Development of radiation-hard optical links for the CMS tracker at CERN

F. Vasey[1], V. Arbet-Engels[1], J. Batten[2], G. Cervelli[1], K. Gill[1], R. Grabit[1], C. Mommaert[1], G. Stefanini[1], J. Troska[2]

[1]CERN, ECP Division, 1211 Geneva 23, Switzerland

[2]Imperial College, London SW7 2BZ, Great Britain

Abstract

A radiation-hard optical link is under development for readout and control of the tracking detector in the future CMS experiment at the CERN Large Hadron Collider.

We present the optical system architecture based on edge-emitting InGaAsP laser-diode transmitters operating at a wavelength of 1.3µm, single mode fiber ribbons, multi-way connectors and InGaAs Pin photodiode receivers.

We report on radiation hardness tests of lasers, photodiodes, fibers and connectors. Increases of laser threshold and pin leakage currents with hadron fluence have been observed together with decreases in laser slope-efficiency and photodiode responsivity. Short lengths of single-mode optical fiber and multi-way connectors have been found to be little affected by radiation damage.

We analyze the analog and digital performance of prototype optical links transmitting data generated at a 40MSamples/s rate. Distortion, settling time, bandwidth, noise, dynamic range and bit-error-rate results are discussed.

I. INTRODUCTION

The Compact Muon Solenoid experiment (CMS) [1] is a large, general purpose experiment under construction at CERN for operation in the Large Hadron Collider (LHC). Large quantities of optical fiber links are planned for analog and digital data readout as well as digital control and timing signal distribution. Front-end links connecting tracker and calorimeter detectors to the front-end driver and controller modules will need to be radiation resistant, and thus deserve special developments and validation procedures.

A radiation-hard optical link featuring characteristics suitable for analog as well as digital data transmission is being developed for the CMS tracker. Analog signals from $12x10^6$ microstrip detector channels will be time-multiplexed (at 256:1) and transmitted at 40MSamples/s (MS/s) along ~50000, 100m long, optical links [2]. A few thousand digital optical links will also be used to transfer timing and control signals to and from the tracker. The optical link configuration can be adapted to a great variety of system architectures, due to the 4, 8 or 12-way modularity of the fiber ribbons, cables and connectors, and the use of a flexible assembly procedure to package the optoelectronic components.

II. DESCRIPTION

The optical link under development for the CMS tracker is schematically shown in Fig. 1. It is a multi-way unidirectional system based on edge-emitting laser transmitters (Tx) coupled to single-mode optical fibers, multi-way MT connectors and pin-photodiode receivers (Rx). The wavelength of operation is λ 1310nm. The driving and receiving electronics is designed according to the system application: analog for the readout-, and digital for the control-system of the CMS tracker for instance. The total length of the link is approximately 100m, of which about 10m is within the high radiation environment.

The optoelectronic transmitter and receiver components are assembled using Si-submount technology. The laser diodes are commercially available Multi-Quantum-Well (MQW) InGaAsP edge-emitting devices selected for their good linearity, low threshold current (~9mA) and proven reliability. Photodiodes are epitaxially grown, planar InGaAs devices of small active volume.

All tests reported below have been performed with one-way mini-Dual-In-Line (mini-DIL) packages, but the final system will be based on assemblies of up to four laser- or pin-diode submounts (or a mixture of both) housed in a single custom developed package approximately 15mm x 10mm x 4mm in volume.

The passive optical components (fibers and connectors) are of the single-mode type. Fibers with pure silica core, F-doped cladding and UV-cured acrylate coating are intended to be used in

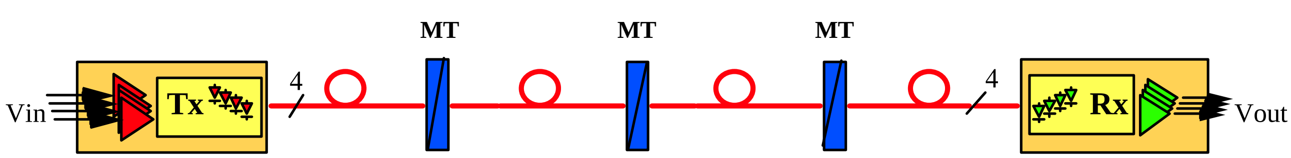

Figure 1: Generic optical link block diagram.

the high radiation environment of the detector, while Ge-doped core, pure silica cladding fiber will be used outside.

