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Status Report on the RD-23 Project

Optoelectronic Analogue Signal Transfer for LHC Detectors

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1. Introduction - History of the project

This is the fourth and final status report on the RD23 project, which started with the recommendation for approval by the DRDC in February 1992. A detailed account of the history of the project can be found in [1]; here a brief summary is given for convenience.

The main goal of the project was to develop optical fibre links for volume application in analogue signal transfer in the front-ends of tracking detectors at LHC. Key requirements were radiation hardness, low power dissipation and affordable cost. The technique proposed initially was based on external modulation, and the project was targeted at the development of electro-optic intensity modulators as transmitters. This approach was considered at that time to be susceptible of offering substantial advantages with respect to the one based on the direct modulation of light emitting diodes (LEDs), which was already being investigated by other groups outside CERN. Laser diodes commercially available at that time were found to be too expensive and of uncertain long-term reliability.

Two alternative modulator technologies, already proven or susceptible to offer the required radiation hardness, were initially investigated:

(a) Mach-Zehnder interferometric modulators (MZM) on lithium niobate;

(b) III-V semiconductor multiple-quantum-well (MQW) asymmetric Fabry-Perot (AFPM) reflective modulators.

Multi-channel demonstrator prototypes were developed and successfully tested in both technologies, in collaboration with an industrial partner of recognized expertise. In the first status report of Aug. '93 [2] the conclusion was reached that the lithium niobate MZM system would be of prohibitive complexity, size and cost, while the semiconductor AFPMs could eventually lead to volume production at affordable cost. The prototype 4-channel arrays of AFPMs (phase 1) were far from being optimised, both in material structure and in packaging, but the performance was reasonably close to meeting the requirements. Preliminary results from neutron irradiation showed that AFPM devices were rad-hard. It was also acknowledged that the AFPM technology was not yet mature and contained a considerable degree of risk, but the industrial partner was confident in their capability to make quick progress, and it was finally decided to concentrate the effort on the development of the semiconductor devices.

The RD23 activity in the following year was therefore focused on the optimisation of the packaging 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 [3]. 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. Results of extensive gamma irradiation tests on optical fibres were presented, showing that suitable fibres were commercially available. A much improved modulator package, with butt-coupled fibres and miniature size suitable for LHC detectors, had been developed and tested in the lab. However, the new (phase 2) AFPM chips assembled in the package were found to deliver disappointing performance, with a lower than expected modulation depth, and a leakage current in several devices well above the specified figure. The RD23 work programme for the following year was targeted at the optimisation of AFPM packages and chips (wafer growth and processing) and at the assessment of technologies suitable for the production of compact hybrid transceivers.

The third status report was presented in Oct. 1995 [4]. 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. Good progress was reported on the optimisation of the AFPM package, which could be considered quite close to the final version. An extensive programme of systematic irradiation tests of modulators, initiated in '95 and continued until recently, confirmed that the radiation hardness of these devices exceeds the LHC requirements.

However, the reasons for the poor performance of the 1994 (phase 2) AFPM structures had not been fully understood, and further attempts by our industrial partner to optimise the growth and processing of AFP modulator structures (phase 3) had resulted in unexplained partial failures. It became apparent that the technology was not mastered as well as the previous development phase had suggested and that the consolidation of the processes towards production would require substantial additional investment, which we could not afford, and delay the project by one or more years.

Furthermore, realistic estimates of the projected cost of the modulator-based optical link were still significantly higher than the target set in the costing of the experiment. This, together with the technical difficulties and risk of a full custom development from a single source, prompted us to look into alternative solutions.

Considerable advances had been made in MQW laser diodes, with increasingly lower thresholds, higher coupling efficiency and decreasing cost. 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. The major issues were radiation hardness and power dissipation.

The radiation hardness of several types of MQW laser diodes, both under gamma rays and neutron irradiation, has been measured and the results are reported here. We found that several devices are satisfactory, and edge emitting structures in particular deliver very good performance even in the most demanding conditions. We can safely assume that the electrical power dissipation of the laser diode will remain below 30mW during the lifetime of the experiment. This value is higher than in the case of modulators (< 1mW), but the corresponding power dissipation of the optical transmitters (in the typical case in which 256 detector channels are time multiplexed into one link) remains below 10% of the total front-end power dissipation, which is considered acceptable.

In this report, together with the referenced supporting documents, we show that the key issues of the fibre optical link have been understood, suitable devices and technologies have been identified, and prototypes have been fabricated and tested. The laser based link configuration has been adopted as baseline choice in the CMS experiment. The RD23 project has now reached a stage in which it can best be continued and optimised within the specific constraints of the CMS experiment itself. It is understood that other experiments interested in these developments will have access to the relevant information and possibly to the final product in due time. This report is the final one of the generic R&D phase; further progress will be reported in CMS technical notes as well as in the appropriate workshops, conferences and journals.

A Web site has been established for the RD23 project, with URL: http://www.cern.ch/RD23 .

2. Fibre optic link technologies

A brief reminder of the relevant aspects of optical fibre analogue links in the front-ends of LHC experiments may help in placing the work done so far into perspective and in understanding the critical importance of the choice of the most appropriate method and technology. The main elements of a fibre optic link are schematically shown in Fig. 1.

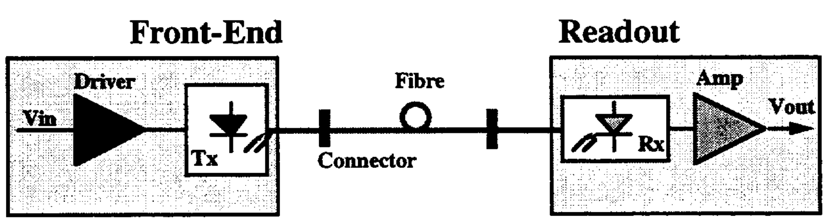

Fig. 1. Elements of a fibre optic link.

Electrical drivers and optical transmitters (Tx) at the detector front-end convert the electrical outputs of the analogue pipelines into optical signals and send them over a relatively short (≈ 100m) optical fibre to the readout electronics station, where PIN photodiode receivers (Rx) and amplifiers convert the optical signals back to electrical. Optical connectors allow the individual link elements to be factory tested before delivery and facilitate the system installation and maintenance. Altogether, six components require evaluation: two electrical (driver, amplifier), two optical (connector, fibre) and two opto-electronic (Tx, Rx).

Two techniques can be used to generate optical signals at the transmitter side (Fig. 2): (a) direct intensity modulation of an active light emitter (laser or LED), and (b) external modulation of a continuous-wave (CW) laser beam via an electro-optic modulator. Both techniques have been investigated by the RD23 collaboration.

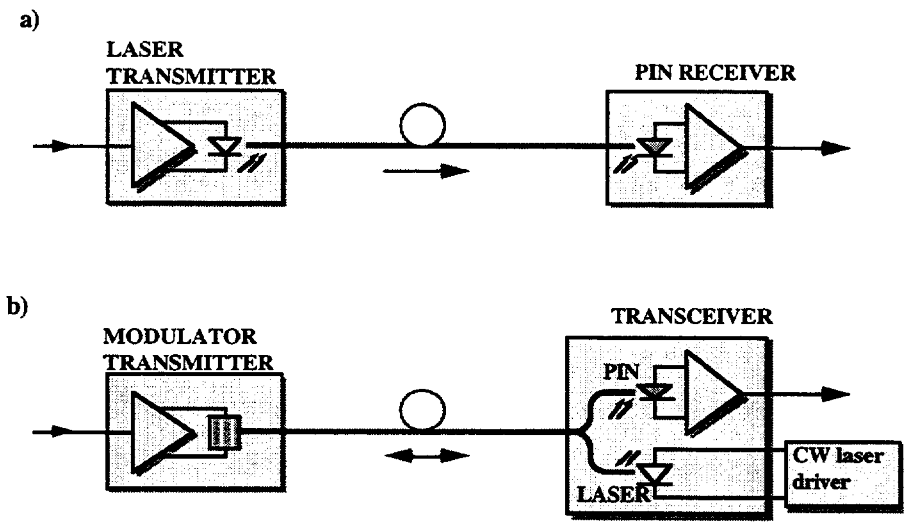

Fig. 2. Two investigated technologies for light modulation: a) direct modulation, b) external reflection modulation.

The *direct modulation* (Fig. 2.a) of laser diodes (or LEDs) is generally used in telecom and datacom applications where it offers the advantage of relative simplicity. In the case of the LHC experiments, placing active emitters in the tracker front-ends raises challenging technical problems in view of the radiation environment and the requirements and constraints of power and reliability.

In the *external modulation* technique (Fig. 2.b), the laser source is in a remote location outside the detector, and the modulator - at the front-end - is essentially a passive component. This potentially offers advantages in terms of power dissipation, radiation hardness and reliability of the transmitter, at the cost however of increased technical complexity of the transceiver.

The technology initially retained in the RD23 project was the one based on external modulation with semiconductor reflective AFP Modulators. The reflective configuration allows using one fibre for both the incoming laser source beam and the modulated signal. The transceiver at the readout end includes the CW laser diode, the receiver, as well as couplers and splitters. The modulator and the transceiver were based on state-of-the-art optoelectronic technologies and were both full custom developments for the LHC application.

