Compact Frontend–Electronics and Bidirectional 3.3 Gbps Optical Datalink for the H1–Experiment

Lüders S., Baldinger R., Eichler R., Grab C., Meier B., Streuli S., Szeker K.

Institute for Particle Physics, ETH Zürich, 5232 Villigen PSI, Switzerland
Stefan.Lueders@desy.de

Abstract

The upgrade of the multi–wire proportional chamber (CIP) of the H1–experiment at HERA (DESY) increases the number of channels to 9600. These channels have to be read out within the time between two bunch crossings of 96 ns and made available to the z–vertex trigger. With the extremely tight spatial conditions at the rear CIP endflange a fast and compact bidirectional read–out electronics is required, keeping the power consumption and the amount of dead material in the H1–experiment to a minimum.

This contribution presents a solution using 40 identical optical link modules, stacked on top of each other in groups of five and each transferring the trigger information with a data rate of 4×832 Mbps (an effective rate of 4×625 Mbps) via optical fibers out of the H1–experiment.

I. Introduction

With the year 2000 upgrade of the HERA electron–proton collider at DESY, an increase in luminosity by a factor of five is anticipated. The expected higher background rate, predominantly proton–wall and proton–gas reactions, necessitates a redesign of the H1–experiments' central inner multi–wire proportional chamber (*CIP*) to provide high background rejection efficiency of the z–vertex trigger [1, 2, 3].

The new CIP [4] is built of five concentrical cylinders (*layers*) with radii from 157 mm to 193 mm. In the azimuthal angle, each layer is equally subdivided into 16 *segments*, at which each segment consist of 120 separate *pads* [1] along the symmetry axis (z*–axis*). These 9600 channels provide space points which define the direction of tracks needed for the z–vertex trigger.

To retain high acceptances for the CIP and neighbouring detectors in the H1–experiment, the available space for mechanics and electronics is limited at the backward endflange[2] of the CIP to a 130 mm long open cylinder with inner and outer radii at 150 mm and 200 mm, respectively. These extremely tight spatial conditions have to be shared between frontend electronics (*on–detector electronics*), their suspension and cooling, low and high voltage power cables and gas supply lines (figure 1). Therefore one

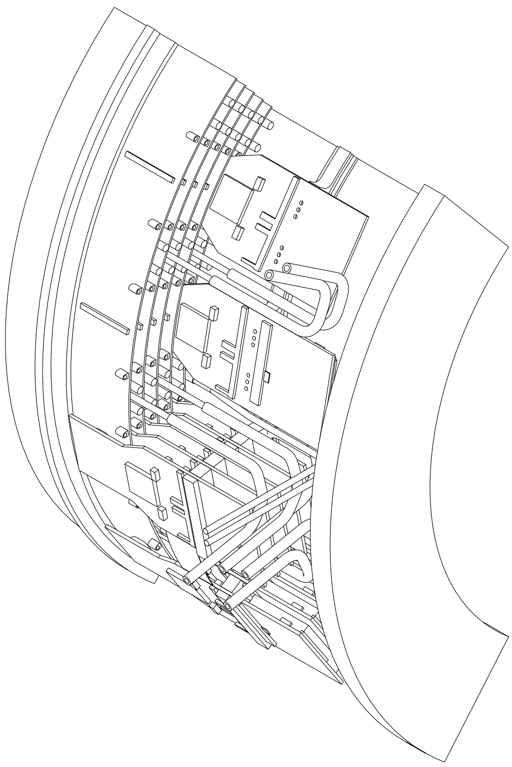

Figure 1: On–detector cards mounted on the CIP. To the left the five layer CIP with gas tubes and HV cables. Plugged on five on–detector units stacked on top of each other and supported by cooling blocks.

on–detector electronics unit is limited in size to 130 mm length, 2×49 mm width at most and 8 mm height. Its power consumption has to be kept to a minimum to avoid too much heat dissipation inside the H1–experiment because of a limited water cooling.

Furthermore, to cope with these tight spatial constraints, only optical fibers allow high transmission rates while reducing the number of cables to a minimum. A read–out with copper cables as presently done would in-

[1] In fact, the CIP uses a projective geometry requiring 119 pads on the innermost layer, and 112, 106, 99 and 93 pads on the following layers, respectively. But for symmetry reasons, each optical link module will be capable to handle 120 pads.

