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The Versatile Link common project: feasibility report

F. Vasey,[c,1] **D. Hall,**[a] **T. Huffman,**[a] **S. Kwan,**[b] **A. Prosser,**[b] **C. Soos,**[c] **J. Troska,**[c] **T. Weidberg,**[a] **A. Xiang**[d] **and J. Ye**[d]

[a]*Department of Physics, Oxford University, Oxford, United Kingdom*
[b]*Electronic Systems Engineering (ESE) department, Fermilab, Batavia, IL, U.S.A.*
[c]*Physics Department, CERN, Geneva, Switzerland*
[d]*Department of Physics, Southern Methodist University, Dallas, TX, U.S.A.*

E-mail: francois.vasey@cern.ch

ABSTRACT: The Versatile Link is a bi-directional digital optical data link operating at rates up to 4.8 Gbit/s and featuring radiation-resistant low-power and low-mass front-end components. The system is being developed in multimode or singlemode versions operating at 850 nm or 1310 nm wavelength respectively. It has serial data interfaces and is protocol-agnostic, but is targeted to operate in tandem with the GigaBit Transceiver (GBT) serializer/deserializer chip being designed at CERN. This paper gives an overview of the project status three and a half years after its launch. It describes the challenges encountered and highlights the solutions proposed at the system as well as the component level. It concludes with a positive feasibility assesment and an outlook for future project development directions.

KEYWORDS: Optical detector readout concepts; Radiation-hard electronics; Front-end electronics for detector readout

[1]Corresponding author.

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1 Introduction

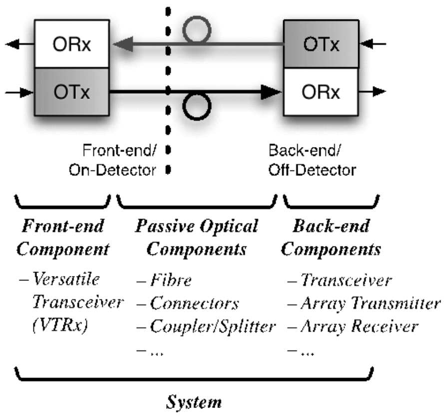
The Versatile Link is a joint ATLAS-CMS project, launched in April 2008 [1–3]. It aims at developing a radiation-tolerant bi-directional digital optical data link operating at rates up to 4.8 Gbit/s over a distance of typically 100 m. The project is broken down in 4 concurrent workpackages (each managed by a different institute): one at the system level (Southern Methodist University) and three at the component level: front-end components (CERN), back-end components (Fermilab) and passive components (University of Oxford). This paper reports on the completion of the second project phase, assessing link feasibility. It gives a broad status overview, while leaving most of the technical details to additional contributions presented in these proceedings by the individual workpackages [4–9].

1.1 Versatility

The Versatile Link is developed in both multimode (MM) and singlemode (SM) versions operating at 850 nm or 1310 nm wavelength respectively. This versatility is driven by the need of many experiments to reuse their installed fibre plants. SM and MM components of legacy as well as state of the art types must thus be validated for use in the optical systems under development.

The Versatile Link generic architecture and its implementation options are presented schematically in figure 1. In its basic point-to-point configuration, the link is driven by two transceivers,[1] one at each end. Their form factor was selected early on to be of the SFP+ type [10]. This choice

[1] A transceiver is the combination of an optical transmitter (OTx) and optical receiver (ORx) in a common package (TRx).



Front-end VTRx	Fiber	Back-end TRx
EE laser, 1310 nm		LR-SFP+ TRx
VCSEL, 1310 nm	SM	Board-edge Tx, Rx
InGaAs Pin, 1310 nm		Mid-board Rx
VCSEL, 850 nm		SR-SFP+ TRx
GaAs Pin, 850 nm	MM	Board-edge Tx, Rx, TRx
InGaAs Pin, 850 nm		Mid-board Tx, Rx, TRx

Figure 1. Versatile link generic architecture (left) and implementation options (right)

allowed a quick determination of the test system interfaces and also contributed to narrowing down the choice of commercial module types to be evaluated as reference components. At the link back-end however, the SFP+ form factor is perceived as too bulky by many experiments. Their need for high density calls for the deployment of parallel optics (including driver, receiver and controller ASIC), either in the form of board-edge optics (such as for instance SNAP12 modules [11]) or of mid-board optics (also frequently referred to as optical engines). Available as array transmitters, receivers or transceivers, these multi-channel modules are typically only interfaced to MM fibre ribbons. A few receiver arrays are nevertheless compatible with SM systems and recently even SM transmitter arrays have been identified. Several array-device types are currently being evaluated for use in the SM and MM back-end implementation of the Versatile Link [4].