In the course of 1996, in view of various severe problems found with the development of an externally modulated system (AFPM wafer growth and processing, complexity of the transceiver technology), the decision was taken to discontinue this approach and to focus instead on the direct modulation of laser diode transmitters. Edge emitting semi-conductor laser diodes operating at a wavelength of 1.3μm were chosen. Laser diode and PIN photodiode in die form are commercially available devices tested for radiation resistance and assembled into a customized package.

3. Objectives, results and strategic decisions in 1996

Since March 1995, CERN has taken full responsibility for the management of the RD23 industrial programme, which was previously coordinated by an industrial partner. At the time of the 1995 status report it had been established that links based on AFP modulators could meet the performance requirements of the tracker, but only a relatively small number of them (48) had been characterized at that stage. To meet the requirements and timescales of the LHC experiments, the following priority objectives were set for 1996:

3.1) confirm that the AFP modulator based link could be manufactured in large quantities at an affordable cost by the current pool of industrial partners, and establish a second sourcing strategy for AFPM technology. Make further progress in the development of a compact transceiver;

3.2) assess the radiation resistance of commercially available MQW laser diodes and evaluate the feasibility of analogue links based on direct modulation;

3.3) meet the CMS milestone for mid-96: choice of optical technology.

A summary of results and strategic decisions in 1996 follows. Additional details can be found in sections 4 and 5.

3.1 Modulators and transceivers

The three industrial partners involved in the modulator based link development programme have been:

- GEC-Marconi Materials Technology (GMMT): AFP modulator design, growth and packaging.
- ITALTEL: Optohybrid transceiver design, hybridisation and packaging.
- EUROPTICS: fibre cables, multiway ferrules and connectors.

A 10 months work programme (phase 3) with GMMT was launched in August 95 to re-establish confidence in the AFPM growth and processing after the unsatisfactory results of phase 2. However, GMMT failed to deliver functional chips due to unexplained problems in processing the grown wafers. The results of the GMMT-phase 3 programme are discussed in section 4.1.1.

The disappointing outcome of the GMMT developments, together with the increasing cost of their work programme, prompted us to look for alternative suppliers of AFP modulators. In Europe, we could not find any industrial partner with the required expertise and willing to meet the challenge, but several academic institutes showed their interest. A 6 months programme was eventually launched in February 96 with the University of Oxford-Interdisciplinary Research Centre for semiconductor materials (IRC) to design, grow and process modulator chips. The intent was not to establish IRC as a second source production center for modulators, but rather to test the validity of their designs with the option of subsequently transferring production to an industrial grower. The outcome of this programme was disappointing and no chips had been delivered to CERN by end of 96 when the contract was eventually canceled. Details can be found in 4.1.2.

A 7 months work programme (phase 2) on transceivers was launched with ITALTEL in March 96. The objective was to hybridize a PIN diode with a transimpedance amplifier on a common Si-submount in view of fabricating a compact transceiver module. A study of feasibility and cost of this compact transceiver module was also commissioned, with an option to start prototyping if required. The outcome of ITALTEL phase 2 was a success with functional PIN-preamp hybrids delivered to- and tested at CERN, and a good working relationship established with the company. However, no follow-up prototyping phase was launched in view of the problems found in the modulator development. The main results of the phase 2 work with ITALTEL are presented in section 4.2.

3.2 Laser diodes

Contacts with laser manufacturers were established as early as 1995. Irradiation tests on MQW laser diodes with γ rays were first carried out in November 95, and were followed by neutrons in April and Novembre 96. It was clearly established that the main effect of radiation damage in MQW lasers is an increase in threshold current, which in practice can be tracked with an adjustable bias current circuitry. The worst-case power dissipation expected at the experiment end-of-life was estimated to be within acceptable limits for the front-end transmitters. It was then concluded that directly modulated MQW laser diodes are a realistic alternative for the transmitters of the tracker front-end links. Results are reported in section 5.

3.3 CMS milestone: choice of optical link technology

The milestone set by the CMS collaboration for summer 96 was to decide on the optical link technology. The planning of the work programmes with GMMT, ITALTEL and IRC, as well as of the laser irradiation tests, had been done so that results would be available in time for the CMS decision.

It had become clear by then that the growth and processing of AFP modulators were not yet well mastered by GMMT and that no second source had been found. The investment (and time) needed to consolidate the modulator technology in view of volume production were not affordable. Moreover, the complex technology of the transceiver module was becoming a significant cost driver. Even assuming that all technical problems could be solved in time, the projected budgetary cost of the external modulation system exceeded the CMS target.

On the other hand, preliminary tests on laser diodes showed very good radiation hardness and excellent operational characteristics for analogue transmission. Second sourcing of laser die and packages was possible. The decision was then taken [1] in mid 96 that the CMS tracker optical readout system should be based on links using directly modulated lasers as transmitters. The modulator activities were terminated, and the RD23 work programme was focused on laser diode transmitters and PIN receivers.

4. Optical link based on external modulation

4.1 Modulator chip developments

The fabrication sequence of optoelectronic chips (and modulators in particular) starts with a design/simulation phase, followed by the growth of the epitaxial material. After testing, it continues with processing of the device structure, characterization, inspection and ends with the packaging phase where the chip is connected electrically and optically to its environment. The epitaxial growth step is what makes optoelectronic developments fundamentally different from standard electronic developments: whereas an electronic designer can usually integrate his chip in a standard Si-wafer and customize only the processing step, an optoelectronic device developer must first specify a custom wafer to be grown, thus adding an extra dimension to the complexity and cost of any custom optoelectronic development.

4.1.1 GMMT modulators

Two batches of packaged modulators had been delivered to CERN by GMMT in the framework of phase 1 (1993) and phase 2 programmes (1994). A 10 months work programme (phase 3) with GMMT was launched in August 95 to re-establish confidence in the AFPM growth and processing after the unsatisfactory results of phase 2.

It should recalled here that the participation of our industrial partner in the project had always been on a "best effort" basis, i.e. without explicit assurance of results, on account of the complexity of the technology and the budgetary constraints.

The phase 3 objective was to grow and process wafers for a significantly large number of devices with a performance comparable to phase 1 deliveries. A first batch of 30 chips, each including 8 AFPM modulators, was to be delivered and mounted on chip carriers to allow for electro-optic tests. Phase 3, if successful, was to be followed by the packaging of the rest of the chips produced.

The outline target specification was to be as measured and reported previously for the phase 1 chips: Operation wavelength 1535nm, max. modulation depth 25%, voltage for 100% modulation 9V, modulation efficiency 6%/V. Process trials were to be performed to verify process changes required for improved wire bondability. Masks were to be re-designed to achieve 8 channel (250µm pitch) functionality. The epitaxy wafers were to be processed and ten 8-channel chips were to be characterised at GMMT for reflection change versus voltage and wavelength. Two of these tested chips were to be delivered to CERN, with test results. A further 20 chips were to be delivered to CERN unmounted and untested.

The epitaxial growth of the AFPM fabrication sequence seemed to be successful, while the wafer processing turned into an unexpected failure. The two main problems were:

- large leakage currents making the low (-10V typ.) reverse voltage operation of the modulator impossible;
- shift in the optical reflectivity characteristics of the processed devices lowering their modulation efficiency.

It should be pointed out that these performance deficiencies had been observed, though at a much lower level, on phase 2 devices already. In the course of phase 3, both problems could be related to processing difficulties, but no satisfactory process route could be determined before the programme had to be terminated in September (after a 4 months contract extension). High leakage current was correlated with the modulator-mesa passivation technique, while degradation of mirror characteristics was coupled to a post-deposition heat treatment [5].

It was judged unrealistic to attempt to stabilize the complex process within the current project constraints (in time and financial resources), and based on the availability of a limited number of epitaxial wafers to draw test material from.

In spite of the failure to deliver AFPM samples to CERN, the GMMT-phase 3 programme was very valuable in pointing out the size and complexity of the problems still to be solved before modulator production could be envisaged. It also confirmed that the funding requested by GMMT to carry out this full custom development was well above the project's possibilities.

4.1.2 IRC modulators

Discussions with the University of Oxford-Interdisciplinary Research Centre for semiconductor materials (IRC) started in early 95 already, but long negotiations on intellectual property rights (in case the designs were to be used by CERN at a later stage) delayed the start of the project. A 6 months programme was eventually launched in February 96. The main goal of the IRC-Phase 1 programme was to demonstrate that AFPM design, growth and processing could be achieved elsewhere than at GMMT, hopefully at lower cost thanks to the favorable conditions available to IRC for accessing foundries in the frame of academic research. According to plans, this was still in time to evaluate chips before the CMS milestone decision.