Individual fibers are grouped into multi-fiber ribbons (4- and 8-way) and multi-ribbon cables (typically 8x8-way) based on currently available commercial products. Three connectorized breakpoints (two inside the detector and one on the backplane of the readout electronics) allow for easy testing, installation and maintenance of the system. Connectors based on angle-polished MT 4- and 8-way ferrules [3] are used throughout, achieving the highest patch panel density currently possible with commercial components.

III. RADIATION DAMAGE MEASUREMENTS

The LHC will collide two 7TeV proton beams at the center of CMS at a rate of 40MHz, with ~20 p-p collisions occurring every 25ns at the highest beam luminosities. The highest particle fluxes will be closest to the beam interaction point. For example, at a radius of 20cm from the beam axis (at the innermost layer of silicon microstrip detectors) the fluence over ten years of high luminosity LHC operation will consist of $\sim 10^{14}$neutrons/cm^2 (~1MeV) and $\sim 2\times10^{14}$/cm^2 charged hadrons (typically several hundred MeV in energy) [4]. In addition, a total ionizing dose of ~100kGy will result from charged particles and gammas. It is expected that the LHC will run for approximately six months per year and the experiments will take data over a period of at least ten years. All of the optical link components situated inside the CMS tracker must therefore be sufficiently reliable and radiation resistant to last the lifetime of the experiment. Maintenance or replacement of components will be very difficult, due to the overall complexity of the apparatus and induced radiation levels.

Most components foreseen to be used in the optical link have been tested for radiation hardness. For example, Table 1 summarizes the test conditions for lasers and pin-diodes.

Neutron tests were conducted at the SARA facility [5] at ISN, Grenoble. Proton irradiation was carried out using the 24GeV proton synchrotron (PS) beam at CERN. The fluences were measured with nickel foils for neutrons and aluminum foils for protons to an accuracy of ~10%. The ^{60}Co source at Imperial College London was used for gamma irradiation. The dose rate was ~1.3kGy/hr and the total dose was measured with alanine dosimeters to ~10% accuracy. All the exposures were carried out at room temperature.

Table 1
Laser and p-i-n test conditions

Radiation	No. of devices	Fluence (or dose)	Exposure period (hrs)	Recovery period (hrs)
neutron ~6MeV	10 lasers 5 p-i-n's	up to 10^{15}/cm^2	102	up to 2100
proton 24GeV	5 lasers 4 p-i-n's	4×10^{14}/cm^2	10	660
gamma ^{60}Co	5 lasers 5 p-i-n's	100kGy	70	60

Detailed reports on the irradiation test measurements can be found in [6,7,8]. A brief summary of the results is given below

A. Lasers

Both laser threshold current I_t and slope efficiency E were monitored during irradiation. Neutron damage results are shown in Figs. 2 and 3 for 5 devices irradiated at the same time but with different neutron fluxes. Both the threshold increase and the efficiency loss are roughly linear with fluence. Similar effects are seen for proton irradiation, but for a given fluence, 24GeV protons are 4-6 times more damaging than the ~6MeV neutrons. In contrast, a gamma dose of 100kGy caused negligible damage.

The radiation induced changes to threshold current and slope-efficiency annealed with a log(t) dependence, with a rate of about 15% per decade (at 27.5°C).

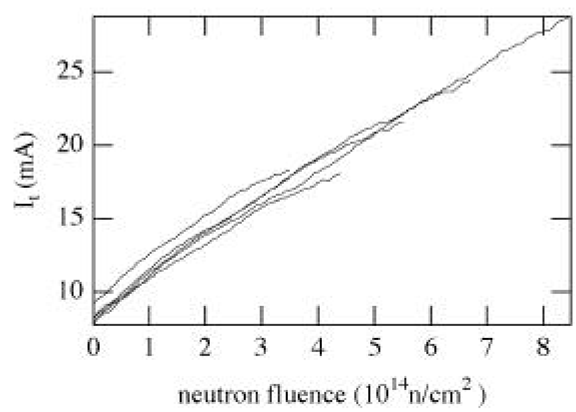

Figure 2: Threshold current increases during neutron irradiation.