[2] The term "backward" labels the end of the H1–experiment pointing in the direction of the electron beam, i.e in the $-z$ direction.

crease the present volume by a factor of ten, consuming even more space at the endflange and producing an unwanted high contribution to the dead material. Optical fibers are not likely interferring escaping particles due to its small radiation length compared to copper cables.

Via 40 identical *optical link modules*, the pad information is read out every 96 ns (the time between two bunch crossings) i.e. with a rate of 10.4 MHz (*HERA clock signal*) to the *trigger electronics* located outside the H1–experiment. Thus the total digitized trigger information per module sums up to an effective data rate of 4×625 Mbps according to 2×120 pads from two adjacent segments of one layer (*double segment*). Vice versa, the on–detector electronics component must be synchronized with the global HERA clock signal — requiring bidirectionality — and analog signals from each pad should be accessible for remote monitoring purposes. The ETH Zürich group has already built an optical read–out for the H1–experiment, which has been successfully operated since 1995 [5].

Each optical link module consists of an on–detector unit, two optical hybrids, optical fibers and a receiver unit. The *on–detector electronics unit* amplifies the signals from the pads, discriminates and serializes them to 4×16 bit words as explained in section II. Two *optical hybrids*, performing opto–electrical (re)conversion, maintain the optical link between on–detector electronics and the receiver electronics. Their functional design is presented in section III. Section IV. describes the *receiver electronic unit* which retrieves the multiplexed signals and distributes them to the trigger electronics. The performance of the optical link electronics is presented in section V.

II. On–Detector Electronics Unit

Each on–detector unit collects the charge from 2×120 pads, amplifies and digitizes this information and performs a two step multiplexing (four– and 16–fold). After electro–optical conversion, these light pulses are sent to the receiver unit (figure 2).

For each segment, the charge on the pads is read–out via micro coax cables to the rear endflange of the CIP and passed to a pair of analog read–out chips : *CIPix* [6]. Each CIPix chip amplifies, discriminates and fourfold multiplexes the signals from 60 pads. Synchronously with the fourfold HERA clock signal, its 15 digital output channels give four successive words with 15 bits each. The *First-Word bit* tags the first of these words and will allow to maintain the synchronization with the HERA clock signal at the trigger electronics. Together they form the 16 bit *trigger word*. An EmptyDataSet–signal, generated in the case of missing inputs on all 64 input pads of the CIPix, serves as the *EmptyDataSet bit*. This 17th bit will also be used for a very fast cosmic trigger.

A 16 fold multiplexer serializes the trigger word and addes a four bit encoding word proceeding the trigger word.

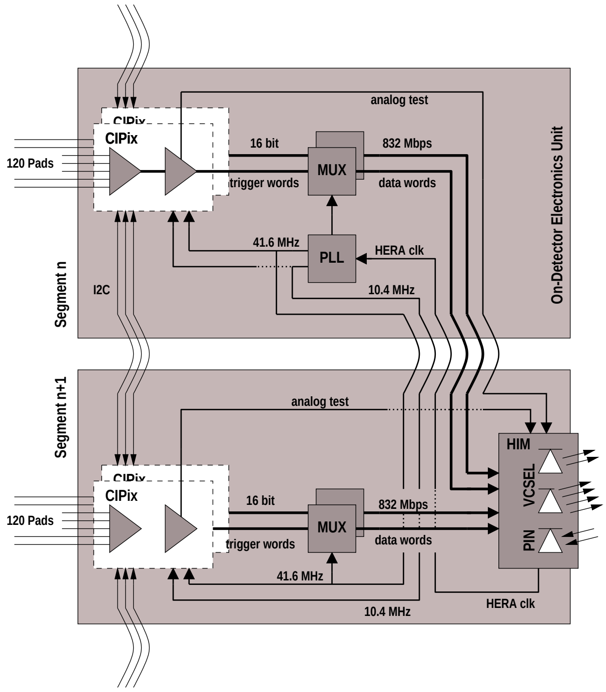

Figure 2: Signalflow of the on–detector electronics unit.

