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The Compact Muon Solenoid Experiment

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Fibre optic link technology for the CMS tracker

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Abstract

This note is intended to summarise the technical developments and decision elements leading to the choice of technology for the optical links in the CMS tracker. The technical aspects, relative advantages and estimated cost of the two alternatives - direct or external modulation of light - are discussed. Results of measurements of the radiation hardness of laser and modulator transmitters are presented. The choice of a system based on directly modulated laser diodes is proposed; the arguments for this choice are presented and discussed. Timescale and cost estimate of further developments required to reach production are presented.

1 Introduction

The CMS central tracker [1.1,1.2] is based on silicon and gas microstrips with an inner pixel detector system. The detectors will be operated in a 4T solenoidal magnetic field contained in a cylindrical volume of 1.3m radius and length 7m. The total number of microstrip channels to be read out is 11×10^6 MSGC and 3×10^6 silicon. Similarities between silicon and MSGC signals allow a single electronic readout scheme [1.3,1.4] to be envisaged for both detector types with minimal variations only where essential.

A major and novel component of the proposed system is the use of analogue data transmission using an optical fibre link. There are several strong reasons for the choice of an analogue system: optimal position resolution, immunity to noise and minimisation of custom radiation hard electronics. However, it is only practical by using *optical* means of data transmission, which is a fast moving technological area. Although much of the momentum arises from digital communications there are also important analogue applications, such as cable TV and broad spectrum antenna remoting, and the limited dynamic range and weak linearity requirements for a tracker mean that a wide range of transmitting elements could be utilised. Over the past few years, mainly through R&D work carried out in the RD23 project, this has been narrowed down to a small number which could meet the special requirements of long term operation in the highly irradiated volume of an LHC tracker where space and power are at a premium. A final narrowing of the options to a single transmitter technology must be made before production and it was agreed that this decision should, if possible, be made in mid 1996. This note is intended to summarise and explain the technical choices which have been made for CMS. It is not intended to contain all the background technical information, only relevant selected details where required.

1.1 Overview of CMS tracker readout system

Each microstrip is read out by a charge sensitive amplifier with a time constant 50nsec whose output voltage is sampled at the beam crossing rate of 40MHz. Samples are stored in an analogue pipeline for up to 128 crossings (3.2µsec) and, following a level 1 trigger, are processed by an analogue circuit which forms a weighted sum to confine silicon signals to a single beam crossing interval. Because of the drift time in the gas volume a variant of the signal processing element is planned for the MSGCs.

Optical data transmission is considered essential for the CMS tracking system to minimise the material budget and transfer data immune from electrical interference. An analogue data link avoids on-detector digitisation and reduces internal power consumption. The linearity (<2%) and dynamic range (<7-8bits) for tracking requirements are not especially large and a 40MS/s transfer rate is well below the full bandwidth of the fibre link. In the CMS tracker the deadtime caused by transferring 256 values (in 6.4µsec) can be tolerated provided buffer depths are adequate.

A simplified schematic diagram of the proposed system is shown in Fig. 1.

The external data acquisition for the tracker is based on a VMEbus system housed in the barracks outside the experimental area after cable paths of up to 100m. The pulse height data from each channel of the front end chips, with no zero suppression, will be serially transferred at 40MS/s by the optical link to a receiver module using a multiplexing level of 256 detector channels per fibre. Since each analogue value corresponds to 6-8bits of information, the effective data transmission rate is ~300Mbit/s. In the counting room, a Front End Driver module digitises the analogue data, performs zero suppression and simple cluster finding and stores the results in a local memory until required by the higher level data acquisition.

A dedicated module, the Front End Controller, will distribute the LHC clock and trigger signals which will be passed to it from the TTC system developed at CERN [1.5]. Commands will be passed to the front end readout chips and responses from control signals will be returned. Data monitoring the system environment will also be transmitted from the interior of the tracker. A digital optical fibre link, acting effectively as a bi-directional bus, will transmit all these signals to an internal control module which will distribute them locally electrically. It is envisaged to make use of the same optical technology used for analogue data transfer for transmission of the digital signals.

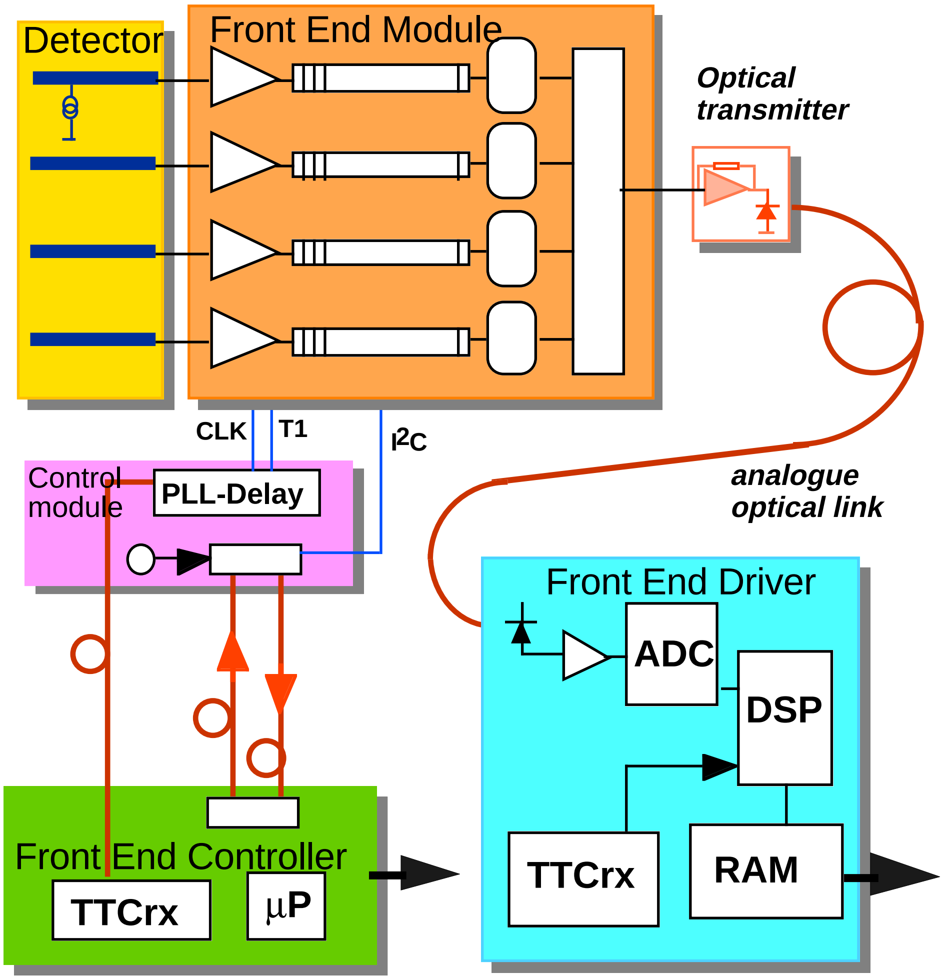

Fig. 1. Simplified schematic of the readout system

1.2 Timescale and constraints

The Technical Design Report for the CMS tracker is expected to be submitted at the end of 1997, allowing production to commence in 1998. It is envisaged that, once approval is given, there will be a gradual ramp-up of manufacturing activity during 1998 as funds become available and deliveries from the first major orders begin. The most urgent electronic elements will be the front end chips, which must be available early to permit hybrid construction and detector module assembly. Subsequently, the remaining internal electronics and optical link components will be required on a large scale. The VME Front End Drivers and Controllers will probably be the last items to be produced in large quantity, although working prototypes will be essential.

In this scenario, large scale production of the optical link may not commence until 1999, or possibly 2000. However, it must be sufficiently well specified as soon as possible in areas where it interacts with the rest of the readout and control system. It must also be defined sufficiently so that a reliable cost estimate can be made and evaluation requirements be clear. This is underway [1.6]. The internal components should be delivered over, at most, a 3-4 year period.

The operating environment is reasonably well defined [1.2] and is expected to present challenges, but not insurmountable obstacles, for optical components. The power consumption of the front end chip (APV6 version) is estimated to be 2.2mW/channel. Within the tracking volume there will be additional power dissipation from ancillary electronics, including transmitters, (~20%?), power losses in cables (10-20%) and silicon detector leakage currents (~10%). With a multiplexing level of 256 detector channels per optical channel, power dissipation of the transmitter and driver of ~30mW/optical channel appears acceptable.

Operation at ~0°C in the vicinity of the silicon detectors and ~18°C in the vicinity of the MSGCs is acceptable. The radiation levels are most severe in the inner layers and 30Mrad dose and 3×10^{14} cm^{-2} charged particle fluence are expected at a radius of about 20cm. Even higher levels will be encountered in the pixel detectors, which is likely to employ the same technology for transmitting data (digital, but packed to gain bandwidth [1.7]).

However the number of fibre channels is so small compared to the microstrip system and the pixel detector will be replaced at least once during its lifetime that this does not seem to motivate special concern.

