradation, should have actually been rejected by the supplier following burn-in, based on its high threshold current increase during the purge phase.

The irradiated lasers continued to anneal throughout the 4000 hours at 80°C, therefore the ageing related wearout was obscured for these devices and a wearout rate could not be accurately determined. However, as the annealing rate decreases with increasing time, the results suggest that the wearout rate of the irradiated lasers is not significantly greater than in the unirradiated samples.

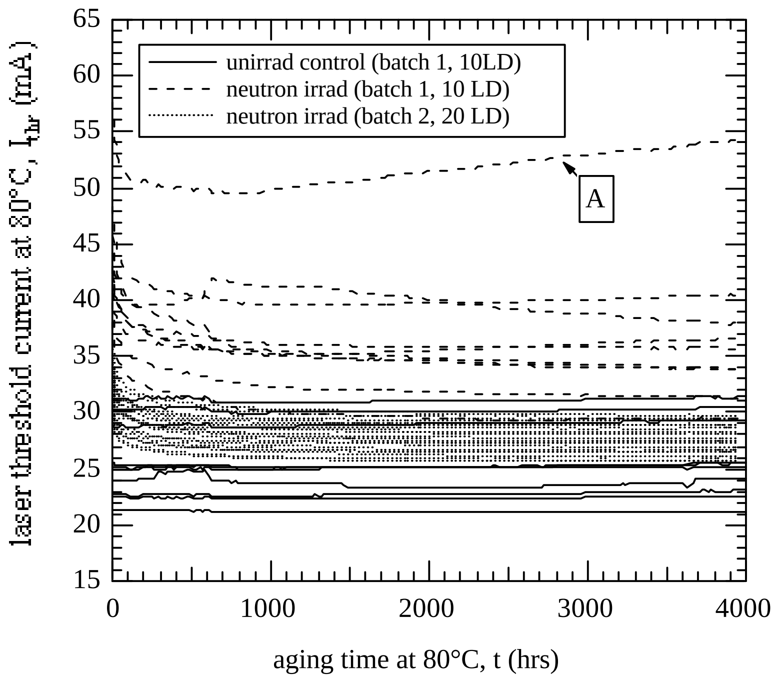


Figure 9: Laser threshold current during aging.

Failure rates can be extrapolated from ageing test results such as shown in Fig. 9, by defining failure criteria and calculating acceleration factors. A detailed estimation of the reliability of irradiated lasers and pin-diodes in the CMS tracker is in progress. Reliability tests have also been performed on optical connectors: repeated mate/demate tests on irradiated MT ferrules are reviewed in [11].

5. CONCLUSION

Environmental constraints combined with demands of high reliability and functionality at low cost present a unique challenge in designing and constructing optical link for HEP experiments. The use of COTS lasers, fibres, connectors and photodiodes benefits from the rapid progress made by telecom components suppliers and allows cost levels compatible with HEP experimental budgets to be reached, but dictates the need for through validation schemes.

The optical links for the CMS tracker have been designed making as much use of COTS as possible, in order to minimise cost and development time. Three types of validation tests have been described that are being carried out on the components under evaluation: functionality tests (compliance to system specifications), environmental tests (resistance to radiation and magnetic field) and reliability tests (ageing of irradiated components). Candidate COTS devices, including lasers, fibres and receivers have been found that pass all validation tests, and a selection is underway based on the performed tests. Custom developments of opto-packages, fibre-cables and electronics are now close to completion. Pre-production of the CMS tracker optical links is expected to begin in the year 2000.

6. REFERENCES

[1] "CMS Collaboration, Technical Proposal", CERN/LHCC 94-38.

[2] "The Tracker Project Technical Design Report", CERN/LHCC 98-6.
[3] G. Hall, G. Stefanini, F. Vasey, "Fibre optic link technology for the CMS tracker", Technical note CMS Note 1996/012, Dec. 1996.
[4] F. Vasey, C. Aguilar, V. Arbet-Engels, C. Azevedo, G. Cervelli, K. Gill, R. Grabit, F. Jensen, C. Mommaert, P. Moreira, "A 4-channel parallel analogue optical link for the CMS-Tracker", proceedings of the fourth workshop on electronics for LHC experiments, Rome, September 21-25, 1998, pp 344-8.
[5] A. Marchioro, P. Moreira, T. Toifl, T. Vaaraniemi, "An integrated laser driver array for analogue data transmission in the LHC experiments", proceedings of the third workshop on electronics for LHC experiments, London, September 22-26, 1997, pp 282-6.
[6] F. Faccio, M. Campbell, K. Kloukinas, A. Marchioro, "An Amplifier with AGC for the 40MHz Optical Receiver of the CMS digital optical link", these proceedings.
[7] J. Troska, J. Batten, K. Gill, F. Vasey, “Radiation effects in commercial off-the-shelf single-mode optical fibres”, proceedings of the SPIE, Vol. 3440, 1998, pp 112-9.
[8] G. Cervelli, V. Arbet-Engels, K. Gill, R. Grabit, C. Mommaert, G. Stefanini, F. Vasey, "A method for the static characterisation of the CMS tracker analogue optical links", Technical note CMS Note 1998/043.
[9] F. Jensen, C.S Azevedo, L. Björkman, G.Cervelli, K.Gill, R.Grabit, F.Vasey, "Methodology for evaluation and selection of analogue optical links for the CMS tracker", to be published as CMS Note.
[10] K. Gill, V. Arbet-Engels, G. Cervelli, R. Grabit, C. Mommaert, G. Stefanini, J. Troska and F. Vasey, “Effect of Neutron Irradiation of MQW Lasers to 10^{15}n/cm^2”, CERN CMS Experiment Technical Note 1997/044.
[11] K. Gill, C. Aguilar, V. Arbet-Engels, C. Azevedo, J. Batten, G. Cervelli, R. Grabit, F. Jensen, C. Mommaert, J. Troska, F. Vasey, "Comparative study of radiation hardness of optoelectronic components for the CMS tracker optical links", proceedings of the fourth workshop on electronics for LHC experiments, Rome, September 21-25, 1998, pp 96-9.
[12] J. Batten, K. Gill, J. Troska, F. Vasey, "Radiation tolerance of MT multi-way single mode fibre-optic connectors to gamma and neutron irradiation", Workshop record of the data workshop, RADECS conference on radiations and their effects on devices and systems, Cannes, Sept 17, 1997, pp 75-80.
[13] J. Troska, K. Gill, R. Grabit, F. Vasey, "Neutron, proton and gamma radiation effects in candidate InGaAs pin photodiodes for the CMS tracker optical links”, Technical note CMS Note 1997/102.
[14] F. R. Nash, “Estimating device reliability: assessment of credibility”, Kluwer Academic Publishers, Massachusetts, 1993.