Whereas the transceivers located at the Versatile Link back-end sit in a standard crate environment, the front-end Versatile Transceivers (VTRx) must withstand radiation, operate in a magnetic field and be as low mass as possible. The SFP+ modules to be developed for the Versatile Link front-ends thus need to be customized to include a radiation hardened transceiver chipset along with a radiation-qualified laser diode and photodiode. The module housing must also be customized to reduce as much as possible its material budget while maintaining both EMI susceptibility and emission within acceptable limits.

1.2 Challenges

The status of the Versatile Link project at the end of its first development phase (proof of concept) was presented at the end of 2009 [1]. The second Versatile Link project phase being reviewed here (feasibility study) had several challenges to face. Among those, the following three will be highlighted in this paper:

a) The radiation levels specified for High Luminosity LHC (HL-LHC) tracker environments are extremely high (500 kGy, 2×10^{15} n/cm^2, 1×10^{15} h/cm^2). In particular, the responsivity-drop of pin photodiodes and the radiation-induced attenuation in fibres at these doses and fluences bring the down-link power budget dangerously close to its limit.

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b) The design of a radiation resistant laser driver versatile enough to drive either a Vertical Cavity Surface Emitting Laser (VCSEL) or an Edge Emitting Laser (EEL) is a difficult compromise.

c) The development of a complete VTRx prototype meeting all system requirements must integrate together several custom designed and independently optimized parts to overcome a combination of optical, electrical as well as mechanical constraints.

The following sections (2 and 3) will review how the above challenges (a, b and c) were met, and how the Versatile Link feasibility could eventually be demonstrated.

2 Radiation-induced impairments

It has long been established that the performance of lasers, pin diodes and fibres degrades when the devices are subjected to radiation [12–14]. For lasers and fibres, this degradation is not only dependent on dose and fluence, but also on dose rate and flux. It cannot be directly inferred from accelerated irradiation tests unless significant annealing data is collected and folded into the performance model [5]. For pin diodes however, very little rate dependence is observed, and the severe degradation measured during accelerated HL-LHC irradiation tests is to first approximation irreversible. The high level of damage that will be incurred by pin diodes located inside an upgraded tracker, combined with the radiation-induced attenuation of their optical fibre is a cause of serious concern for the down-link (from back-end to front-end) power budget. We will concentrate here on this part of the link only, the up-link (from front-end to back-end) power margin being much more relaxed.

2.1 Optical fibers

Radiation Induced Absorption (RIA) in optical fibers is highly dependent on the dose, dose rate and temperature of their environment. Given an equal integrated dose, fibers suffer greater RIA when that dose is delivered at a higher rate and/or at lower temperatures. Since many detector locations are actively cooled, tests of Versatile Link fiber RIA were performed with cooled fibers. First tests at -25 deg. C at 27 kGy(Si)/hr showed mixed results where some of the SM fiber candidates appeared to have acceptable RIA but all of the MM fiber candidates experienced attenuations greater than the dynamic range of the test equipment [15].

In order to qualify for deployment and meet the overall link power budget, the Versatile Link fibers must suffer less than 1.0 dB of total RIA. The values initially measured for the MM fibers were far above this limit. A second test in the cold at a reduced dose rate of 0.66 kGy(Si)/hr later demonstrated that all tested fiber types in fact meet the RIA threshold, be they SM, MM, standard telecom grade fiber or specifically labeled as rad-hard [6]. It is worth noting that the dose rate used in this second test is still more than an order of magnitude above the worst expected HL-LHC rate and that the presented RIA estimates do not take annealing into account. These two facts result in a very conservative upper limit calculation being presented here which clears the way to the use of several brands of SM and MM fiber in the cold regions of upgraded HL-LHC detectors.

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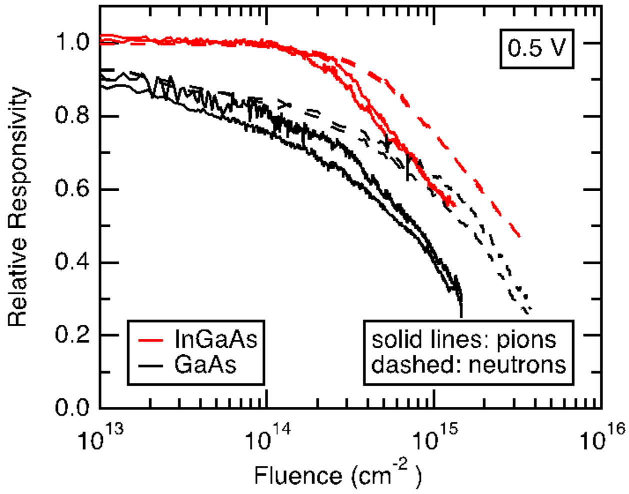

Figure 2. The effect of 180 MeV pion and 20 MeV neutron irradiation on the responsivity of InGaAs and GaAs photiodiodes [17].