Space is an important issue. Small volume components are required in several places, especially transmitters mounted inside the tracker, optical connectors throughout the system, including dense multi-fibre connections to VME boards, and optical cables. Although all these require attention, they appear to be well within the practical range from discussions with manufacturers.

The other major constraint is cost. The tracker system is estimated to cost ~90MCHF, of which approximately 40% is in electronics. The two major contributors to the overall cost of the readout system are the front end electronics chips and the optical links.

2. Background to the milestone decision

The motivation for a major decision on the choice of optical technology in mid 1996 was to minimise the cost and resources utilised in developing the system from the prototype to production stage. Despite the fast increasing use of optical fibre transmission, many of the requirements for applications in LHC experiments are uncommon: very high density analogue links, low mass compact transmitter packages, miniaturised connectors in large arrays. Some of the specifications and combinations of them are unique, in particular the high radiation tolerance and high reliability at very low cost. The tight budgetary constraints urge the use of custom developments only where essential.

The novelty of optical communications technology in particle physics, the specialist skills and equipment required and the large scale of the application envisaged mean that a collaboration or partnership with a commercial supplier of packaged components is almost mandatory. However, this is initially expensive because low cost, short distance *analogue* links are not the driving force behind optical transmission systems and present unit costs for small quantities are still high. It was considered unrealistic to evaluate fully a large number of alternative solutions.

The tight construction timescale for LHC experiments meant that an informed selection had to be made before approval of the Technical Design Report since the transmitters, fibre ribbons and connectors form part of a highly integrated tracker system. Mid-1996 was approximately the last date when a major technology choice could be made. Even if the modulator solution is not yet fully prototyped, the several years of R&D effort, to which several groups and companies have contributed, should allow a judgement of whether we can proceed with complete confidence to production in 1998 or 1999. If an alternative to the reflective modulator system is to be selected, enough time must be available to produce prototypes, identify suppliers and establish costings before the Technical Design Report.

The transmitting element is the most crucial component in the system and a packaged version suitable for installation inside the tracking volume is required. This is where most of the emphasis has so far been placed, while concurrently gradually establishing the contacts with suppliers of fibres, connectors and assembly and testing facilities. Therefore the major choice was to identify the most promising transmitter technology and, having verified that the final system cost is expected to be in an acceptable range, commit ourselves fully to this solution and avoid competition between alternatives.

Having made this choice, a meaningful specification of the link can be completed which can then be presented to manufacturers as a working definition of the CMS system. Interactions with several suppliers have been in hand for some considerable time but these can now be extended to other potential sources.

3. Technical decision elements

The generic optical link being considered in this paper is schematised in Fig. 2. A transmitter (Tx) situated at the front end converts the electrical detector signal into light and sends it through a short length of optical fibre (typically 100m) to the readout station. There, a receiver device (Rx) converts the optical signal back to electrical and transfers it to the readout electronics. Optical connectors allow the system to be easily installed and maintained while making the individual link elements factory testable. Altogether, six components require evaluation: two electrical (driver, amplifier), two optical (connector, fibre) and two opto-electronic (Tx, Rx).

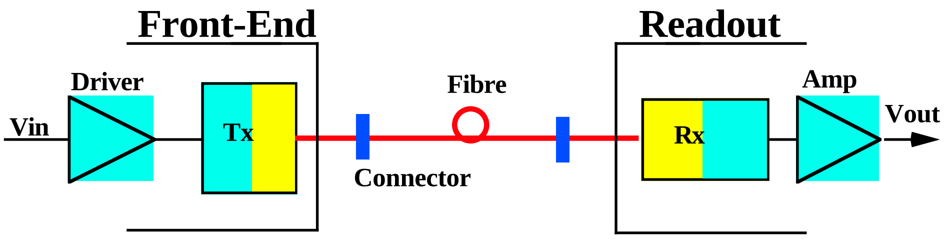

Fig. 2. Generic optical link

Due to the stringent and partly LHC specific requirements of the front end link side, most emphasis in this document will be placed on the transmitter characteristics of the analogue readout links. It should however be remembered that control and timing distribution links will also have to be installed, with receivers and amplifiers at the front end. This development (a few thousand links) will greatly benefit from the progress made on the readout side and will be the subject of another publication.

3.1 Two technologies: direct or external modulation

Two approaches are commonly used to generate modulated optical signals: direct intensity modulation of an active light emitter (laser or LED) or external modulation of a CW beam with an electro-optic modulator. The latter technique is implemented when high performance is required (high speed, high linearity, low chirp) and cost not too critical. In the past years, the boundary between the two architectures has moved to ever higher performance systems, with steadily improving directly modulated laser specifications. Monolithically integrated lasers and modulators for high speed low chirp transmission systems have also appeared on the market. Both direct and external modulation approaches have been investigated in view of the CMS application, as shown in Fig. 3. The choice between the two is the object of the milestone discussed in this document.

In the *direct modulation* architecture (Fig. 3.a), the electro-optic transmitter is directly linked to a PIN photodiode receiver. This architectural simplicity must be traded off against the risk of putting an active light emitter at the front-end (see appendix). The preference for a laser Transmitter to an LED source is essentially motivated by the advantageous optical to electrical power ratio of the laser. This is of primary importance in an analogue transmission system where the signal to noise ratio must be optimised over a broad dynamic range, given a tight electrical power budget at the front end. The strong market demand for more efficient lasers led to the commercial introduction in the past two years of low threshold high reliability devices compatible with our requirements. The pre-production units tested under neutron irradiation (see section 3.3) indeed demonstrated good radiation resistance.

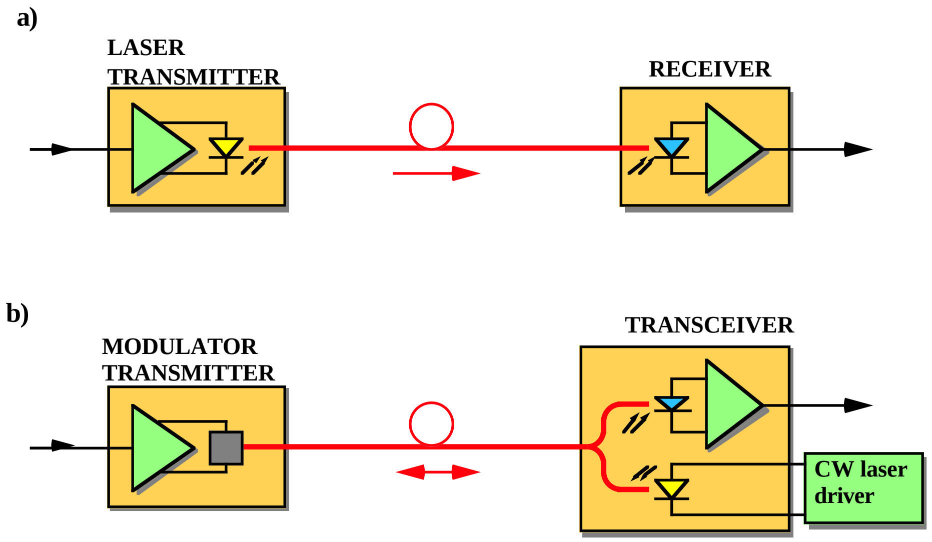

Fig. 3. Two investigated approaches for data transmission: a) direct modulation, b) external reflection modulation

In the *external modulation* architecture (Fig. 3.b), a passive component is placed at the front end with a corresponding advantage in terms of power dissipation and potential link reliability. In the case of a reflective link, however, this is obtained at the cost of a technologically complex element at the readout end of the link (the so-called transceiver), which performs CW light generation, fanning, splitting and reception functions. Feasibility has however been demonstrated in the framework of the RD23 project [2.1, 2.2] and a precise cost estimate has been established.

The original system proposed for CMS was developed by the RD-23 collaboration and is based on the external modulation approach (see section 3.2.2 for technical details). The use of a reflective modulator offers significant advantages but leads to a quite complex system. Moreover, the devices required, both modulator and transceiver, are not commercial developments but custom built for this application, which may be unique. Relatively few alternative transmitters are readily available which could meet CMS requirements, although there would be a clear benefit in taking advantage of commercial developments if possible. Within RD23 several options have been examined for feasibility (see Annex A): Mach-Zehnder interferometric waveguide modulators on lithium niobate, LEDs and semiconductor lasers. The most promising are directly modulated laser diodes, where the last few years have seen impressive improvements in performance, which continue as quantum well devices exhibiting further dramatic gains become more common [3.1-3.3]. Until recently lasers appeared to have disadvantages of relatively high power dissipation, poor radiation hardness and low reliability compared to the LHC requirements [3.4]. However a number of low threshold current semiconductor lasers have now been evaluated, for some of which mean time to failures in excess of 10^6 hours have been measured by the manufacturers. In general it appears that the trend towards more reliable, lower power and, ultimately, low cost semiconductor lasers will continue, driven by applications in the telecom and datacom markets (for both analogue and digital data transmission). Also, the operation of lasers at temperatures lower than ambient will improve their reliability and lower their quiescent power dissipation.