This encoding scheme saves an additional clock signal line between multiplexer and demultiplexer. The four differential high–speed data channels — one for each CIPix — are transmitted by the optical hybrid to the receiver electronics unit with a data rate of 4×832 Mbps (16 bit trigger word plus 4 bit encoding word). Thus information from 120 pads is transmitted with an effective data rate of 4×625 Mbps. In addition, the analog signals are branched off before entering the CIPix discriminator to monitor the CIP. These *analog test signals* are also transmitted.

The overall synchronization is done with the global HERA clock signal received by the optical hybrid. A low jitter phase–locked–loop (*PLL*) unit generates a fourfold HERA clock signal, distributed to the multiplexer and — in addition to the HERA clock signal — to the CIPix chip.

For compactness, one optical hybrid serves a double segment and is mounted on one of the two separate halves of the on–detector unit. The other half holds the PLL unit and provides the power supplies. Due to the curvature of the CIP, the high–speed data channels, analog test signals and HERA clock signal of the other segment need to be bridged to the optical hybrid via a thin four layer flex–capton print.

III. Optical Hybrid

The optical hybrids constitute the interface of the electrical and the optical regime.

Following the dataflow from the CIP to the trigger electronics, the optical hybrid on the on–detector unit (*HIM*) acts as a driver for the outgoing data words and analog test signal channels and as a receiver for the incoming HERA clock signal. The optical hybrid on the receiver unit side (*DeHIM*) acts vice versa.

Each HIM / DeHIM pair serves one double segment, i.e. transmittes four multiplexed data channels, two analog test signal channels and two HERA clock signal channels via an optical fiber array with eight fibers. Commercial solutions fail, because of the asymmetric bidirectionality and the very tight spatial boundary conditions. The outer dimensions of the optical hybrid are 41 mm × 33 mm × 6 mm at most.

A driver IC matches the signals of the four data channels to vertical cavity surface emitting laser diodes (*VCSEL diodes*). The VCSEL convert the current-modulated electrical signal into power-modulated optical pulses. After 40 m optical fibers, PIN diodes reconvert the optical back to electrical signals. These are amplified by a receiver chip and produce four differential data signals. The specifications for the used VCSEL and PIN diodes are given in table 1.

Table 1: Specifications of the VCSEL and PIN diodes.

Optical spec's :	VCSEL	PIN
Wavelength	850 nm, multimode	850 nm
Bamprofile	round	
Beamdivergence	$<10°$	
Active area diameter	18 μm	
Sense area diameter		100 μm
P_{out} / Response	$>$ 0.5 mW	$>$ 0.5 A/W
Electrical spec's :	**VCSEL**	**PIN**
$U_{operating}$	1.7–2.3 V	
$U_{reverse}$		$>$ 10 V
Serial impedance	typ. 30 Ω	
I_{laser}	3-4 mA	
I_{dark}		$<$ 40 nA
C_{total}		$<$ 0.7 pF @ 1.7 V
$\tau_{rise/fall}$	$<$ 250 ps	100 ps
Crosstalk		$>$ 30 dB
Mechanical spec's :	**VCSEL**	**PIN**
Operating temp.	$<$ 85 °C	
Chip thickness	150 μm	
Pitch diode/diode	250 μm	

In case of the HIM, six VCSEL and two PIN diode array dies are aligned with a precision of 5 μm with respect to two guiding pins and to each other keeping a pitch of 250 μm in order to match the pitch of conventional optical fiber array connectors (*MTP connectors*). The guiding pins adjust the connector to the diode arrays. On the DeHIM side, six PIN and two VCSEL diode dies are aligned with the same accuracy.

Because of a distance of less than 9 mm between two layers, it is not feasible to mount the MTP connector above the VSEL / PIN array. Even if the connector is reduced to its inner core (the *ferrule*), adjusting the ferrule perpendicular to the hybrid leaves no space to properly fix the connector to the optical hybrid. In addition, it complicates the installation of the fibers directly at the endflange. Thus this requires to mount the ferrule parallel to the optical hybrid i.e. parallel to the z–axis. While the diodes send the light perpendicular to the die, the 62.5 / 125 μm fibers are bent within 2 mm of height by modifying the ferrule and by using special fibers. The performance of the transmission line remains stable. The attenuation at each deflection lies below 2.0±0.2 dB.