The objective of the workprogramme was to fabricate one-way AFP modulators to be mounted on chip carriers and tested at CERN and IRC. Specifications required a wavelength of 1550nm, an operating voltage of less than 3Vpp on a DC bias level greater than -8V with less than 2% deviation from linearity. Designs were to maximise reflection efficiency and/or minimise DC bias voltage. First, material options were to be surveyed for the electroabsorptive section of the modulator and measurements of test structures were to provide a base for device modeling. Then, complete simulations of 3 designs were to be sent to CERN for review and two options were to be grown and processed. Fabricated devices were to be evaluated at IRC and CERN as appropriate.

Whereas the theoretical design phase of the work progressed slowly, but basically achieved its goal, the practical growth and processing phase turned out to be more difficult than expected. The main problem with the small number of produced devices was the back diffusion of p-dopant in two of the growths, and the oxidisation of the Ag/Au back mirror on processed samples. By Dec. 96 (six months after scheduled sample delivery), no functional devices had been produced. In Jan. 97, after contract termination, operational samples had been processed, characterised and found to have considerably lower performance than expected [6].

No IRC AFP modulator chips were delivered to CERN, confirming the difficulty of mastering the technology.

4.1.3 Modulator driver

As part of the work on modulators, an 8-channel driver circuit module has been developed by the team of the University of Perugia. Each channel consists of a 2-stage transimpedance amplifier circuit transforming the output current generated by the APV front-end chip into a voltage compatible with the modulator requirements. A DC voltage generator supplies a bias common to all channels. The module uses standard off-the-shelf electronics. The interest of the module, which had been fully simulated, was to test the performance of the circuitry in view of a future implementation in rad-hard ASICs. Three modules have been fabricated and evaluated at Perugia and CERN. A transimpedance of 6kOhm and a settling time of 20ns to 2% were measured [7].

4.2 Hybrid multiway transceiver developments

The basic building blocks of a multiway transceiver are illustrated in Fig. 3.

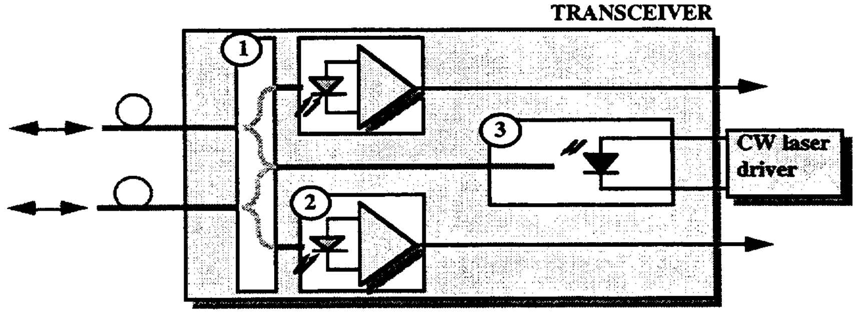

Fig. 3. Generic 2-way transceiver module: (1) passive waveguide router, (2) PIN photodiode-transimpedance amplifier hybrid on Si submount, (3) laser on Si-submount. Blocks (1), (2) and (3) are linked by short fibre sections.

Whereas lasers and PIN photodiodes on Si-submounts, as well as silica-on-silicon passive waveguide devices, are all part of the internal developments of our industrial partner ITALTEL, three custom developments were required for the RD23 project: realization of a passive waveguide element performing the transceiver specific routing function, hybridization of a PIN photodiode with a high gain transimpedance amplifier to match the low noise constraint imposed by the tight link power budget, and assembly into a compact package to reach the level of density required at the link back-end.

The passive routing device samples were delivered in Feb. 96 as part of the phase 1 discrete transceiver contract. The hybridization and study of a compact package were both part of the ITALTEL phase 2 contract started in Feb. 96.

4.2.1 Discrete transceiver

The modulator-based link feasibility had been demonstrated in 1994 already using discrete transceivers assembled at CERN using standard fibreoptic components. In early 1996, another discrete transceiver was built based entirely on ITALTEL components and matching the electrical pinout and footprint of the Front-End Driver board (FED) developed at RAL. The functional block diagram of the ITALTEL transceiver is shown in Fig. 4.

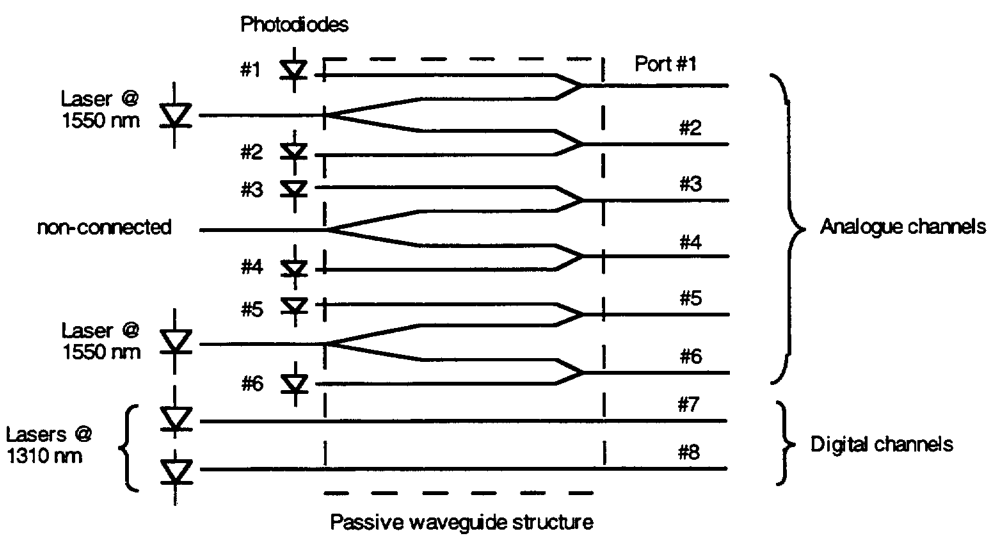

Fig. 4. ITALTEL transceiver.

The passive routing structure was built using the glass-on-silicon technology developed by ITALTEL. The light of three emitters is injected into the 6 analogue channels via 3 x (1 x 2) splitters. Out of the three emitter ports, two were directly spliced with ITALTEL lasers operating at 1550nm whereas the third port was non-connected, thus allowing to test other lasers available at CERN. Together with CERN custom developed CW laser drivers and analogue transimpedance amplifiers, a complete module was built, tested in the lab and compared to the transceivers previously assembled at CERN. Both passive and active components were characterized under various configurations. The overall performance of the ITALTEL transceiver was found to be satisfactory but the signal to noise ratio was lower than in the modules assembled using conventional fibreoptic components. This was attributed to a higher insertion loss in the passive routing structure. Moreover, the 1550nm lasers packaged by ITALTEL featured a high noise level and a poor temperature stability. Other lasers had to be used for the tests. Additional details can be found in [8].

4.2.2 *Compact transceiver package*

As the need for a transceiver unit more compact than the discrete modules became evident, we commissioned a feasibility study by ITALTEL to compare the size and cost of various options leading to a module suitable for volume production. Interestingly, the most conservative configuration (linking individual laser, receiver and passive components by short segments of optical fibre) turned out to feature the largest projected size (200mmx25mm per 4-way module) and cost (220SF/way).

The smallest achievable footprint was evaluated at 55mmx13mm per 4-way module and had a projected cost of 155SF/way. It required to hybridize the PIN photodiodes and transimpedance preamplifiers directly onto the passive waveguide device thus removing the need for short fibre connections to the photodiodes and reducing the amount of handling necessary to assemble the package. The technology required to directly couple light out of a passive waveguide into a receiver was however still under development at ITALTEL at the time the report was issued, thus increasing the potential risk of engineering this small footprint option.

This feasibility study made it very clear that the transceiver was becoming the cost driver of the modulator based optical link and would require further development to reach an appropriate footprint. A prototyping phase was scheduled as a follow up to the feasibility study, but was canceled following the milestone decision in CMS to choose laser based links as baseline technology.

4.2.3 *PIN photodiode-preamplifier hybridization*

The objective of the hybridization programme was to modify the existing ITALTEL PIN diode submount and mount close to the photodiode a variable gain CMOS transimpedance preamplifier developed in the CERN-MIC group. The ITALTEL part of the work included redesign and fabrication of the Si-submount, design and procurement of a suitable package, hybridisation of the components, and testing jointly with CERN. The CERN part of the work included optimization of an existing chip design, integration, fabrication of evaluation boards for the transimpedance chip alone and for the hybrid module, and testing.

The module with hybridized PIN diode and preamplifier is schematically shown in Fig.5.