3.2 Performance

Due to the unequal level of investigation of both types of directly or externally modulated systems, we present in this section experimental results which are not fully comparable in terms of completeness. The experimental setups are schematised in Fig. 4.

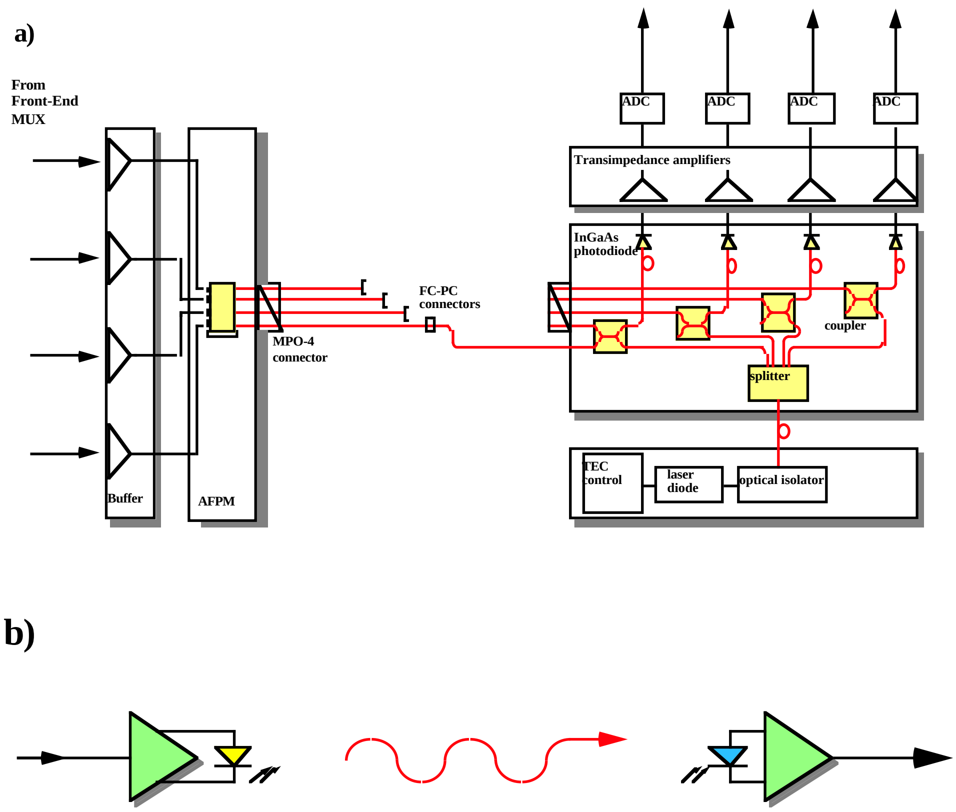

Fig. 4 . Experimental set-ups. a) AFPM based link, b) laser transmitter

For the *directly modulated*, laser based link, we only show results obtained with laser die emitting in air (Fig. 4.b) in direction of a PIN photodiode and amplifier. We thus essentially characterise the transmitter element of the link, and assume no major surprise will be found when constructing a complete fibre link. This of course will need to be carefully checked in the future. Potential industrial partners have been identified with packaging technologies that would require only minimal customisation to satisfy our requirements. Tests on packaged and pigtailed modules are currently under way.

In the *externally modulated* case, we present results of full link performance including packaged modulator, fibre, connectors and transceiver (Fig. 4.a) The 4 channel custom package of the modulator array is described in [3.5].

3.2.1 Directly modulated, laser based link

Four different commercially available laser types covering a broad spectrum of applications have been evaluated, all of them based on Quantum Well active regions:

a) 850nm Vertical Cavity Surface Emitting Laser (VCSEL) arrays

b) 980nm high power edge emitters

c) 1300nm edge emitting laser arrays

d) 1300nm edge emitters

a) VCSELs have recently appeared on the market in the form of arrays emitting at 850nm or 980nm into multimode fibre. Their very small active area (typical pixel diameters are on the order of 10μm) makes them excellent candidates for low power dissipation (typ. 1mA threshold) and possibly indicates good radiation resistance. Their manufacturability as dense 2D arrays also makes them potentially cheap and on-wafer testable. However, most devices produced commercially show poor linearity and despite promising indications [3.6,3.7], no field record attests high reliability to date.

b) The evaluated 980nm high power edge emitters are almost exclusively used as pump lasers for Er-doped fibre amplifiers. They feature impressive reliability when operated at low power (estimated from data to be better than 100 FITs [3.8]) and arrays have been packaged into 4-way multimode modules [3.9] Only small quantities of these lasers are produced annually, making the CMS projected quantities attractive to the particular manufacturer approached in this case. Close contacts have been established and could be re-activated should a laser die custom development become necessary.

c) and d) 1300nm edge emitters are extensively used in the telecom network and present a more advantageous power/price ratio than their 1550nm counterparts. They usually feature excellent linearity and good reliability (typically 1000 FITs) with low threshold devices (I_{th} < 10mA) now available on the market. They are usually packaged into modules with single mode fibre pigtails, which however makes them more expensive than shorter wavelength datacom multimode products.

Altogether, over 70 lasers have been characterised. We present in this section results obtained with type d lasers only, as their characteristics best match our current view of the readout system architecture in terms of performance, wavelength, type of optical fibre, modularity, package etc....[3.10,1.6]. Other laser types may present better characteristics in particular respects. A detailed comparative report will be published elsewhere [3.7].

Figure 5.a shows a typical laser light power vs. driving current (L-I) characteristic above threshold. The threshold current is defined as the point above which stimulated emission occurs. The efficiency is defined as the slope of the output characteristic above threshold. This L-I characteristic clearly indicates suitability for analogue modulation: a broad linear range well adapted to a unipolar signal drive and high optical output power levels (milliwatts in air, hundreds of microwatts in fibre). Threshold currents below 10 mA at room temperature (for ~1V forward voltage drop) imply that quiescent power dissipation around 10mW might be achievable. Figure 5.b shows the laser signal to noise ratio measured in a 10Hz-30MHz bandwidth. The noise was computed as the ac coupled root-mean-square value of around 10 consecutive 10ms oscilloscope traces, after subtraction of the photodiode, amplifier and oscilloscope contributions. The signal was simply taken as the dc component of the output. The dynamic range required for the tracker should clearly be achieved with a comfortable margin, even keeping in mind the fact that noise measurements on fibre links may yield different results than those shown.

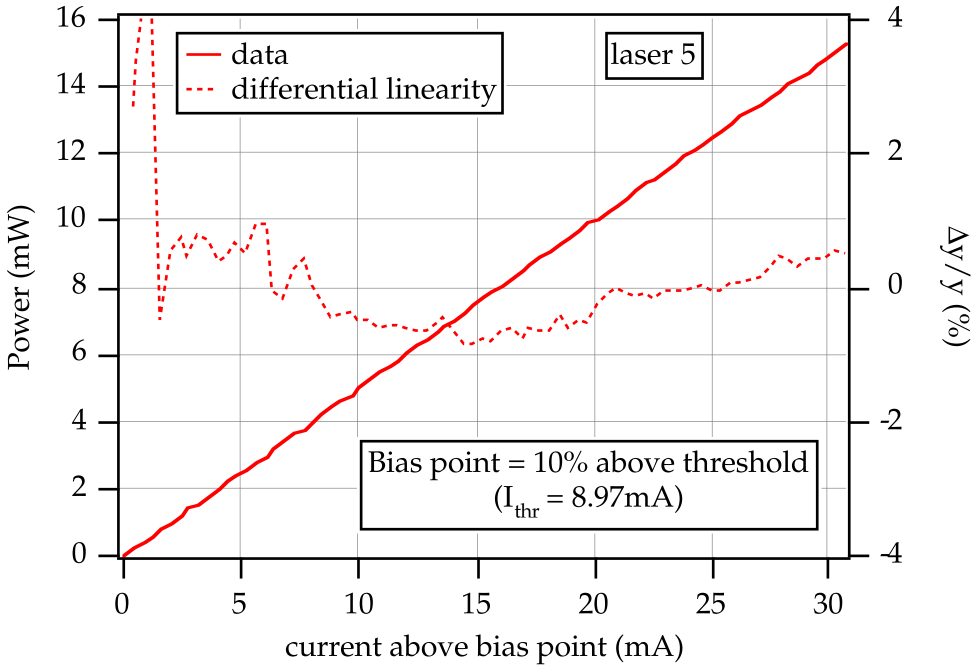

Fig. 5 a) L-I characteristic and differential linearity of laser type (d) above threshold