Each optical hybrid is embedded in an aluminum casing, to provide robustness and handiness, to avoid electrical induction from outside and to shield the VCSEL and PIN diodes from dust. Brackets at the end of the aluminum casing give a proper mechanical connection of the hybrid with fiber tails of 700 mm length (350 mm at the DeHIM) and prevents outside stress to derange the precise mechanical adjustment of the ferrules to the diodes.

IV. RECEIVER ELECTRONICS UNIT

The receiver electronics unit provides the signals of four adjacent pads i.e. four successive trigger words and the EmptyDataSet bits to the trigger electronics (figure 3).

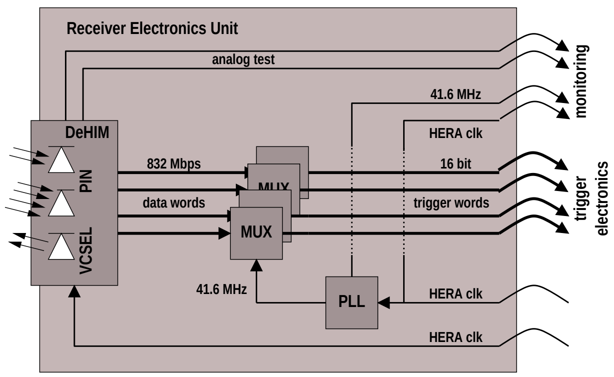

Figure 3: Signalflow of the receiver electronics unit.

The DeHIM receives the high speed data signals and passes them to four demultiplexers regaining the trigger words. Latches feed the remaining fourfold signals and the EmptyDataSet bit to the backplane that connects both trigger and receiver electronics.

The incoming HERA clock signal is received via the backplane and directed to the on–detector PLL unit via the DeHIM. It is also passed to the receiver boards' low jitter PLL unit producing the fourfold reference clock signal used by the demultiplexer. This fourfold clock signal and the FirstWord bit are passed to the trigger electronics for synchronisation of different receiver units.

At the receiver units' frontend, the following signals are available for monitoring purposeses : the 16 bit trigger word, the differential analog test signals, the HERA clock signal and the fourfold HERA clock signal.

V. PERFORMANCE

The optical link modules will be operated at $z = -1$ m well within the 1.16 T magnetic field. They will thus be exposed to radiation and not be accessible from outside without major effort. Therefore, the modules need to be tested beforehand in the H1 environment for long–term stability, reliability and robustness.

Prototypes of the module are operated since end of 1999. Neither break–down of any of the used components nor a decrease in the power output of the VCSEL diodes have been observed.

The lasering of the used VCSEL diodes typically starts at a current of 4.5 mA (figure 4). With appropriate settings

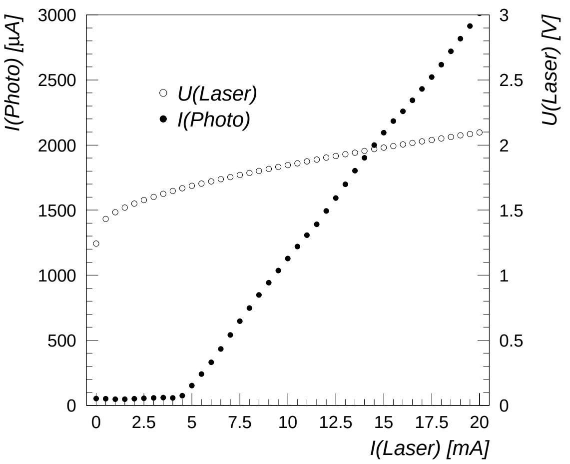

Figure 4: Output power ($\sim I_{Photo}$) and characteristic curve (U_{Laser}) of a VCSEL diode.

for the average and modulation current of the HXT 2000, the working range i.e. the digital signal levels have been optimized. They vary beween -49.1±4.5 dBm for logical "low" and -3.7±0.8 dBm for logical "high", leading to a dynamic range in optical output of 45 dB. The crosstalk lies above 20 dB. The high response gain of the PIN diodes drives the HXR 2004 receiver into saturation. Thus noise is suppressed.

Several bits of the data words have been accumulated for the eye–diagram (figure 5). Their density distribution is given by the grey scale. The rising and falling edges are well separated. The measurement of the zero–crossing of the rising edge results in a jitter of the data words of 61 ps.