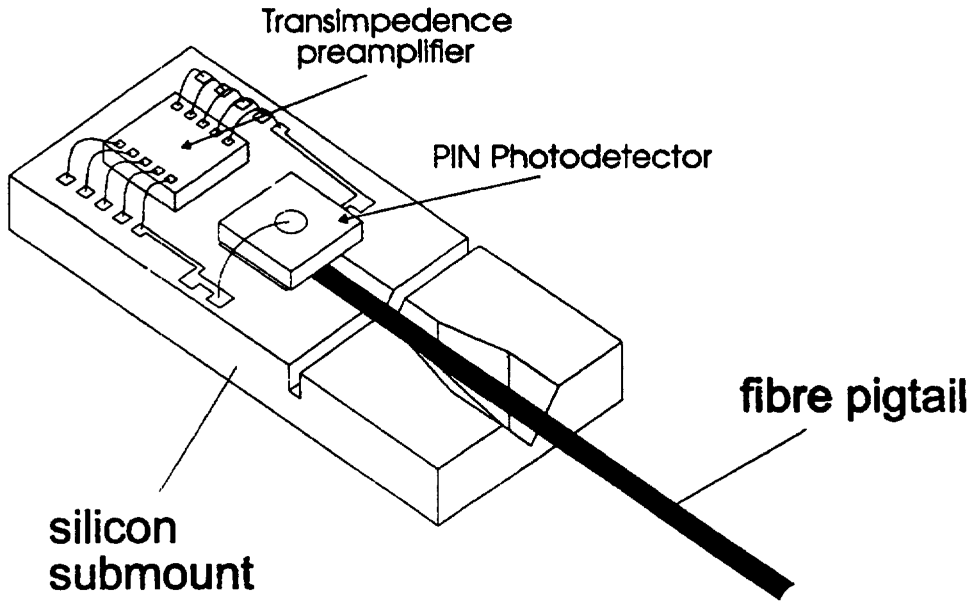

Fig. 5. Hybrid assembly of transimpedance preamplifier and pigtailed PIN photodiode.

The CMOS variable gain transimpedance preamplifier designed by the ECP-MIC group is based on the current mode active feedback principle described in [9]. The photodetector chip-type and pigtailing procedure are the same as used in ITALTEL's standard PIN photodiodes. Only the Si-submount size has been increased to allow for bonding of the electronic chip. Preamplifier chips were delivered from foundry in May 96 and first hybrids were successfully tested in Sept. 96. A total of 30 photoreceiver modules were tested, out of which 11 were based on the hybrids delivered by ITALTEL, while the other 19 were discrete assemblies built at CERN with commercial, individually packaged photodiodes. A comparison of the gain and bandwidth properties of the two types of modules as a function of feedback current is shown in Fig. 6.

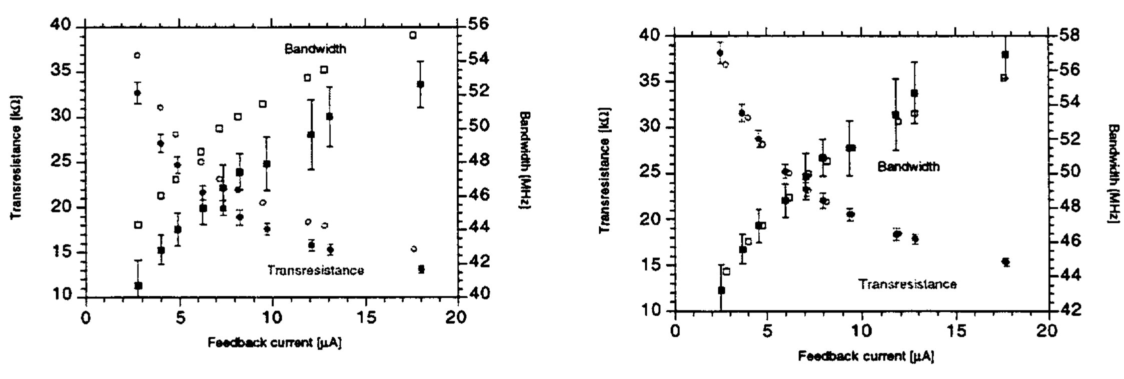

Fig. 6. Bandwidth and transresistance gain as a function of the control current (I_{feed}). Empty symbols correspond to discrete assemblies and full symbols to hybrid modules. Left: as measured, right: after numerical correction for diode responsivity and capacitive output load.

In comparison with the discrete assemblies [10], the hybrid modules show inferior gain and bandwidth performance. The low gain is related to an incorrect determination of the photodiode responsivity as measured at ITALTEL, while the lower bandwidth is attributed to a high capacitive output load caused by a modified socket holding the hybrid package (it was known from simulations and measurements that the source-follower buffering the preamplifier output showed limited driving capabilities for capacitive loads exceeding 2-3pF). By compensating for these two factors, it could be shown that both gain and bandwidth performance of the hybrid modules matched those of the discrete assemblies. More details can be found in [11].

4.3 Experimental results: overall stability in time

It may be useful to recall that no new modulator chips or packages were delivered to CERN in 1996. All tests reported below were thus performed with the phase 2 modulator devices already described in the 95 status report.

The long term investigation of the modulator-based link stability was started in 1995 and continued in 1996 [12]. Four links were evaluated, corresponding to two AFPM modules (at the front-end) and one transceiver module (at the back-end). The total observation time was 5539 hours (about 8 months). The transimpedance amplifier output voltage was periodically monitored as a function of modulator input voltage at constant light input power (typ. 100μW in the fibre) and wavelength, to evaluate the link transfer characteristic and the modulator transmitter functionality. The optical link transfer characteristic was processed off-line to determine the linear region of operation for each acquisition. We define the linear region as the range where the link output $y=f(x)$ can be approximated by a regression $y_{lin}=y_o+G(x-x_o)$, with an integral linearity deviation α smaller than ±1% of full scale. We call the slope G the link gain and the center of the linear range x_o the bias point. Plotting G and x_o as a function of time allows to quantify the link analogue performance and the biasing requirements of the modulators in varying operating conditions. Figure 7 shows the link transfer function bias point x_o and gain G plotted as a function of time for the four optical links under test.

Despite one noisy channel (20.1), it is clear that the modulator bias fluctuations remain within ~10% of the initial x_o value. Those variations are caused by the strong temperature dependence of the AFPM chip electro-absorption properties at the wavelength of operation. The observed gain fluctuations however appear to be much larger than expected. Due to the complexity of the reflective system under investigation, it is extremely difficult to unfold the various effects which might cause such an instability.

We note that the reverse photo-current measured simultaneously to the transfer characteristic is stable to better than ~10%. The absorbed incident light thus remains reasonably constant while the reflected signal widely fluctuates, indicating that either the reflective nature of the link (and the difficulty to develop a stable fibre-modulator-fibre coupling scheme) or the high sensitivity amplifier electronics might be responsible for the large gain variations observed.

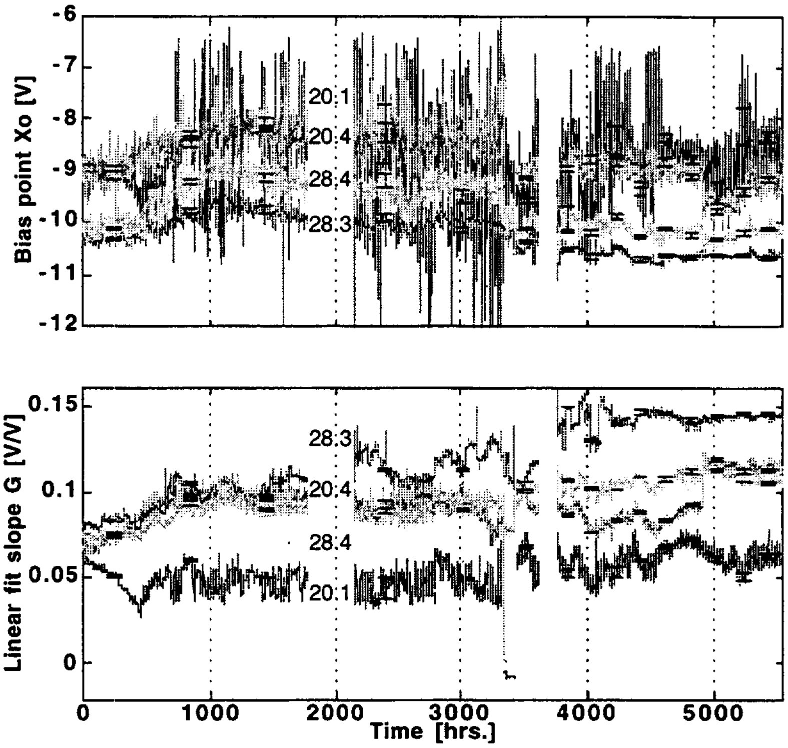

Fig. 7. Long term stability of link transfer function bias point (x_o) and gain (G).

The analogue link will need recalibration to achieve the required accuracy over the long term. A periodic recalibration procedure is proposed based on the re-calculation of the linearisation readout parameters G and x_o at regular time intervals T_c. The data set collected during the final 1500 hours of testing is used to simulate the procedure. The link gain and bias point are chosen such that the integral linearity deviation is minimised (in general smaller than ±1%) within the linear range $x_o \pm \Delta$ (Δ=1.5V) at time t=t_o. The optical system then evolves freely during a time interval T_c as G and x_o are held constant. The integral deviation drift as a function of time is computed until a new calibration takes place at time t'=t_o+T_c.