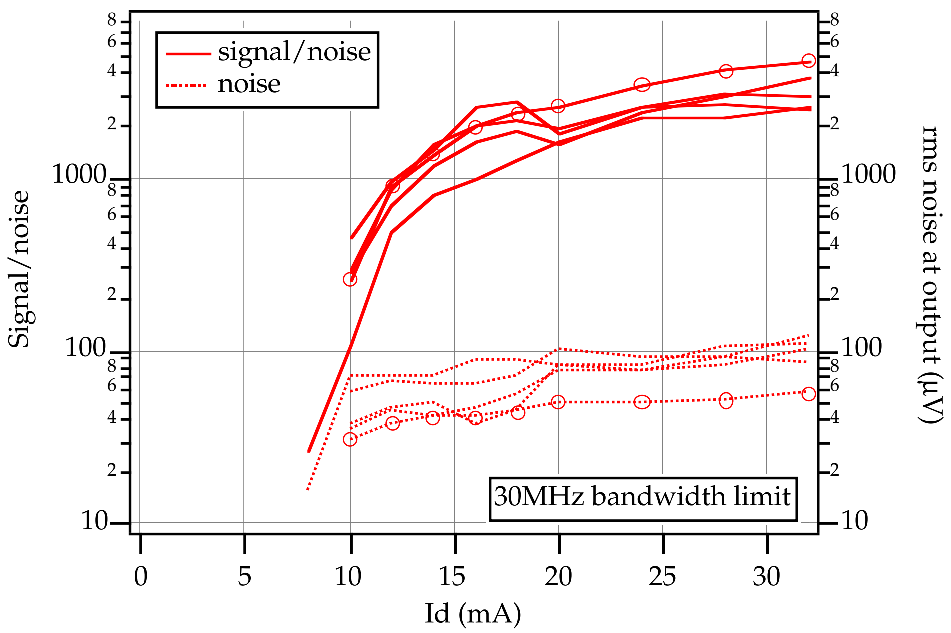

Fig. 5 b) Noise and signal to noise ratio measured in lasers before irradiation.

3.2.2 Externally modulated, modulator based link

Over 48 optical channels have been thoroughly characterised and tested by four groups within the RD23 collaboration. Detailed results can be found in the RD23 status reports [2.1, 2.2] and references therein.

Figure 6 plots a typical modulator reflectance characteristic. The S-shaped curve is best matched to bipolar analogue modulation around the inflexion point. A unipolar mode of operation as foreseen in the CMS tracker case would be possible, but would cause either the loss of almost half of the input range, or high distortion levels to the small detector signals. Typically, optical signal powers in the microwatts range arrive at the readout end, making the link power budget extremely tight; at most two connectorised optical breakpoints can be foreseen between front- and back-end. Measurements indicate that at least a 100:1 peak signal to rms noise ratio should be achievable on all channels, but with little margin and some remaining uncertainty linked to the choice of Fabry-Perot or DFB CW laser in the transceiver. Being a passive element, the modulator electrical power dissipation is extremely small. It is determined by the CW photocurrent flowing across the reverse biased junction and amounts to a few hundred microwatts per optical channel.

Setting the priority in having a passive component at the front end implies that a more complex element needs to be placed at the back end of the link. The transceiver combines functions such as CW light generation (laser), fanning and splitting (passive waveguide component) and light reception (PIN photodiode). Eight 8-way transceiver modules must fit on the Front End Driver (FED) board, meeting stringent size requirements. Estimates for one 8-way module range from 200mm by 50mm down to 55mm by 13mm. The manufacture of this component in its most compact form still presents a technological challenge, particularly from the packaging/hybridisation point of view.

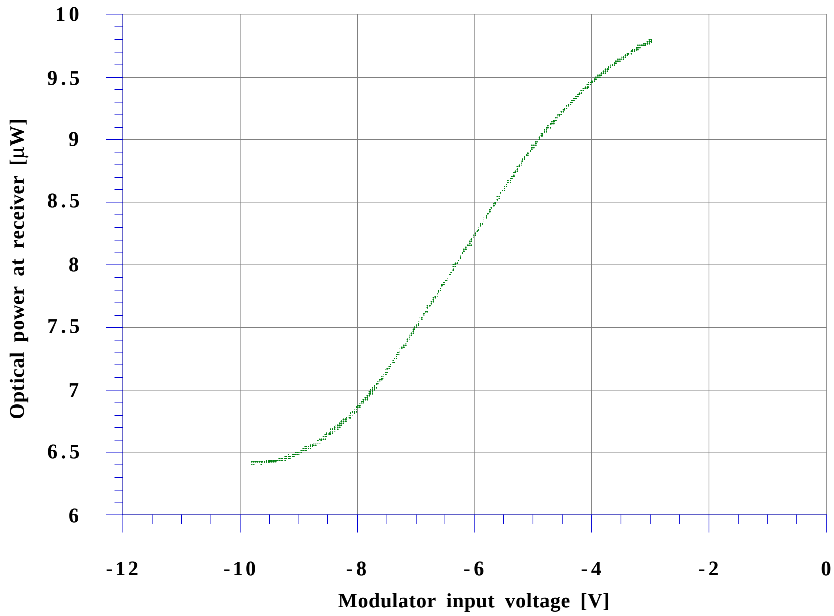

Fig. 6. Reflectance characteristic of AFP Modulator transmitter

3.3 Radiation resistance

Both packaged and unpackaged modulators, but only bare laser die have been subjected to γ and neutron irradiation tests. The same measurement schemes as shown in Fig. 4 have been used, whereas in the laser test case, the photodiodes (which had to be inside the irradiation cell to monitor the optical power emitted in air) were appropriately shielded.

3.3.1 Laser transmitter

Only lasers of type b (see section 3.2.1) were tested under ^{60}Co γ ray irradiation. Within a few percent accuracy, no laser chip degradation was observed and no correlation could be found between threshold and dose or between efficiency and dose.

Whereas γ rays generally only ionise the laser material, neutron irradiation frequently creates lattice damage and hence increases the number of non-radiative centres in the active region of the lasers. Neutron tests are thus expected to be much more difficult to pass than γ tests. All four laser types were irradiated with 6MeV neutrons up to a fluence of $1.1*10^{14}$ n/cm^2. We show results for type d only, but note that all lasers of all types survived the test and qualitatively showed similar behaviours. Details will be published in [3.11].

Figures 7.a and 7.b show the on line measurements of threshold and efficiency as a function of time. A quasi-linear threshold current increase followed by some annealing is clearly visible. The efficiency plots are more difficult to interpret, as they are dependent on the evolution of both the laser and the receiver characteristics.

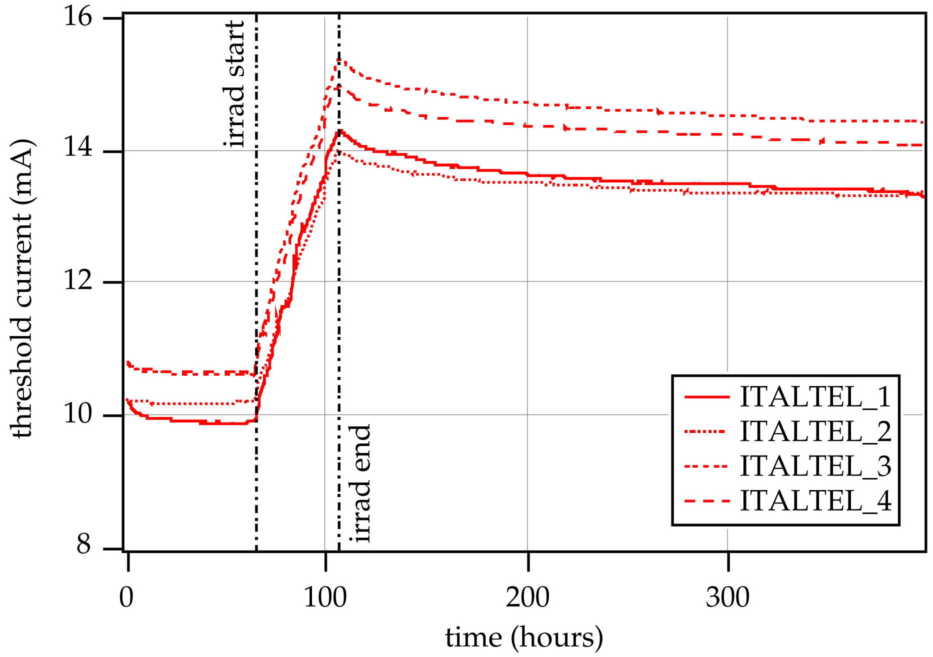

Fig. 7 a) Laser threshold current measured during the irradiation test. The threshold was defined at the point of the transfer characteristic where the output voltage interpolated to 0.05V.