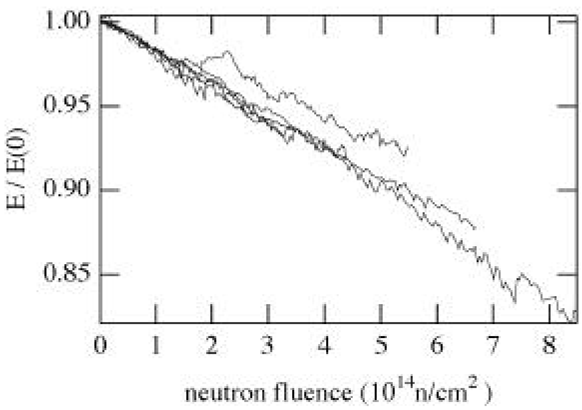

Figure 3: Normalized efficiency loss for lasers during neutron irradiation.

B. P-i-n photodiodes

The leakage currents I_{leak} measured at 2.5, 5, 7.5 and 10V reverse bias are shown as a function of fluence in Fig. 4 for neutron and proton damaged p-i-n detectors. The radiation induced leakage current increases non-linearly with fluence by up to 6-7 orders of magnitude more than pre-irradiation values of ~10pA. Approximately 10 times more neutrons were required to cause the same increase in dark current as for protons.

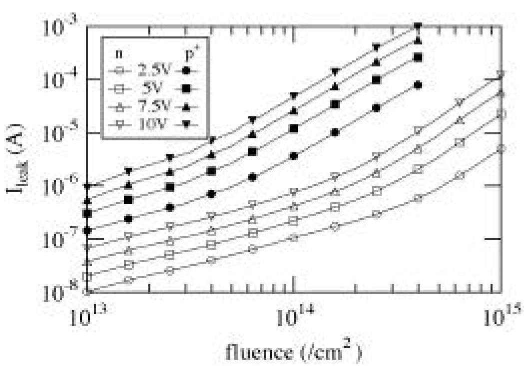

Figure 4: Leakage current increase p-i-n detectors during neutron (n) and proton (p) irradiation.

The effect of neutron and proton irradiation on the p-i-n response is illustrated in Fig. 5, showing the photocurrent I_{PC} for a 100μW DC optical signal, normalized to the initial pre-irradiation value $I_{PC}(0)$. There is only a small decrease in photocurrent up to a certain fluence, around 1-4x10^{14}n/cm^2 or 2-8x10^{13}p/cm^2, depending upon the bias voltage. Above this fluence, there is a rapid decrease of the response.

In contrast to the hadron irradiation results, devices that were irradiated with ^{60}Co gammas to 100kGy showed a much smaller increase in leakage current, of ~3 orders of magnitude, and no change in photocurrent.

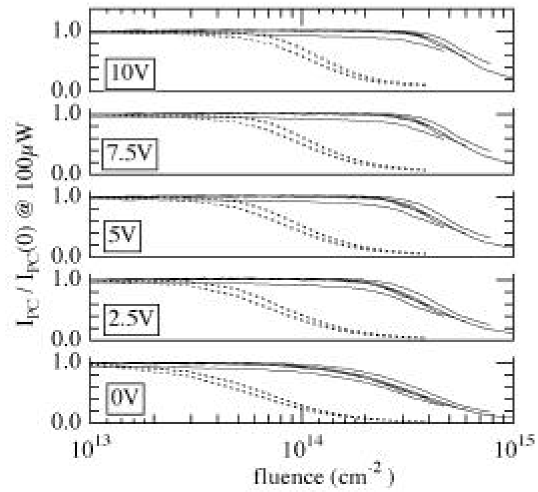

Figure 5: Decrease in photocurrent I_{PC} for 100μW optical signal during neutron irradiation (solid lines) and proton irradiation (dashed lines) for bias voltages between 0V and 10V.

Annealing of the leakage- and photo-current was also measured after each irradiation test. The neutron-irradiated devices were measured for the longest period (3 months), during which time ~20% of the leakage current damage annealed, but no recovery of response was observed. For the gamma-irradiated devices no significant recovery of the leakage current was observed in 80 hours following irradiation. Recovery measurements on the proton-irradiated p-i-n diodes were consistent with the neutron damage results.