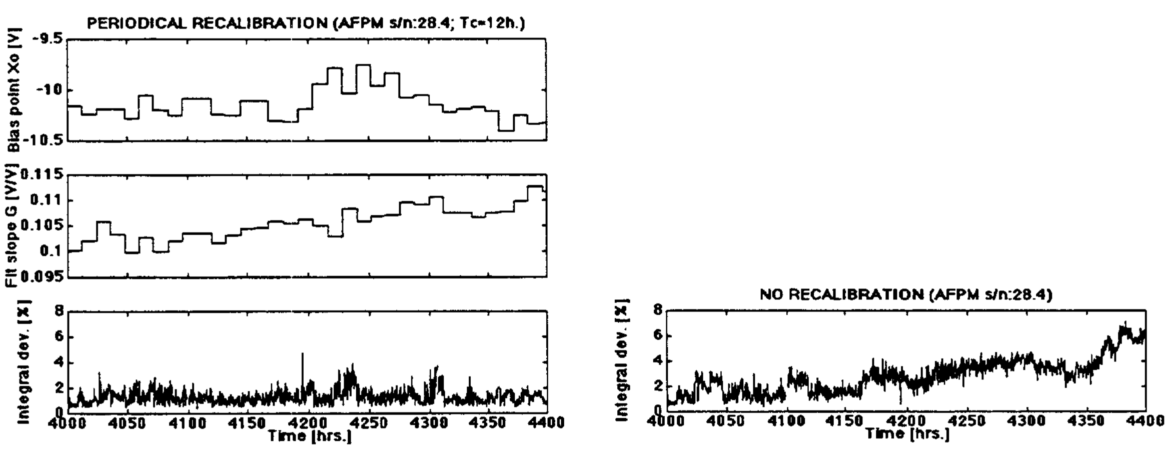

Fig. 8. Integral linearity deviation with (left) and without (right) periodic re-calibration.

The integral linearity deviation of an optical link operated during 400 hours (t_0=4000h) without ($T_C \geq 400h$) and with (T_C=12h) periodic recalibration is shown in Fig. 8. The periodic re-calibration allows to efficiently limit the linearity deviations to within a few percent.

Figure 9 shows the distribution of the maximum integral non-linearity (75% confidence level) as a function of recalibration period T_C for 3 optical channels monitored from t=4000h to 5500h.

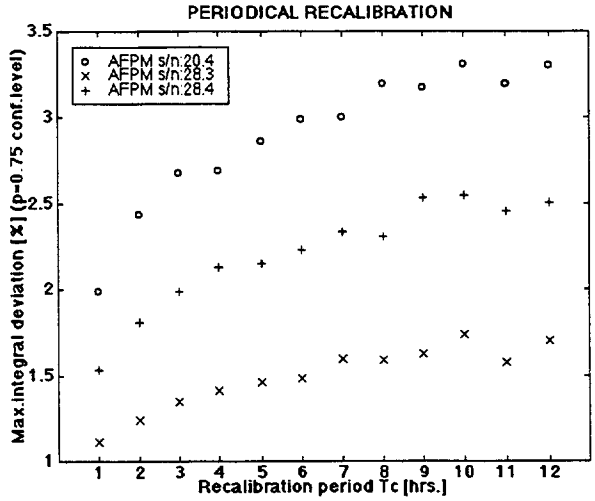

Fig. 9. Distribution of maximum integral linearity deviation. In 75% of the cases, the computed maximum deviation in any interval T_C was smaller than the plotted value.

In spite of the small number of channels tested, these results confirm that stable operation of modulator-based optical links can be achieved provided the system is re-calibrated on the order of twice per day, possibly not so frequently in a temperature controlled environment.

More details can be found in [13].

4.4 Radiation hardness

Bare modulator chips irradiated with both neutron and γ rays showed no change in their optical characteristics measured before and after irradiation at doses and fluences in excess of 10Mrad and 10^{14} n/cm^2 ($\langle E_n \rangle$ = 1MeV), respectively.

The operation of a 4 channel system under γ ray, neutron and proton irradiation of the front-end components was successful. The correlation between link gain G (measured on line) and γ dose is shown in Fig. 10 [14].

While the two channels of package S/N 20 show a decrease in efficiency, the two channels of package S/N 28 show a corresponding increase. This effect is well within the range of the long term fluctuations shown in Fig. 7, and is attributed to packaging or receiver electronics instabilities rather than to intrinsic modulator chip operation.

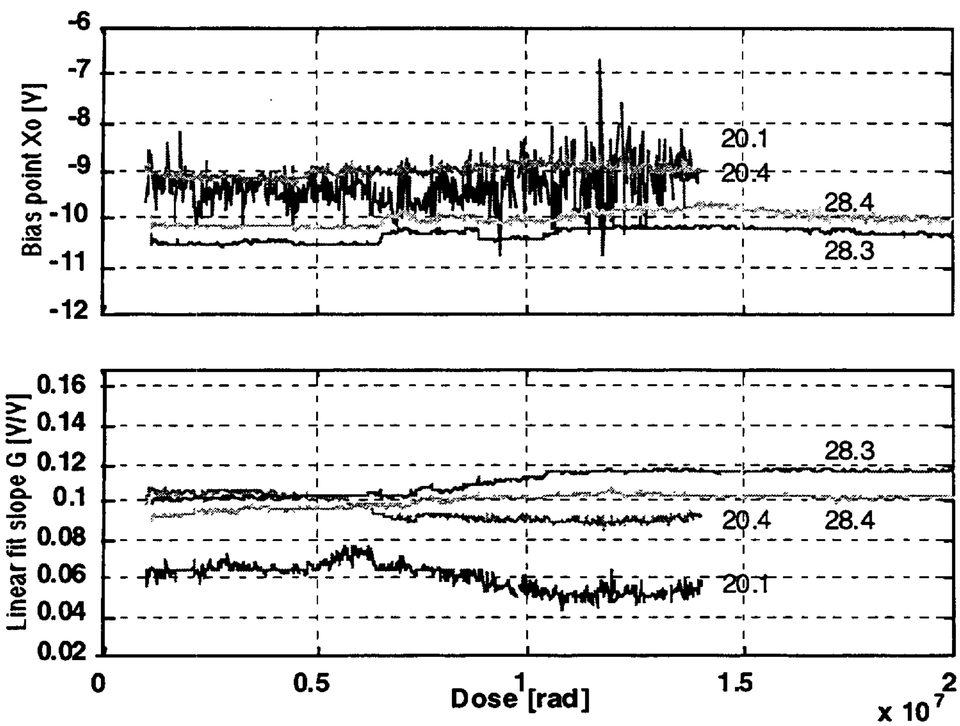

Fig. 10. Correlation between optical link gain G and γ dose during high dose rate irradiation of front-end transmitters.

While ionizing radiation does not seem to affect performance, a small degradation of the link gain (less than 10~20% for all measured channels) after a $5x10^{14}n/cm^2$ ($<E_n>$ = 1MeV) fluence was observed [15]. After the proton irradiation ($6x10^{13}$ p/cm^2), measured additional degradation on the same devices was less than ~30 %.

We found however a significant increase of leakage current under both γ and heavy particle irradiation. In some devices the leakage current always remained well below the photocurrent levels and eventually recovered once the irradiation was stopped. In others it steadily increased even when the sources were turned off and reached levels comparable to the photocurrent. This latter effect is attributed to a defective polyimide passivation layer. In spite of the assurance that this problem is technologically solvable, no stable processing route was found by GMMT during the phase 3 development programme (see section 4.1.1). After off-line subtraction of the dark current component, the monitored photocurrent characteristics show remarkable stability with time, dose and fluence.

5. Optical link based on direct modulation (laser based)

5.1 Laser diode and PIN photodiode submount developments

One of the key reasons for choosing lasers as transmitters was the availability of a commercial technology for assembling and pigtailing devices which fulfilled the tracker requirements. This technology is based on a silicon platform where both die and fibre are attached after active or passive alignment. The resulting assembly is a low mass, small footprint (typ. 2mmx2mmx1mm), lens-free, epoxy-free (in the laser transmitter case) module, and qualifies to telecom standards. Several vendors offer products based on this technology, generally in the form of a 1-way module housed in an 8-pin mini-DIL package.

We have selected, for functionality and radiation hardness evaluations, the ITALTEL 1-way mini-DIL packages, which are standard commercial products. They are based on the same subassemblies as we intend to use in the compact package. The results of the tests performed with these components are reported in sect. 5.3 and 5.4.

In the case of the CMS tracker, a 4-way modularity is required, which necessitates a custom package development (see 5.2) and a slight modification of the Si-submount metalisation to ease the bonding process.

5.2 Compact 4-way package development for transmitters and receivers

The package outlined in Fig.11 is currently being developed by ITALTEL under the phase 3 work programme (started in Jan. 97).