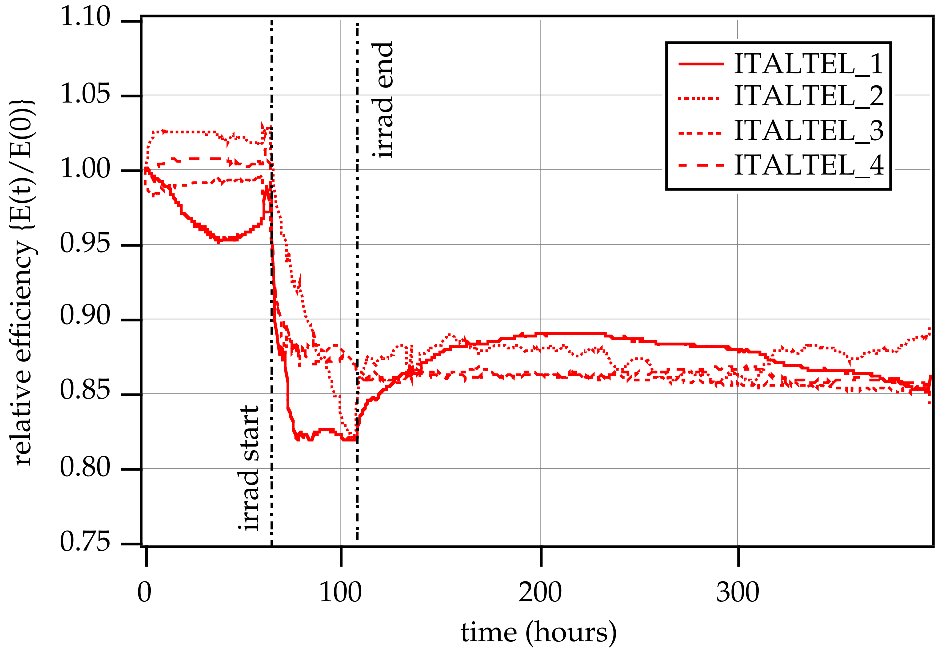

Fig. 7 b) Laser efficiency relative to the start of the test, where efficiency was the gradient of the transfer characteristic at an output voltage interpolated to 0.2V.

After the irradiated devices were recovered from the radiation source, they were characterised again in the laboratory as shown in Fig. 8.

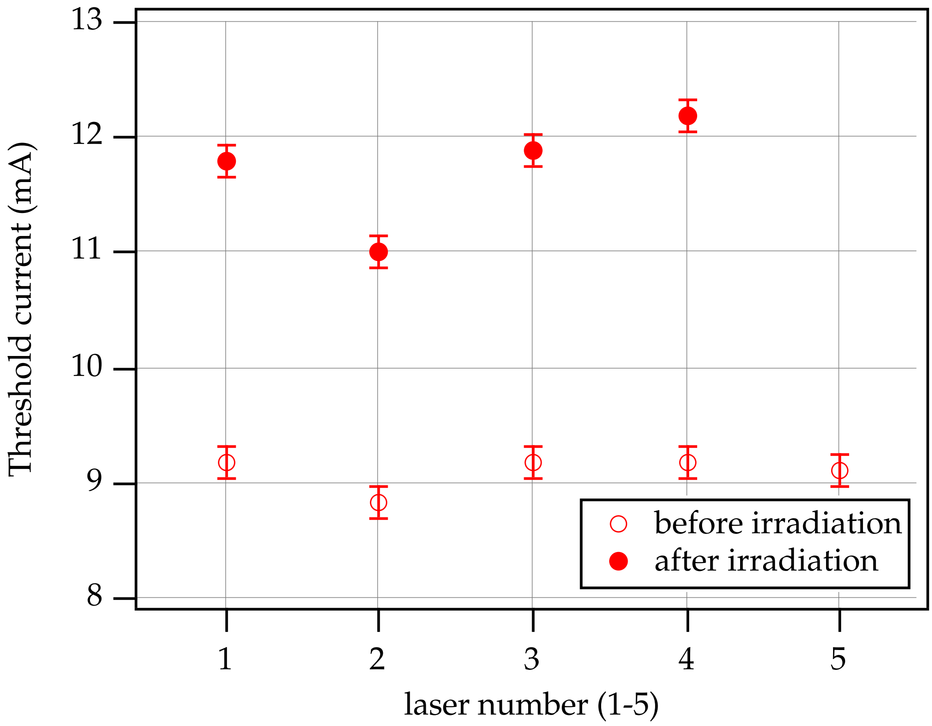

Fig. 8 a) Threshold currents before and after irradiation for lasers of type d). Threshold current in this plot is defined as the peak position in the second derivative of the transfer characteristic. Laser number 5 was not irradiated.

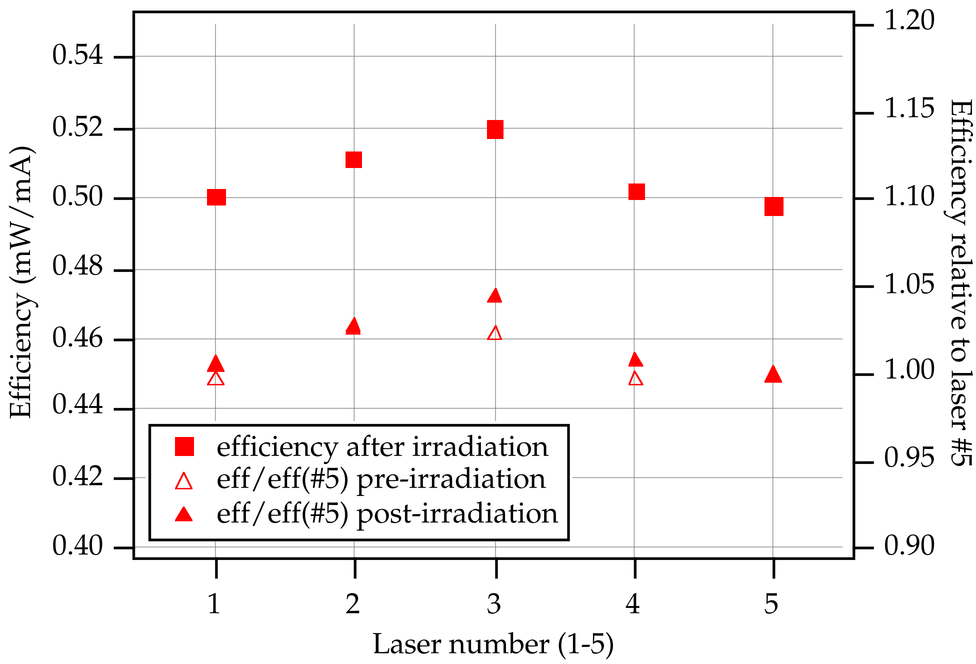

Fig. 8 b) Efficiency (at 22C) from linear fit to transfer characteristics above threshold for lasers of type d) after irradiation. No absolute values for efficiency were available before irradiation therefore the efficiency calculated from the data sheet results normalised to laser #5 was used for comparison with the post irradiation results. Since laser number 5 was not irradiated the results suggest that no radiation damage to the efficiency occurred.

The increase in the threshold current due to radiation damage was confirmed. In the laboratory measurements, in contrast to the values measured during irradiation, the laser efficiency was not significantly lower than that determined from the data-sheet plots for the lasers prior to irradiation. Laser #5 was not irradiated and the relative efficiencies of the irradiated lasers compared to laser #5 were very similar before and after irradiation. The degradation in the laser efficiency observed during irradiation was therefore concluded to be mainly due to radiation induced damage of the photodiode. Dosimeter data indicates a 10^{11} n/cm^2 fluence at the detector.

The signal to noise ratio for the lasers was not significantly degraded by radiation damage.

3.3.2 Modulator transmitter

Bare modulator chips irradiated with both neutrons and γs showed no change in their optical characteristics measured before and after irradiation at doses and fluences in excess of 10 Mrad and 10^{14} n/cm^2 (1 MeV). Similarly, complete systems based on packaged modulator units monitored on line show no correlation with dose. Figure 9 shows the link transfer function measured during γ tests (Fig. 9.a), as well as the variation in inflexion point position and slope (link gain) as a function of time (Fig. 9.b). The dose rate was ~100krad/h yielding an accumulated dose in excess of 10 Mrad. The observed increase in gain is not representative of an intrinsic AFPM response to irradiation, as other monitored channels show a gain decrease in the same time interval. Such gain fluctuations are well within the variations observed when a link is monitored during several hundreds of hours [3.12]. Results of neutron and proton tests are reported in [3.13]. Degradation of the link gain due to a $5x10^{14}$n/cm^2 (1MeV) fluence is less than ~20% for all measured channels. For the proton irradiation ($6x10^{13}$ p/cm^2), measured degradation on the same devices which had been previously damaged by neutrons was less than ~30 %.

Despite this impressive radiation resistance we note a significant dark current increase under both γ and heavy particle irradiation. In some devices this dark current remained well below the photocurrent levels and eventually recovered when stopping the irradiation. In others it steadily increased even when the sources were turned off and eventually reached levels comparable to the photocurrent. This latter effect is attributed to a defective polyimide passivation layer, and no clear processing route has been identified to this date, that would allow one to confidently state that the problem has been solved.