2.2 Pin diodes

Pin diodes subjected to particle irradiation show a drop in responsivity and, for some material systems, an attendant increase in dark current [16]. In order to be confident that the devices selected to be used in the Versatile Link VTRx will survive HL-LHC fluence levels, an extensive test programme was established and a broad spectrum of pin diodes were tested using both neutron and pion beams. Figure 2 shows the particle-induced drop in responsivity of two representative photodiodes, a MM GaAs pin and an InGaAs pin typically used in SM applications [17]. The observed trend clearly shows that the responsivity degradation is significant at fluences above 10^{14} n/cm^2 and must be accounted for in the system power budget. Furthermore, it shows that it might — depending upon the target application — be advantageous to use InGaAs photodiodes even for multimode links operating at 850 nm and exposed to very high fluences (10^{15} n/cm^2) as this will lead overall to a lower power penalty since the damage for InGaAs devices is less than for GaAs devices.

2.3 Two radiation tolerance grades

The down-link radiation damage effects described in sections 2.1 and 2.2 above are a source of concern only at the very high doses and fluences found in HL-LHC tracker applications. They can be mitigated by selecting appropriate components for the front-end part of the link (radiation-hard specialty fiber, InGaAs-based pin diodes) and by increasing the transmit power emitted by the back-end components. Both mitigation options come at a price, and the second one unfortunately also brings the back-end transceiver Optical Modulation Amplitude (OMA) outside the typical specification range of Commercial Off The Shelf (COTS) components, especially in the MM case.

In order not to over-constrain systems operating in moderate radiation environments, two Versatile Link radiation tolerance grades have been defined: a calorimeter-grade (10 kGy, 5×10^{14} n/cm^2) which will rely on qualified but standard components, and a tracker-grade (500 kGy, 2×10^{15} n/cm^2, 1×10^{15} h/cm^2) which will be based on a narrower selection of components.

Table 1. Tracker grade and calorimeter grade Versatile Link optical power budget. The down-link (from back-end to front-end) is labeled Tx_VRx, while the up-link is labeled VTx_Rx.

Tracker grade	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-1.6 dBm	-5.2 dBm	-3.6 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	11.5 dB	7.4 dB	11.8 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	5.4 dB	-	5.4 dB
Fiber radiation penalty	1.0 dB	1.0 dB	1.0 dB	1.0 dB
Margin	1.8 dB	2.0 dB	2.8 dB	1.8 dB
Calorimeter grade	**MM_VTx_Rx**	**MM_Tx_VRx**	**SM_VTx_Rx**	**SM_Tx_VRx**
Min. Tx OMA	-5.2 dBm	-3.2 dBm	-5.2 dBm	-5.2 dBm
Max. Rx sensitivity	-11.1 dBm	-13.1 dBm	-12.6 dBm	-15.4 dBm
Power budget	5.9 dB	9.9 dB	7.4 dB	10.2 dB
Fiber attenuation	0.6 dB	0.6 dB	0.1 dB	0.1 dB
Insertion loss	1.5 dB	1.5 dB	2.0 dB	2.0 dB
Link penalties	1.0 dB	1.0 dB	1.5 dB	1.5 dB
Tx radiation penalty	0 dB	-	0 dB	-
Rx radiation penalty	-	2.5 dB	-	2.5 dB
Fiber radiation penalty	0.1 dB	0.1 dB	0 dB	0 dB
Margin	2.7 dB	4.2 dB	3.8 dB	4.1 dB

Calorimeter-grade Versatile Links will predominantly be of MM type (even though a SM variant could be envisaged), will use GaAs-based pin diodes at the front-end and COTS transmitters at the back-end (with a minimum Tx OMA of -3.2 dBm). Tracker-grade Versatile Links will use InGaAs-based pin diodes at the front-end. If SM, they will rely on COTS long range transmitters (LR) at the back-end (with a minimum Tx OMA of -3.6 dBm), but if MM they will have to rely on specially selected transmitters with high output power (with a minimum Tx OMA of -1.6 dBm).

The power budget for all Versatile Link variants is summarized in table 1 [3]. A power margin of at least 1.8 dB is maintained in all cases, guaranteeing error free link operation over an extended lifetime.