C. Fibers and connectors

The radiation induced loss measured in the pure-silica core fiber is ~0.08dB/m after 80kGy, compared to ~0.12dB/m in the Ge-doped core fiber [6]. This low level of damage indicates that both fiber types might be suitable for use in the CMS tracker where only 10m of fiber will be exposed to high radiation levels.

Repetitive mate-demate tests have been performed on irradiated MT ferrules, showing no significant degradation of the optical and mechanical performance of connectors after 100 cycles [8].

IV. ANALOG OPTICAL LINK FOR TRACKER READOUT

The performance required from the CMS tracker analog link can be summarized as follows: (a) full scale dynamic range of 7-8bits, with <2% deviation from linearity, (b) overall link noise contribution (rms) equivalent to less than one third of the least significant bit (LSB), and (c) settling time of 15ns to within 1% of the end value.

A. Electronics

All electronics used in the tests reported below is based on commercial off-the-shelf radiation-soft components.

The laser driver consists of a wide bandwidth (370MHz) operational transconductance amplifier generating a modulation current proportional to the input voltage signal with a measured gain of 5.2mA/V. The laser DC working point is set by adjusting the reference input resistor of a monolithic dual-transistor current mirror.

On the receiving side of the readout chain, a two stage transimpedance amplifier, based on high gain-bandwidth product integrated amplifiers, achieves a transresistance gain of 9.93k , in a bandwidth in excess of 100MHz. The DC-coupled circuit features a bias point compensation network to adjust the output range of the amplifiers to the analog to digital converter (ADC) input range.

Whereas the receiving amplifier might be used as such in the final tracker readout system, the laser driver will have to be integrated into a radiation-hard technology. A 4-way chip has been custom designed in a 0.8μm BiCMOS radiation-soft process, and is currently being evaluated [9]. At a later stage, it will eventually be integrated into a radiation-hard process.

B. Characterization

The measured static response of the analog link is shown in Fig. 6. The relative deviation from linearity is plotted against the right axis; it is defined as the relative error with respect to a linear fit for input signals between 0 and 75% of full scale. The results are well within the 2% linearity specification.

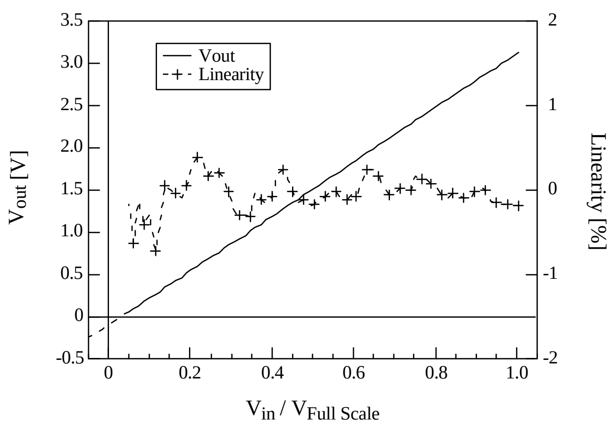

Figure 6: Optical link transfer characteristic and relative deviation from linearity.

The optical link step response is shown in Fig. 7. The solid line is the normalized link input signal. It is representative of a large signal which might be delivered by the front-end chip with a rise time of 5ns and a plateau of 20ns. The dashed line represents the output signal V_{out}. We measure on the output pulse an overshoot of 4% of the pulse height and a settling time of 10ns to within 1% of the end value. It is worth recalling that signals will have to be digitized within the 25ns sample period.

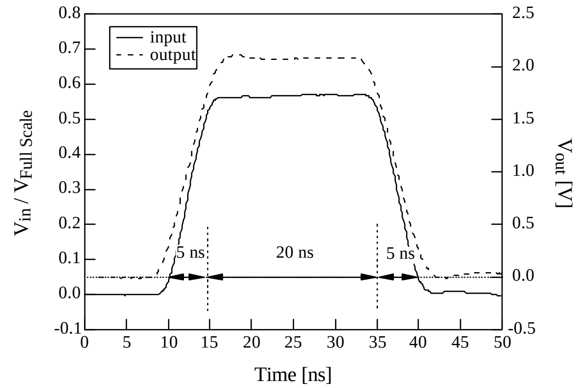

Figure 7: Optical link response to an input pulse representative of a large front-end chip signal.