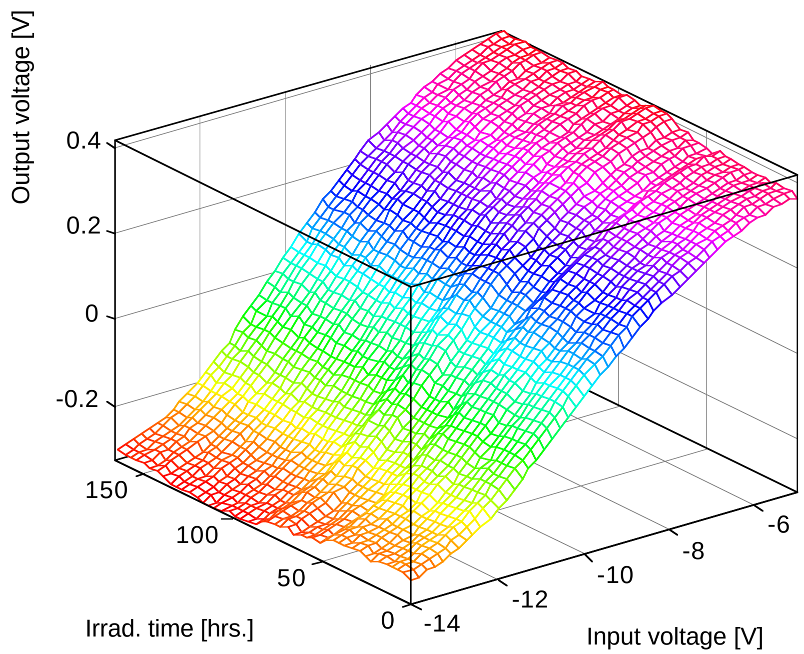

Fig. 9 a) AFPM based link transfer function during γ irradiation test

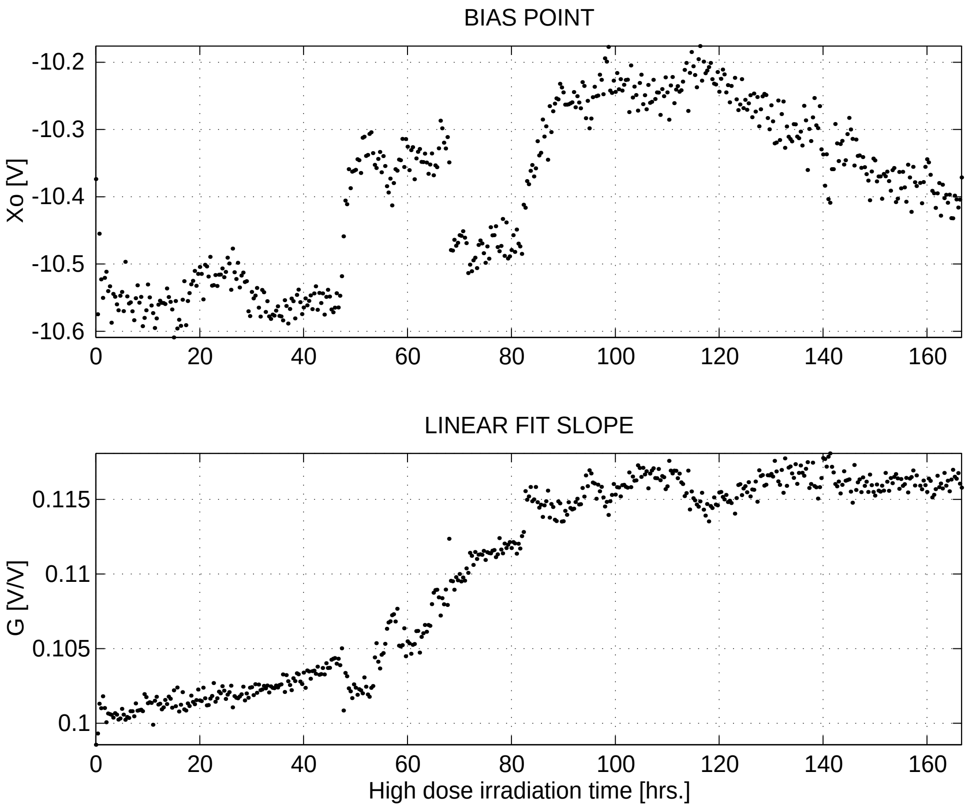

Fig. 9 b) AFPM based link bias point and gain vs time during γ irradiation test

3.4 Reliability considerations

The reliability issue is particularly relevant for the optical link transmitters when one considers the difficulty of accessing and replacing front end components. The operational lifetime of an optoelectronic transmitter is usually determined for a 50% drop in output signal at constant drive conditions. It shows an exponential dependence on junction temperature.

Laser diode chips nowadays exhibit mean time to failure values of a few 10^6 hours. The manufacturer of die d) indicates a random failure rate of less than 870 FITs with a confidence level of 60% at 55˚C junction temperature. Assuming an LHC operational lifetime of 40000 hours, this would correspond to a failure probability of 3.6% after 10 calendar years (not taking into account the much smaller wearout failure rate of 75 FITs after 5 years).

Electro-optic *modulator* chips are structurally similar to photodiodes so that one might extrapolate MTTF values in excess of 10^9 hours, provided similar chip processing techniques were used in both cases.

Good die reliability may however easily be degraded by the package being used, and great care should be taken when developing semi-custom packages.

The reliability data for commercially available devices is typically based both on measurements of several thousand units over several thousand hours and on the field record. Despite noteworthy efforts [3.14], it is unlikely that a similar knowledge base can be gained on the semi-custom or custom packaged devices that will be used in the LHC detectors. It may thus be essential to rely on the known properties of commercial components and on established packaging techniques.

3.5 Required developments to reach manufacturability

Whichever optical link technology is chosen for the CMS tracker, significant developments are required on both transmitter and receiver sides to reach manufacturability. We do not consider here the developments that will be similar in both cases, such as hybrids, patch panels, timing and control distribution network etc...

If a *directly modulated* laser based solution is chosen, commercial laser and photodiode die may be used, provided it passes irradiation and performance tests. In any case, new industrial programmes must be launched to develop semi-custom packages for the transmitters and eventually also for the receivers. Discrete laser drivers and PIN receivers must be designed (based on available ICs if possible), built and tested to distribute evaluation links to the CMS community. Performance of complete fibre links must be characterised. Integrated laser drivers must be designed in rad hard technology to implement the final system.

The development time is estimated as one year to demonstrate feasibility and produce first prototypes, plus one year to reach pre-production. No safety margin is included in this number.

If an *externally modulated* solution is preferred, the developments launched by the RD23 collaboration will be continued with the same industrial partners: on the transmitter side a stable die fabrication process must be re-established, and the custom developed package must be refined to meet high volume manufacturability requirements. On the transceiver side, a compact prototype must be produced to confirm feasibility and cost studies. An integrated modulator driver must be designed in rad-hard technology. Most of the testing work is complete and evaluation links could soon be delivered to the community, provided transmitters are delivered by the industrial partner. However, based on our experience with this particular company and due to our single customer situation, the time scales to pre-production are clearly dominated by their share of the work.

We estimate that at least two years of further developments will be required with one industrial partner for transmitter and one for transceiver.

4. Financial decision elements

We differentiate between two financial elements: the cost of the industrial development programmes still required to reach manufacturability and the purchasing cost of optical links in large quantity once production will have started.

4.1 Development cost

The estimated development costs have been discussed in closed sessions [4.1]. Quoted figures were based on previous experience with industrial partners in the framework of the RD23 collaboration. They were not based on formal proposals, but relied on numbers which appeared on numerous occasions, in particular at meetings and on similar project proposals. The modulator based link development costs appeared ~50% higher than the laser based ones.

4.2 Purchasing cost

In the framework of the RD23 collaboration, a detailed cost model for the 8 way *modulator based* link has been constructed. It relies exclusively on written industrial quotations for modulators, transceivers, connectors, fibre ribbon and cable. It yields a cost of ~240 SF/fibre excluding driving and receiving electronics.

CMS Target	150 SF/Link
RD23 achieved	240 SF/Link
Hitachi 12 way parallel interconnect	330 SF/Link (1996)
Motorola 10 way parallel Optobus	100$/Gbit/s (forecast)
	100SF/Link assuming 800Mb/s/link

If we compare the 240SF/fibre figure with announced costs of commercial laser based parallel links, we note that despite the mismatch between CMS targeted and RD23 achieved costs, the internally quoted numbers are not unreasonably different from the commercial ones.

In the case of the *laser based* link, a reliable cost estimate will only be available once a detailed feasibility study will have been undertaken. In any case, the inherent simplicity of the point to point architecture should tend to make it cheaper than a modulator based reflective link. Also, a competitive situation between two vendors and a multi-application market will significantly increase our level of confidence in quoted costs.

5. Choice of optical technology

The milestone decision for the CMS tracker is to select the transmitter technology on which to focus future efforts. The options have been narrowed to two alternatives, modulators and lasers, whose main advantages and drawbacks have been analysed in the previous chapters. The following sections summarise the considerations for the choice of optical technology, the milestone decision, and finally an overview of other relevant issues.