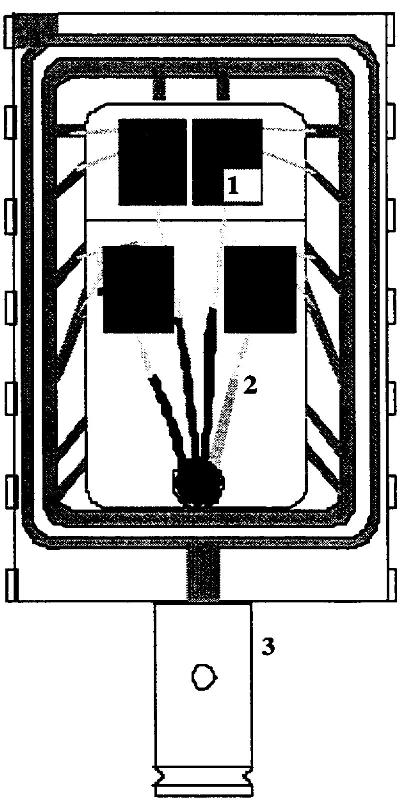

Fig. 11. 4-way module under development. The 1-way subassemblies (1) can be either transmitters or receivers. Optical fibres protected by a 250μm external diameter acrylate coating (2) exit the package through a metallic ferrule (3).

The main objective is a compact package in which four Si-submounts can be assembled, electrically connected and optically pigtailed (Fig. 11). The submounts can be populated with laser diodes or PIN photodiodes. The same package can be used for lasers only, PIN photodiodes only, or a mixture of both. This flexibility is valuable to accommodate detector modularity requirements. It is useful as well in digital applications such as bi-directional digital links for front-end control. Advanced 4-way prototypes have been delivered to CERN in March and will be tested shortly [16].

5.3 *Experimental results: one-channel prototype analogue link*

The performance of the laser-based analogue readout chain has been evaluated with a prototype one-way link at CERN. The laser diode and the PIN photodiode are one-way commercial devices based on the Si-platform technology described in section 5.1. The laser driver and the receiver amplifier are based on discrete off-the-shelf components. Very compact boards have been developed with the purpose of optimising the circuit configuration and layout for high speed and low noise. Typical values obtained are driver transconductance G_m~5.3mS and amplifier transimpedance R_t~10kΩ.

Figure 12 shows the analogue link response to a 25ns input pulse with 5ns rise and fall times representative of a full scale signal. A clean flat-top response with no overshoot has been achieved. An overall link gain of 11.5 and a settling time of 10ns to 2% have been measured. The 3-dB frequency of the overall system (DC coupled) is in excess of 100MHz.

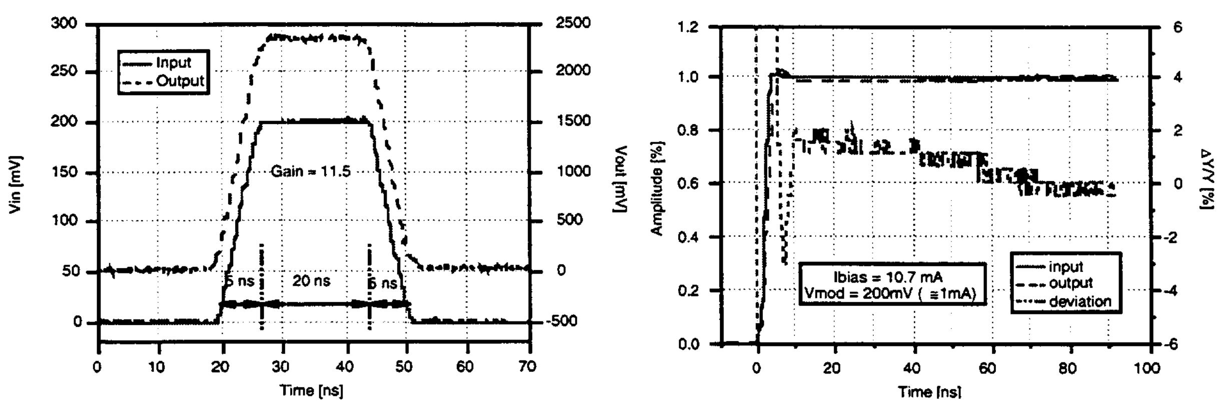

Fig. 12. Optical link analog pulse shape response (left) and settling time (right)

Prototype analogue optical links are now in the process of being distributed to interested groups in the community. In parallel to the hardware development effort, software drivers and evaluation routines are being written to emulate a front-end chip and test the full tracker readout chain performance. Results will be reported elsewhere.

The 1-way laser diode and PIN photodiode devices will be replaced in due time by the 4-way package, without major changes in the associated electronics.

Custom ASICs are also being developed and will replace the discrete electronic front-end components so as to meet the tight requirements in power consumption, footprint and radiation hardness. A 4-channel laser driver (standard BiCMOS technology) has already been designed in the ECP-MIC group. Tests of the prototype are in progress. The design will be implemented in a rad-hard process at a later stage.

5.4 Radiation hardness

Gamma and neutron irradiation tests were carried out in 1996, using the ^{60}Co source at Imperial College, London, and the SARA synchrotron facility at the Institut des Sciences Nucleaires, Grenoble. In both cases, the performance of the devices under test were monitored before, during and after irradiation with no optical system break-up allowed during the whole test (several weeks in general). The irradiations were carried out at room temperature; the temperature in the irradiation cell was monitored but not controlled.

5.4.1 Lasers

In semiconductor lasers, displacement damage effects are reported to be more important than ionisation damage effects [17]. Lasers irradiated with γ rays up to 10Mrad indeed did not present any shift in operation characteristic and the major effort was put on neutron irradiations. Five different types of 1300nm edge-emitting, multi-quantum-well lasers obtained from different vendors were irradiated with fluences up to ~$2x10^{14}$n/cm^2 ($<E_n>$=6MeV). All devices were unpackaged and emitted in air towards a photodiode located at ~1m distance and shielded. Several samples of one laser type were also irradiated in a fibre-pigtailed package up to $8.5x10^{14}$n/cm^2. Monitoring photodiodes were in that case situated inside the control room.

The output power versus input current characteristic (L-I curve) was measured for each laser at regular time intervals. For the remainder of the time, all lasers were biased (a few mA) above threshold to simulate realistic operating conditions. Monitoring took place for ~100 hours before irradiation, then for 102 hours during the irradiation, followed by a further 1500 hours (~2 months) to assess the annealing behavior.

The two parameters used to measure the performance variations during irradiation were the laser threshold and laser slope efficiency (dL/dI). The laser threshold effectively determines the d.c. operating point of the transmitter and the slope efficiency affects the gain of the optical link.

Figure 13 shows the effects of neutron irradiation on laser diode characteristics. The laser threshold current increases while the efficiency decreases almost linearly. A recovery of both the threshold shift and the efficiency was observed in the two month period following irradiation, indicating that the amount of damage depends upon both flux and fluence. The measurements made at high flux thus represent a worst case estimate of the degradation to be expected in real operating conditions. The observed damage in the fully packaged lasers was parameterised with a simple defect kinetics model. The effect of a neutron fluence profile, similar to that expected in the CMS tracker, has been simulated and performance degradation under LHC operating conditions is being estimated.

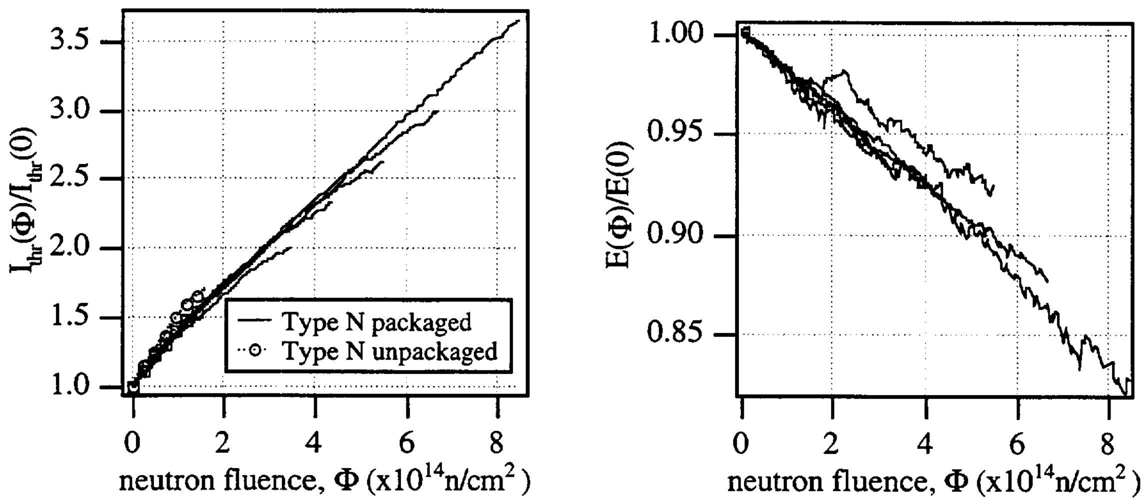

Fig. 13. Dependence on neutron fluence of laser transmitter normalised threshold current (left) and efficiency (right).

The deviation from linearity, the signal to noise performance and the spectrum of the laser output were measured before and after irradiation, showing very little (if any) dependence on fluence.