The link frequency response characteristic, shown in Fig. 8, was measured using a spectrum analyzer equipped with a tracking generator. Dots are experimental data and the solid line is a fit with a second order filter function. The -3dB cut-off frequency is 110MHz, essentially limited by the receiver bandwidth. By applying an inverse Fourier transformation on the fit, the temporal step response was synthesized and the measured 10ns settling time value within 1% was confirmed. Additional results can be found in [10].

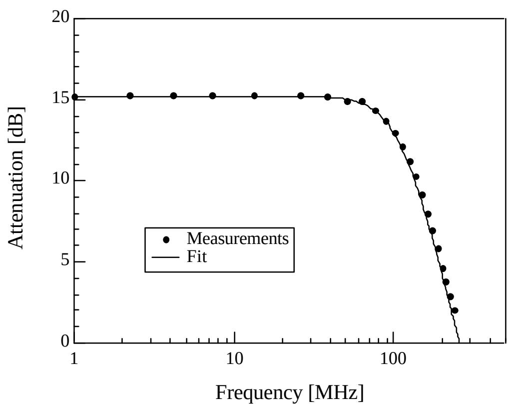

Figure 8: Optical link frequency response.

C. Integration into a readout chain

The laboratory setup used to evaluate the performance of a readout chain is depicted in Fig. 9. The laser diode is biased between 13mA and 17mA, and generates a CW optical power between 180µW and 420µW. The CMS prototype Frond End Driver board (FED) is housed in a 9U VME crate. One of its 64 input channels is connected to the photodiode receiver part of the optical link. A 10-bit, 40MS/s ADC digitizes the analog data transmitted by the link and stores samples in a Dual Port Memory (DPM) before VME readout.

Data and timing signals are generated by a 1GHz Arbitrary Waveform Generator (AWG), providing one analog and two digital outputs. Timing signals (clock and trigger) needed to operate the FED are synchronized with the data. Sampling occurs at 40MS/s (FED), but stimulus signal generation (AWG) occurs at a higher frequency; each 25ns pulse to be transferred

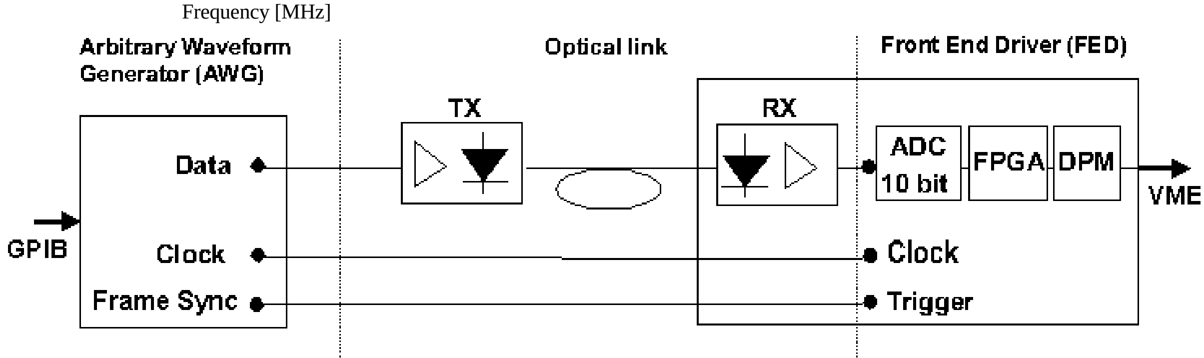

Figure 9: Test setup for the characterization of the optical readout chain, from arbitrary waveform generator and optical link to front end driver.

through the optical link is reconstructed with 20 AWG points generated at a frequency of 800 MHz.

A typical analog readout sequence generated by a front-end chip after a level 1 trigger occurrence is shown in Fig. 10, as emulated by the AWG; it consists of a digital header followed by 128 analog samples, time-multiplexed at a 40MHz rate.

The correlation between optical link input signal (as shown in Fig. 10) and data digitized by the FED after transmission through the optical link is shown in Fig. 11.