5.1 Summary of considerations for choice - Milestone decision

The *reflective modulator system* has been thoroughly investigated over several years of development in the RD23 project. Although the investment costs, which were shared with the manufacturer, have been considerable they should probably be compared to other sophisticated technological areas and a great deal of expertise and tools have been acquired as well as important industrial contacts established. Radiation hard low power modulator transmitters have been designed, fabricated and characterised under realistic operating conditions. However, only a few working prototype links exist and CMS would be the unique customer of a single manufacturer. Significant further investment would be required to develop transmitters and receivers in a form suitable for large scale production.

Of the two alternatives, the modulator system is undoubtedly more complex and some issues still give cause for concern: the dynamic range is adequate but fundamentally limited by noise sources intrinsic to the reflective optical system, few connector breakpoints are permitted, the operational wavelength must be matched to the modulator and adjustment of the modulator bias voltage is likely to be required at the individual module level, among other issues. As further experience is gained improvements can be expected. However it has become evident that the modulators are still challenging to manufacture. The transceiver is practical but the most costly element. Overall the system is considered feasible but more costly than the CMS budgetary target and there is a high risk factor attached.

The *laser based solution* is attractive because there have been dramatic developments over last decade or so which are motivated by strong commercial considerations, particularly the drive towards more reliable, longer distance telecommunication applications and, potentially, shorter distance fibre to the home and computer links. Much new information on laser diodes has been gathered in the last year, with very positive results, so although laser links have not yet been evaluated in the same detail as modulators there is a strong incentive to continue. Of special importance has been the evaluation of several low threshold current devices which are compatible with the electrical power dissipation requirements of the tracker. Some of them are known, from manufacturer's information, to have ultra-high reliability. Since it is unlikely that any system (of any type) developed for particle physics could accumulate sufficient statistics for comparison, this is highly relevant.

The lasers which have been tested have different structures, all of the quantum well type, and operate at different wavelengths. In each case the achievable dynamic range looks much larger than could be reached with modulators. The radiation tolerance demonstrated is impressive and, since it is exhibited in all devices studied, could be a fundamental feature. The basic physics and design of the modern semiconductor laser diode suggests good reasons why this should be so and supports the conclusion that further developments of lower electrical power lasers will not worsen the radiation hardness and could even improve it. The laser based system is simpler and can take advantage of assembly techniques already investigated for the transceiver of the modulator system. The choice of wavelength is non-critical and the receiver is simplified considerably. There are multiple sources of laser die and probably packaged devices; discussions are under way with two potential vendors at present. Overall the system is expected to have a lower risk.

Based on the arguments presented in this note, we have reached the conclusion that the CMS tracker readout system should be based on optical links using directly modulated lasers as transmitters. The final decisions on specific components to be used will be agreed in conjunction with manufacturers. For this purpose, as well as to complete the definition of the system, a detailed specification of the optical link is in preparation.

5.2 Other issues

Among the questions not yet fully answered, the laser based link cost is the most important. From experience of many projects which require industrial collaboration, cost estimates may not be reliable until prototyping has been under way for some time and unexpected problems have been brought to light. This is a particular concern when new technologies are involved. However, the likely packaged laser module is rather similar but less complex than the transceiver. Some transceiver prototyping has been undertaken and a cost analysis of three different designs carried out over a six months period. The cost of the modulator link is dominated by the transceiver which in turn is dominated by "materials"; the CW laser and passive waveguide components are important contributors to this.

In the case of a packaged laser transmitter module, with typically 4 laser die per unit, the assembly would be similar to the transceiver in many ways but should be much simpler. As with the transceiver, alignment of the emitters with the fibres is one of the key points. The receiver is trivial in comparison, involving only pigtailed photodiodes with no critical alignment required. Thus the link cost is now dominated by the transmitter and fibre and connector costs can be reliably estimated from commercial information obtained for the modulator system. The first provisional estimate of the link cost which has been obtained from the transceiver manufacturer is slightly higher than the CMS target. However, it is based on present day laser costs which are anticipated to continue to fall considerably during the next few years. The "commercial risk" or profit element is not well known to us but preliminary discussions with a second commercial source suggest that a lower price can be obtained. Further discussions are now urgently being planned as the risk factor for cost can probably be reduced by vendor competition.

An important point to be borne in mind is that, unlike the modulator, the custom laser transmitter is rather similar to transmitters which are required for other commercial applications which are growing rapidly. At present, the size of our system is still of significant commercial interest. Over the lifetime of the project it should gradually be dwarfed by commercial applications.

There is, as yet, little experience in the HEP community in operating a directly modulated laser link. In principle, there might be technical problems which have not yet become visible. This is considered unlikely as a consequence of experience with the modulator link where some of the issues are virtually identical (e.g. fibres, connectors, characterisation methods). The laser system is much more tolerant of typical concerns, such as temperature in the transmitter region or laser spectral variation. Unexpected optical power changes should easily be compensated for by calibration, which will be a regular part of system operation, and there is large margin of spare optical power.

The laser link is applicable in several other sub-systems, e.g. the preshower and pixel system, for digital or analogue transmission. Except for the pixel detector, most other applications should present a less hostile environment than the tracker. In the innermost radii the charge particle fluences exceed those to which the lasers have yet been irradiated. However, it seems likely from the data so far that, even without further improvements, the lasers could already tolerate the maximum realistic fluences of $5\text{-}10 \times 10^{14} cm^{-2}$ to be encountered. Tests will be carried out later this year to verify this, and the influence of radiation damage on reliability will have to be assessed.

One concern which is sometimes expressed is that a drawback of a rapidly evolving field where new, more powerful and cheaper products are developed is that today’s choice may soon become obsolete. This is not unique to the optical link but merits consideration. It applies particularly and perhaps solely to the laser. In view of the fact that there are multiple vendors of similar performance lasers with equivalent die layout the main concern is potential radiation tolerance. As explained earlier, we have been encouraged that hardness is not confined to only a few lasers and appears to be intrinsic to the devices. However, it will require to be monitored and purchases carefully planned with manufacturers so that alternative die can be utilised with confidence.

6. Future development objectives

Following the endorsement of the choice of technology by the CMS collaboration, the link specification documents will be finalised and distributed to those concerned in CMS as well as to the industrial partners involved in the link developments.

Discussions are currently taking place to define the industrial programmes that will lead to the delivery of packaged multiway transmitters and receivers. No detailed development schedule will be given before these discussions are concluded, but we present below a tentative list of objectives for the coming two years:

<u>Components availability</u>

Tx, Rx 1 way packages	Q4 96
Link demonstrator, 1way	Q4 96 (CERN)
	Q2 97 (CMS)
Tx, Rx 4 way packages	Q4 97
Link demonstrator, 4way	Q4 97 (CERN)
	Q2 98 (CMS)

<u>Tests</u>

Neutron Irradiation	Q4 96
Gamma Irradiation	Q2 97
Beam Test	Q3 97
Proton Irradiation	date to be defined

As we improve our understanding of electro-optic components, we become increasingly aware of the system aspects of the CMS readout and control network. One of the most positive consequences of a clear choice of optical technology is to allow us to address system related issues on a firm basis. We thus expect that rapid progress will now be made in the definition of the readout and control architecture, together with the physical layout of the optical system.

7. Conclusions

In this note, the most relevant factors (performance, availability, cost, etc.) of the possible technologies for the CMS tracker optical links have been analysed. The use of semiconductor laser diodes with the light output power directly modulated in response to amplified detector signals, is recommended for optical transmission of analogue data from the CMS tracker. This technology is preferred to others which have been considered for reasons explained above and is considered to represent the lowest risk and most cost effective solution matching the CMS readout system. It is also expected to be readily applicable to the transmission of digital signals both to and from the interior of the tracker.

Annex A

Optical links and relationship with RD23 - Historical background

The optical link developments for CMS are the direct outcome of the RD23 project; present members of CMS and ATLAS have actively contributed to the programme from its inception. The RD23 project was approved by the DRDC in February 1992 (the P31 [A.1] proposal had been submitted in Oct. 1991). The goal was to develop rad-hard, low power dissipation fibreoptic links for analogue signal transfer in the front-ends of tracking detectors at LHC. The proposed technique was based on external modulation, and the project was initially targeted at the development of electro-optic intensity modulators as transmitters. These are essentially passive devices; with respect to active emitters (LEDs or laser diodes), this approach was considered at that time to offer potentially great advantages in terms of power dissipation and radiation hardness. Other groups were already investigating direct modulation of LEDs for digital applications, while laser diodes commercially available at that time were found to be too expensive and of uncertain long-term reliability. The collaboration focused the effort on modulators, as it did not have the resources needed to pursue additional lines of activity.

Two technologies were initially investigated:

- Mach-Zehnder interferometric modulators (MZM) on lithium niobate. This technology of waveguide devices was well established since decades with single-channel MZMs being commercially available from several manufacturers;

- III-V semiconductor multiple-quantum-well (MQW) asymmetric Fabry-Perot (AFPM) reflective modulators. The MQW technology (also adopted for PIN diodes and laser diodes) was still "young" but the AFPM devices offered the potential advantage of leading to relatively inexpensive volume production.