5.4.2 Fibres

It is well established that radiation damage in SiO_2 optical fibres leads to a degradation of optical transmission [18]. Optically active defects can be introduced by ionisation or atomic displacement mechanisms, or via the activation of pre-existing defects. The presence of impurities in the fibre, such as chlorine and phosphorus, increases the radiation induced transmission losses at infrared wavelengths. The induced attenuation is determined by the competing rates of creation and annealing (plus activation and de-activation) of absorption centres. Transmission losses due to radiation damage can therefore be sensitive to both total dose and dose-rate, in addition to factors such as transmission wavelength, injected light power and temperature.

In this investigation the radiation induced attenuation was measured, at a wavelength of 1550nm, for a germanium-doped fibre and two types of pure silica core fibres with fluorine-doped cladding. The geometry of each fibre was identical: ~9μm diameter core, 125μm diameter cladding, and 250μm diameter acrylate coating. Pure silica core fibres are generally accepted to be more radiation hard than germanium doped fibres, and results are presented here only for this particular type. Additional information can be found in [19]

The fibre samples were wound on a 6cm diameter spool. No connectors or splices were exposed to radiation. Light of 1550nm wavelength was continuously injected into the fibre samples (~100μW per fibre) during the irradiations and the monitored recovery periods. A fourth, unirradiated fibre was used to record any variations in the laser power allowing normalisation of the power level injected into the irradiated fibres. The light output from each fibre was measured and stored at regular time intervals and the fibre attenuation was subsequently computed.

Figure 14 shows the induced loss in the pure-silica core fibres as a function of gamma dose. The overlap of the different tests performed at different times, with different fibre samples and at dose rates varying over 2 orders of magnitude is remarkable. An attenuation on the order of 0.015dB/Mrad/m is measured and can be directly used to assess the losses to be expected in realistic LHC conditions (test B2). All observed recovery was only temporary in nature and the previously induced losses were re-established as soon as irradiation was re-started.

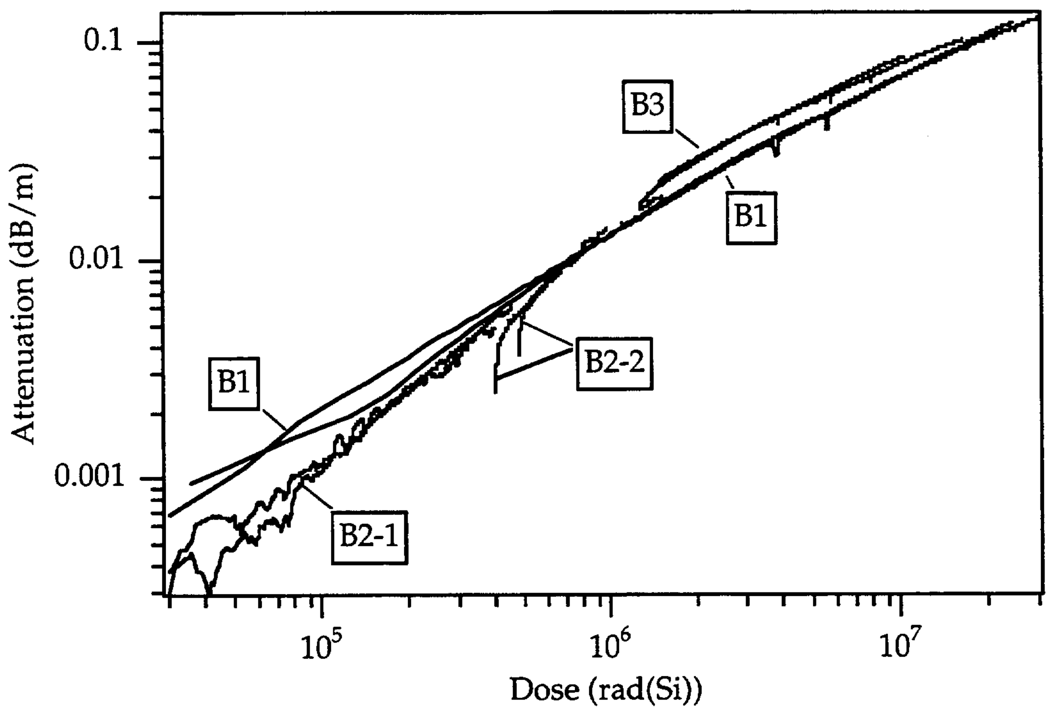

Fig. 14. Results of all gamma irradiations on two types of pure-silica core, F-doped cladding fibre plotted as a function of dose. Dose rates were ~60rad/s (B1), ~0.22rad/s (B2-1,B2-2) and ~26rad/s (B3). Tests B2-1, B2-2 and B3 were performed sequentially with the same fibre samples.

Based on neutron test results carried out up to $4x10^{13}n/cm^2$, pure silica core fibre attenuation will be completely dominated by ionizing radiation damage at LHC.

5.4.3 Connectors

Tests on single mode MT connectors [20] have been carried out to assess the mating loss and repeatability performance following neutron and gamma irradiations up to of $2.3x10^{13}$ n/cm^2 and 10 Mrad doses.

The irradiated samples were 2.2m long patch cords, utilising standard telecom single mode fibre ribbons, and terminated with MT4 connectors (commercially available from Europtics). A diagram of the measurement setup is shown in Fig. 15. A stabilised 1310 nm laser source was used. The measurements were made by Europtics following their standard protocol.

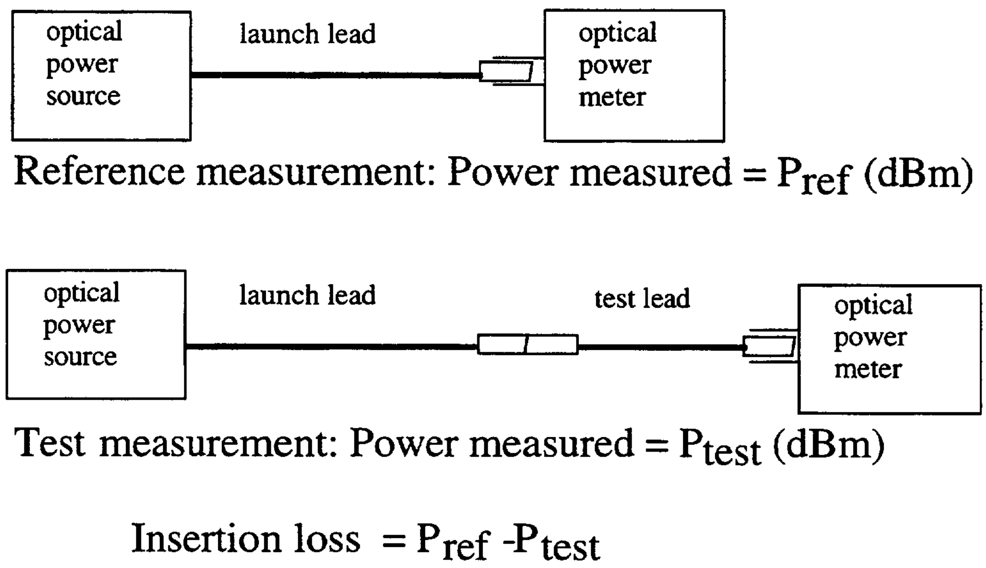

Fig. 15. Measurement method of insertion loss.

The insertion loss of the 10 angle polished connectors after irradiation is shown in Fig. 16. The mean of 0.45 dB is slightly higher than Europtics test figures on the MT4 (0.34 dB) [21], possibly due to an attenuation increase in the fibres as a consequence of irradiation [19].

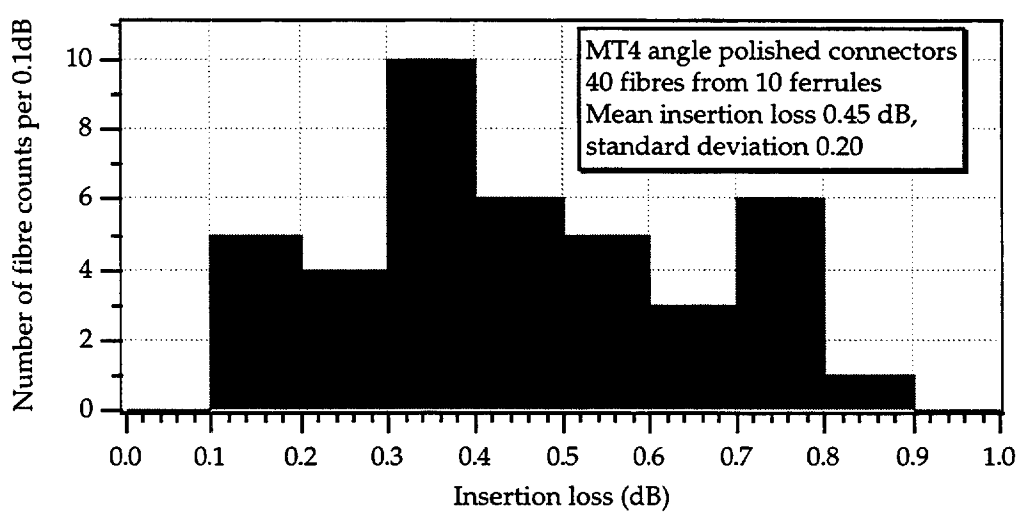

Fig. 16. Histogram of insertion loss of 10 MT4 connectors after neutron and gamma irradiation.