For quantitative test, 16 bit random generated bit patterns simulate the trigger words at the multiplexers' input. After transmission via the full 40 m link and after demultiplexing, these patterns are compared with the original in-

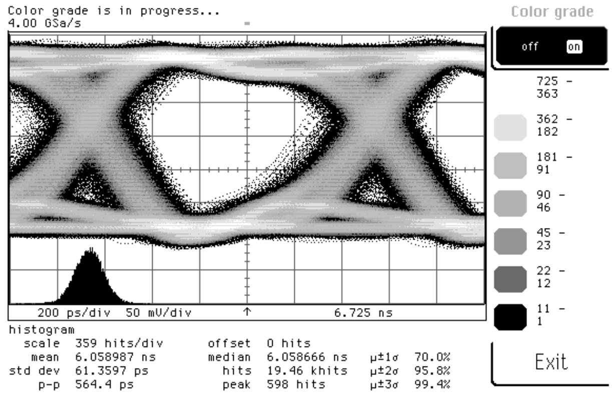

Figure 5: Eye–diagram accumulated for several bits from the data words. Shown is the pulse height as a function of time. The small histogram gives the jitter; the grey scale the density distribution.

put to measure the bit error rate. Over a period of ten days, three errors occured resulting in a bit error rate below 10^{-14}. This lies far below a tolerated rate of 10^{-9}, i.e. one error per second[3]. All errors could be related to instabilities in the external power supply.

Problems with the synchronization between the 16 fold multiplexer and demultiplexer have been seen, if the trigger words imitate the bit pattern of the encoding scheme for some hundred periods. The demultiplexers' Clock Data Recovery unit locks on the comprising bit pattern instead of the encoding word. In the operational mode of concern for the H1–experiment, this would require the same pattern of 60 pads of one segment (in a very special arrangement) repeated over many bunch–crossings. This is expected to be highly improbable.

From the analog signals, a delay time between CIPix input pads and receiver electronics unit frontend of 230 ns has been measured. This is dominated by the optical fibers with a delay of 200 ns.

The total power dissipation at the CIP end flange (i.e. the sum of all 40 modules) is about 310 W, low enough for a water based cooling. A summary of the specifications of one optical link module is given in table 2.

The on–detector unit has been operated in a magnetic field from 0 to 2 T.
The optical output of the VCSEL diodes, the threshold of the CIPix, the analog pulse heights, the noise level and the total power consumption of the on–detector electronics have shown no variations within the measurable precision. The jitter of the HERA clock signal remains stable, while jitter of the fourfold HERA clock signal increases from 49 ps to 53 ps with a phase shift of 18 ps. Thus no losses in the performance of the optical link due to the magnetic field are expected.

[3] The inefficiency of the z–vertex trigger will be dominated by the inefficiency of the CIP.

Table 2: Specifications of one optical link module.

Optical specifications :		
Digital "high"	-3.7 ± 0.8 dBm	
Digital "low"	-49.1 ± 4.5 dBm	
Dynamic range	45 dB	
Crosstalk	>20 dB	
Electrical specifications :		
Jitter HERA clock	43 ps	
Jitter fourfold HERA clock	49 ps	
Jitter data words	61 ps	
Delay time	230 ns (fibers: 200 ns)	
Bit error rate	$< 10^{-14}$	
Power dissipation (digital)	@ +3.3 V	@ -3.3 V
On–detector unit (with HIM)	5464 mW	560 mW
Receiver unit (with DeHIM)	3696 mW	—
Power dissipation (analog)	@ +4 V	@ -4 V
On–detector unit (with HIM)	1300 mW	430 mW
Receiver unit (with DeHIM)	290 mW	270 mW

The radiation at the CIP endflange and thus at the on–detector electronics is estimated to be less than 4 krad per year. The VCSEL diodes have been irradiated to a fluence of about 2×10^{14} n/cm^2, but no measurable change in either threshold or efficiency has been seen [7]. After exposure with 200 Gy ± 4% from a ^{60}Co source, the optical fiber tails and the short distance cables have shown no change in the optical behaviour. The same is expected for the 36 m long cables.

An exposure to radiation of the complete on–detector electronics unit will be done at the Paul–Scherrer–Institutes test–beam in September 2000. But no decrease in the performance is expected.

VI. Acknowledgements

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VII. References

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