The radiation hardness of various lithium niobate devices had already been investigated by several groups. The intrinsic features of MQW structures, as well as the results of very preliminary neutron irradiation tests, allowed to expect good radiation harness properties.

The industrial partner responsible for modulator developments was a European company of established reputation which had in-house capabilities for both technologies.

The first RD23 status report was presented in Aug. 1993 [A.2]. Prototypes of 16-channel arrays of lithium niobate MZMs had been developed and successfully tested. However, this approach was found to be difficult to scale down to the required size and too expensive on account of the complexity of fibre pigtailing (e.g. polarisation maintaining input fibres) and high laser power required. Cost reduction could only be achieved by increasing the number of channels in the MZM array; however, constraints on detector modularity showed that arrays of more than 8 channels could not be used efficiently.

Prototype 4-channel arrays of AFPM reflective modulators had also been developed and tested. Although these devices were far from being optimised, both in material structure and in packaging (micro-lens coupling to fibres), the performance was very close to matching the requirements. Preliminary results from neutron irradiation showed that AFPM devices were rad-hard.

The RD23 activity in the following year was therefore focused on the optimisation of the package of AFPM devices. Moreover, the development study of a transceiver for the readout end of the link was also initiated (the transceiver consists of arrays of CW lasers, splitters, couplers and PIN diodes).

The second status report was presented in Oct. 1994 [2.1]. The overall link performance had been measured in beam tests of Si microstrip detectors with the APV3 front-end chip, using a transceiver made up of discrete components. A much improved modulator package, with butt-coupled fibres and miniature size suitable for LHC detectors, had been developed and tested in the lab. Results of extensive γ irradiation tests on optical fibres were shown. The RD23 work programme for the following year was targeted at the optimisation of MQW structures (wafer growth and processing) and to the assessment of technologies suitable for the production of compact hybrid transceivers.

The third status report was presented in Oct. 1995 [2.2]. The new AFPM structures gave somewhat disappointing results, with a modulation depth lower than expected. The reasons for the poor performance were not fully understood. On the other hand, good progress was reported on the optimisation of the package, which could be considered quite close to the final version. For the hybrid transceiver, a glass-on-silicon technology, available from a major manufacturer of components for telecom applications, had been identified and prototypes of splitter/coupler arrays were being developed.

At this stage of developments, detailed and realistic cost estimates for the modulator-based configuration showed that the overall cost might be some 50% higher than the target figures for CMS. This problem, together with the technical difficulties found in the optimisation of AFPM modulators (a full custom development) and the risk inherent to basically single-source availability, prompted us to look into alternative solutions.

Considerable advances had been recently made in MQW laser diodes, with increasingly lower thresholds and higher coupling efficiency. Several products, in the form of discrete devices and arrays, had been introduced in the market place. Thus, in the work programme proposed in the '95 status report, we decided to include an investigation of laser diodes of various types. This became possible following a substantial increase in the strength of the team involved in the optical links developments. The major issues were power dissipation and radiation hardness.

In parallel with progress in RD23, there has been evolution of the CMS tracker readout architecture. Since the details of the intended application, such as power dissipation, multiplexing level, physical layout, etc., have important implications for the decisions on the optical transmission, and vice-versa, the involvement of potential users from CMS has been essential in choosing the directions and emphasis of the major tasks of RD23. It was found, in particular, that the number of detector channels multiplexed into each optical link could be increased to 256, that is 2x the initial design figure. It also appeared that the power dissipation constraints on the link transmitters could be safely reduced to levels that would allow using certain types of emitters in the front-ends. The electrical power dissipation of MQW laser diodes is expected to remain below 20mW per optical channel (compared to ≈ 1mW for a modulator) during the lifetime of the experiment; this limit is considered still acceptable.

A major effort has been invested in the last year in assessing the radiation hardness of AFPM modulators as well as of several types of MQW laser diodes, both under γ rays and neutron irradiation. The radiation hardness of modulators has been proven up to and well beyond the LHC requirements. Moreover, we found that even in the case of MQW lasers the results were generally satisfactory, actually very good for some structures. Thus we have convinced ourselves that MQW laser diodes can satisfy the constraints at LHC detector front-ends.

On the other hand, the latest (and final) attempts by our previous industrial partner to optimise the growth and processing of MQW modulator structures have resulted in partial failures which again remain unexplained. We believe that they have the capability to understand and solve the problems, but it is now clear that the way ahead to production would require substantial additional investment and time (possibly up to one year), which we cannot afford. This supports our decision to consider MQW laser diodes as a possible technology for the optical link transmitters.

References

[1.1] CMS Letter of Intent. CERN/LHCC 92-3 (1992)

[1.2] CMS Technical Proposal CERN/LHCC 94-38 (1994)

[1.3] G. Hall Proceedings of 1st Workshop on Electronics for LHC Experiments, CERN/LHCC/95-56 (1995) 114-118.

[1.4] G. Hall. "Analogue optical data transfer for the CMS tracker", IC/HEP/96-6 (1996) To be published in Nucl. Instr. & Meths.

[1.5] B. G. Taylor. Proceedings of 1st Workshop on Electronics for LHC Experiments, CERN/LHCC/95-56 (1995) 180-184.

[1.6] "CMS Tracker Optical Readout Link Specifications", Draft Vsn 0.4 July 1996.

[1.7] R. Horisberger. Private communication.

[2.1] RD 23 status report 1994, CERN/DRDC 94-38

[2.2] RD23 status report 1995. CERN/DRDC 95-61(1995)

[3.1] G. P. Agrawal, "Fiber optic communication systems", J. Wiley (New York) 1992.

[3.2] J.Gowar, "Optical communication systems", Prentice Hall, 1993

[3.3] "it seems likely that [QW lasers] will eventually replace most laser types now in existence." P. S. Zory (ed) "Quantum Well Lasers", Academic Press, 1993

[3.4] G. Stefanini. Proceedings of 1st Workshop on Electronics for LHC Experiments, CERN/LHCC/95-56 (1995) 157-159.

[3.5] P.J. Duthie, A.J. Moseley, M.Q. Kearley, D.J. Robbins, C. Edge, J. Thompson, N. Carr, "Passively aligned four-channel reflective InP MQW modulator transmitter", El. Lett., Vol. 31, No. 14, 1995, pp. 1177-9.

[3.6] K.D. Choquette, K.L. Lear, R.P. Schneider, D.M. Geib, J.J. Figiel, R. Hull, "Fabrication and Performance of Selectively Oxidized Vertical-Cavity Lasers", IEEE photonics technology letters, Vol. 7, No. 11, 1995, pp. 1237-9.

[3.7] M.K. Hibbs-Brenner, R.A. Morgan, R.A. Walterson, J.A. Lehman, E.L. Kalweit, S. Bounnak, T. Marta, R. Gieske, "Performance, Uniformity and Yield of 850nm VCSEL's Deposited by MOVPE", IEEE photonics technology letters, Vol. 8, No. 1, January 1996.

[3.8] A FIT is usually employed as a unit of failure rate; 1FIT corresponds to 1 failure unit in 10^9 hours of device operation, D.S. Pech, C. H. Zierdt, Proc. IEEE, Vol. 62, p. 185, 1974.

[3.9] W. Hunziker, W. Vogt, H. Melchior, R. Germann, C. Harder, "Low Cost Packaging of Semiconductor Laser Arrays using Passive Self-Aligned Flip-Chip Technique on Si Motherboard", proceedings of the 46th IEEE Electronic Components and Technology Conf., ECTC 96, Orlando, FL, May 28-31, 1996.

[3.10] G. Hall, G. Stefanini, F. Vasey, "Optical Link Concept for the CMS Tracker", technical note in preparation.

[3.11] K. Gill, R. Grabit, G. Stefanini, F. Vasey, "Radiation Damage Studies of Semiconductor Lasers for the CMS Tracker Optical Data Links", proceedings of the second workshop on electronics for LHC esperiments, Balatonfuered, Sept 23-27, 1996.

[3.12] G. Cervelli, R. Grabit, M. Persello, G. Stefanini, F. Vasey, "Time Stability of Asymmetric Fabry-Perot Modulator Based Analog Lightwave Links", technical note CERN-ECP/96-12.

[3.13] I. Dawson, J. Dowell, J. Homer, I. Kenyon, S. Oglesby, H. Shaylor, J. Wilson, "Irradiation Tests of Electro-Optical Components for Atlas SCT Readout", ATLAS Internal Note INDET-NO-137, June 1996.

[3.14] J. Beringer, K. Bohrer et al., "First Results of a Comprehensive Life Time Test of Irradiated LEDs", proceedings of the second workshop on electronics for LHC esperiments, Balatonfuered, Sept 23-27, 1996.

[4.1] Meeting with CMS referees, Aug. 27, 1996.

[A.1] RD 23 proposal 1991. CERN/DRDC/91-44 DRDC/P31

[A.2] RD 23 status report 1993, CERN/DRDC 93-35