The mechanical performance of the irradiated connectors was assessed by measuring the insertion loss over repeat matings, which gives information about both the loss and repeatability The data are shown in Fig. 17.

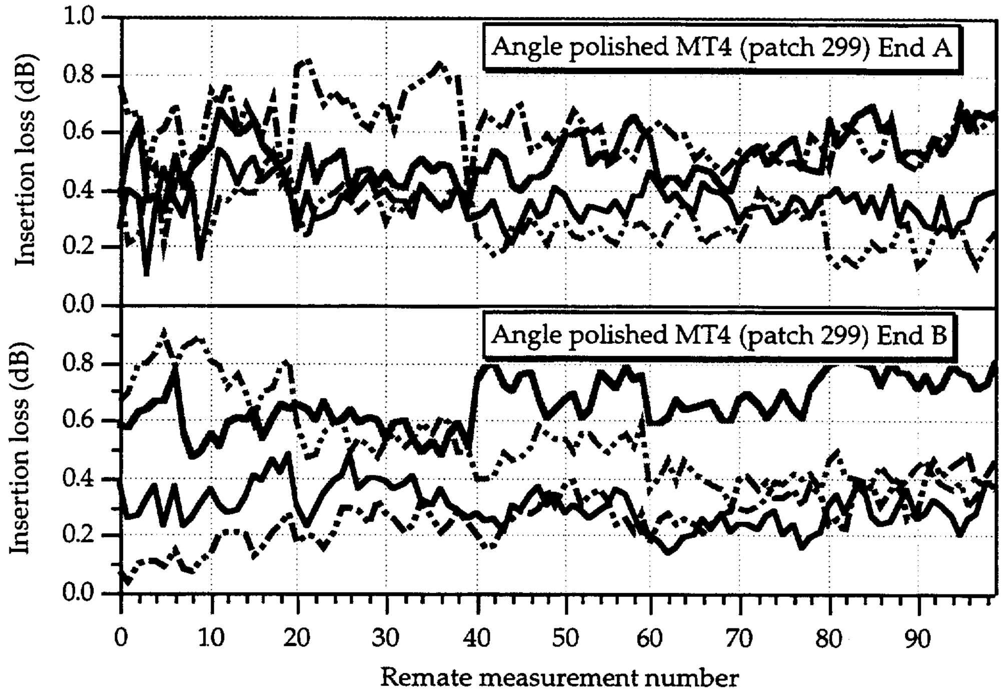

Fig. 17. Insertion loss over 100 matings for an angle polished MT4 patch cord.

All the connectors had insertion losses below 1 dB, thus remaining within specifications, with a typical fluctuation range of 0.2-0.3 dB. The connectors were inspected under a microscope and no degradation in terms of loosening of the fibres within the ferrule, or damage to the ferrule or fibre surface was apparent.

Generally, the performance of MT connectors is encouraging. The range of insertion loss between channels in any one connector can be as high as 0.6 dB, but is typically 0.3 dB to 0.4 dB. With three connector breaks the receiver amplifier gain must cope with a typical channel or re-mate variation of the order of ±0.5 dB on top of an insertion loss of about 1 dB to 1.5dB.

6. System issues

The optical readout system architecture presented in the 1995 status report has been adapted to the specific requirements of the CMS tracker and is shown in its new version in Fig. 18. The two major modifications are:

- Control and readout systems have been clearly separated. The analogue readout lines do not transmit any digital information and the front-end driver (FED) does not perform any timing distribution or control functions. TTC signals are supplied electrically to the detector and transmitter hybrids, and originate from control hybrids located on the detector front-end.

Each control hybrid typically serves 10-100 detector hybrids. Additional information on the control system can be found in [22].

- Modularity of transmitter and receiver is 4 optical channels per package, serving up to 1024 detector channels. In high granularity detector regions, many packages can by assembled onto one transmitter hybrid, while very low granularity regions can be served by partly populated transmitter packages.

A draft specification of the optical readout system is available [23].

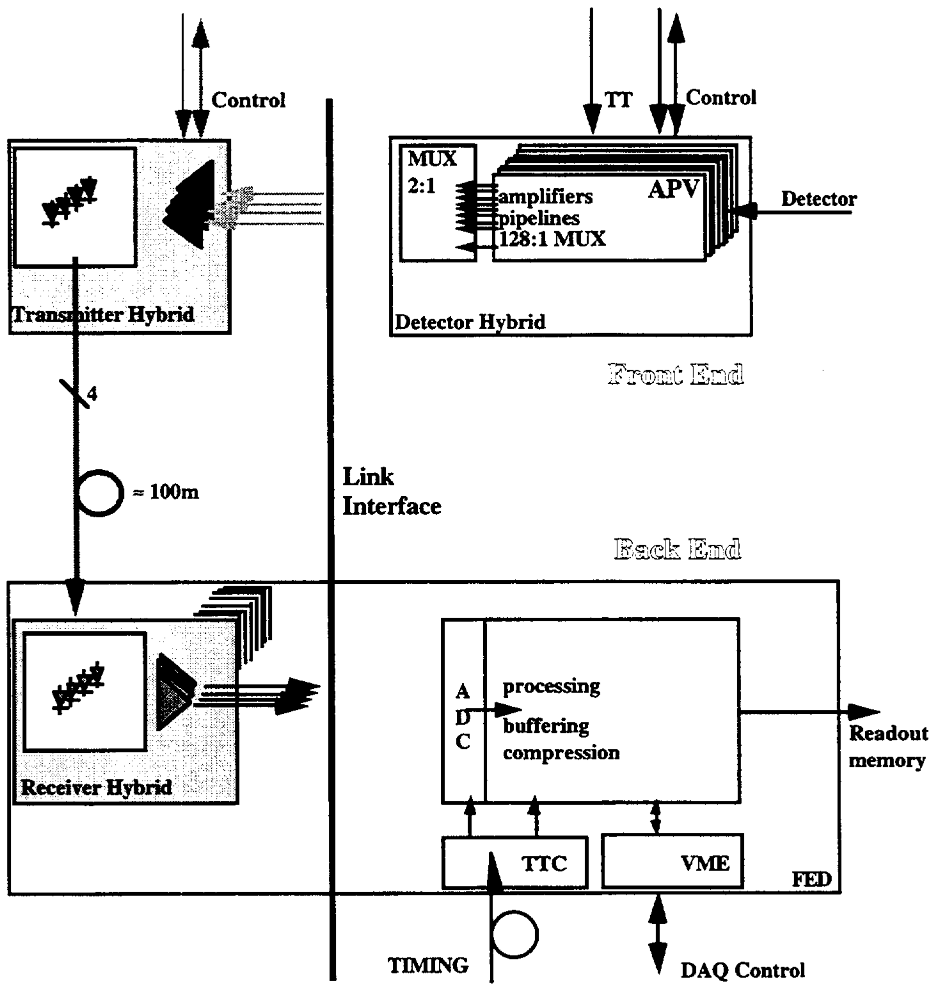

Fig. 18. Embedded optical link system.

7. Towards volume production

We plan to freeze the technical specifications of the optical link components by end 1998, when most of the developments will be completed, and to start volume production in 1999 (or early 2000).

In 1997, functional tests, radiation hardness and reliability measurements will be performed on 1-way ITALTEL packages while 4-way modules are being developed. The first delivery of 4-way units is expected in early 1998.

Potential second source vendors have been identified and a work programme is being established. It can be anticipated that second source deliveries will not take place before 1998 due to the delay in the start of this alternative route. It should be pointed out that these state-of-the-art devices and packaging technologies are available in volume quantities only from leading industrial companies focused on business opportunities substantially larger than the LHC experiments application. Moreover, since the current purchasing rules require an open tender for allocating production contracts, the commitment of vendors in the development phase is not always reliable and the non-recurrent investments have usually to be supported almost entirely by CERN.

The target cost for a complete 4-way link is 600SF or less including transmitter and receiver electronics; the current cost projections are fairly close to this value.

8. Conclusion

The RD23 project has evolved considerably since its start in 1992, and particularly in these last 18 months. The RD23 activity deployed so far is of an unprecedented level at CERN and more generally in the HEP community. Various advanced optoelectronic technologies have been investigated, in collaboration with leading industrial companies. Prototypes have been developed that meet the demanding requirements of the CMS tracker analogue readout, in a technology that is suitable for volume production at an affordable cost.

Developments are still under way, and the activity planned for 1997 will bring results which should be of great interest to all LHC experiments. The corresponding funding requested from CERN is similar to the preceding year. The final optimisation of the link will then be completed in the frame of the CMS collaboration.

We thank CERN and the external agencies that have so far supported us and contributed to the funding of this challenging project. The road to the link switch-on in the LHC experiments is still long but we hope that our work will eventually bring light into what will probably become the largest and most demanding fibre optic link system in modern particle physics experiments.

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PhD Thesis

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