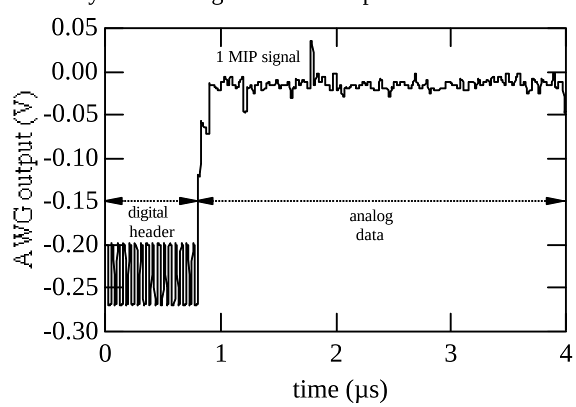

Figure 10: Front-end chip emulation by arbitrary waveform generator.

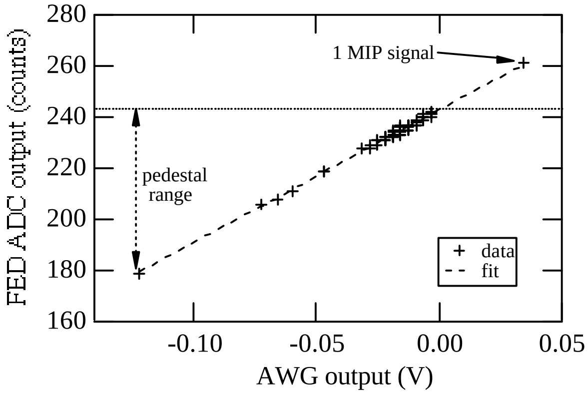

Figure 11: Correlation between the emulated front-end chip output (128 analog samples only) and the FED sampled signal: data points and best fit are shown.

The readout chain performance is presented in Fig. 12, where the FED output signal is plotted as a function of the optical link input voltage [11]. The logarithmic scale is convenient to compare the signal swing level to its error components (noise and nonlinearity), and to give an immediate visual indication of the dynamic range of the system. It is apparent that the magnitude of the error components is limited to ~1 count (rms for the noise) all over the input range. The measured peak signal to rms noise ratio (SNR) is ~300:1.

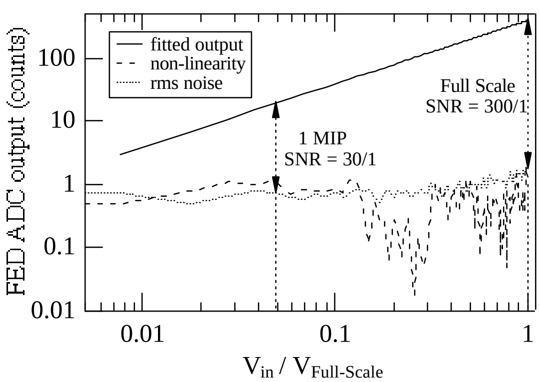

Figure 12: Results of the static evaluation of the readout chain.

V. DIGITAL OPTICAL LINK FOR TRACKER CONTROL AND TIMING DISTRIBUTION

The CMS-tracker control system includes a bi-directional optical link with control data, clock and Level 1 trigger signals (2 fibers) sent from the back- to the front-end as well as status data and clock signals (2 fibers) returned from the front- to the back-end [12]. The bit-rate is 40Mb/s. For redundancy reasons, the number of optical lines is doubled between front- and back-end, resulting in a modularity of 4 transmitters and 4 receivers per package, as in the case of the analog readout system.

The envisaged number of digital links is of the order of a few thousands. Besides transmitters, fibers, and connectors, the receivers (including PIN photodiodes, transimpedance amplifiers, and discriminators) will also be located in the highly irradiated region of the detector and must therefore be validated for radiation hardness.

A. Electronics

All electronics used in the tests reported below is based on commercial off-the-shelf radiation-soft components. The laser driver is a 1.2Gb/s bipolar chip. The receiving circuit is based on a high dynamic range 140MHz bandwidth transimpedance amplifier, AC-coupled to a 155Mb/s postamplifier.

For the final tracker control digital links, both driver and receiving amplifier will have to be realized in radiation-hard form. The digital driver will be a variant of the analog driver ASIC described in section IV.A. The digital receiver is currently being designed.

B. Characterization

The digital link performance was assessed by transmitting a pseudo-random NRZ coded bit stream (2^{11}-1). The injected optical power P_{laser} was -3.25dBm and the received optical power P_{pin} was varied with an optical attenuator. Fig. 13 shows an eye diagram obtained at a bit-rate of 40Mb/s for a receiver power of P_{pin}=-32.2dBm. The Bit Error Rate (BER) corresponding to these conditions is 10^{-12}.

The BER results are shown in Fig. 14 for measurements done at 40Mb/s and 160Mb/s. Data are also shown for an irradiated photodiode having been exposed to a neutron fluence of $6x10^{14}$n/cm^2 and a dose of 100KGy.

A BER of less than 10^{-12} is easily attained with the present digital link configuration. Operating with an irradiated PIN diode shifts the received signal level by 5dB but still preserves an excellent safety margin for operation at LHC. This 5dB penalty is well correlated with the ~70% loss in the photodiode responsivity observed during the irradiation tests (see Fig. 5).

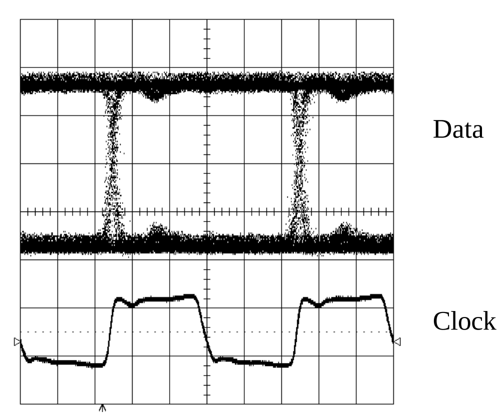

Figure 13: Eye diagrams at 40Mb/s with power at the receiver of -32.2dBm. The data bits are strobed on the falling edges of the clock (5ns/div. time-scale).

The higher BER at 160Mb/s is attributed in part to the clock not being well centered within the eye. Work is in progress to characterize digital links up to 1Gb/s.

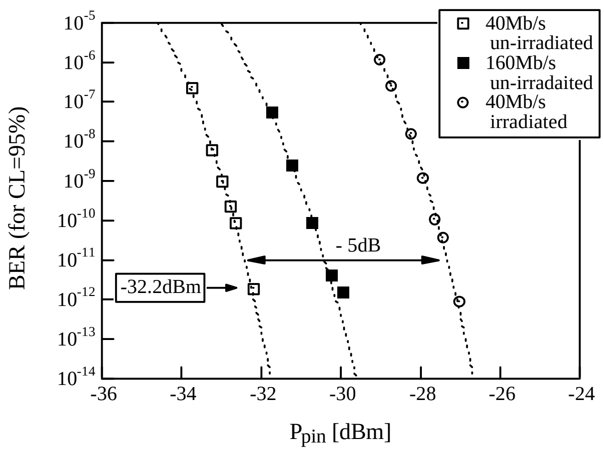

Figure 14: BER plot at 40Mb/s and 160Mb/s for irradiated and un-irradiated PIN photodiodes.

VI. CONCLUSION

Radiation-hard optical links featuring characteristics suitable for analog as well as digital data transmission are being developed for the CMS tracker.

Commercial optoelectronic devices (lasers, pin-photodiodes, connectors, fiber) from several different manufacturers have been tested for radiation hardness with qualitatively identical results; provided that the link operating point can be adjusted to track radiation damage, operation in the CMS tracker environment will be possible for the lifetime of the experiment.

Complete analog and digital data link prototypes have been successfully realized using the same optoelectronic components as tested for radiation hardness, and discrete off-the-shelf electronics. Test results confirm that a dynamic range of 50dB, a linearity deviation of less than 2% and a bit error rate of less than 10^{-12} are achievable with some safety margin. Integration of an analog optical link in an emulated CMS-tracker readout chain has been achieved and a peak signal to rms noise ratio of 300:1 (49.5dB) has been measured.

All validation tests (performance and radiation resistance) have been carried out on one-way transmitter and receiver assemblies. 4-way low mass non-magnetic packages relying on the same die and Si-submount technology are being custom developed.

The proposed optical link establishes a platform which could be common to many analog and high speed digital links across a variety of high energy physics experiments. Specifications will be frozen by the end of 1998, and production will start in 2000.

VII. ACKNOWLEDGMENTS

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