3 Versatile Transceiver prototype

The successful development of a VTRx prototype requires integrating together qualified components of several types: optics (laser and pin diode), electronics (GBLD and GBTIA ASICs), a high speed printed circuit board (PCB), and a mechanical interface for the optical connector. The design of the PCB, and in particular the impedance matching circuit between laser driver and Transmitter

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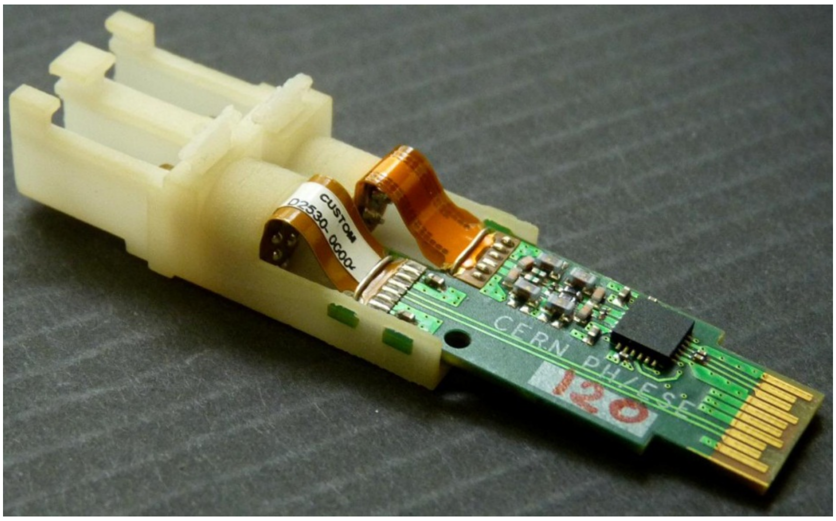

Figure 3. Fully assembled VTRx, with receive path at bottom and transmit path (with laser driver ASIC and impedance matching circuit) at top of PCB.

Optical Sub-Assembly (TOSA) required extensive simulation work [7]. The resulting circuit is compact, performs well up to 5 Gbps and is based on magnetic field tolerant components. The low mass plastic optical connector interface was fabricated using rapid 3D prototyping. This method allows immediate access to samples and quick design iterations during the prototyping phase, and opens the door to the exploration and customization of detector-specific VTRx geometries. Several polymer materials have been used and tested with different levels of success, but the ultimate fabrication method for the production parts remains to be determined.

The photograph of a fully assembled VTRx is shown in figure 3. SM as well as MM devices were built and distributed for system-level as well as irradiation testing. The prototypes operate well and meet the specifications except for the GBLD limitations mentioned in the following section.

3.1 Radiation resistant laser driver and transimpedance amplifier ASICs

The VTRx hosts two custom designed ASICs from the GBT chipset: a GigaBit Laser Driver (GBLD) and a GigaBit TransImpedance Amplifier (GBTIA), both designed in 130 nm CMOS technology. The GBTIA ASIC is a very successful design [18] whose performance and integration with a pin diode in a Receiver Optical Sub-Assembly (ROSA) have been well described in [2]. The GBLD design has proven more difficult, a difficulty exacerbated by the requirement that it should be able to drive both a low current VCSEL and a high current EEL [8]. Figure 4 shows the block diagram of the VTRx device hosting the GBLD and GBTIA ASICs, together with two optical eye diagrams: one measured with a MM VCSEL and one with a SM EEL. Even though below specification in terms of rise/fall time and jitter, this measurement [7] indicates that the GBLD design is on the verge of converging. A new GBLD version is expected to become available in early 2012.

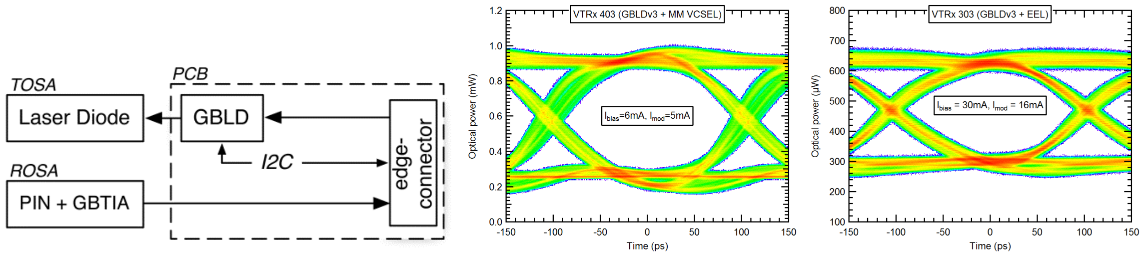

Figure 4. VTRx block diagram (left) and two optical eye diagrams from MM (center) and SM (right) laser transmitters driven by the GBLD ASIC [7].

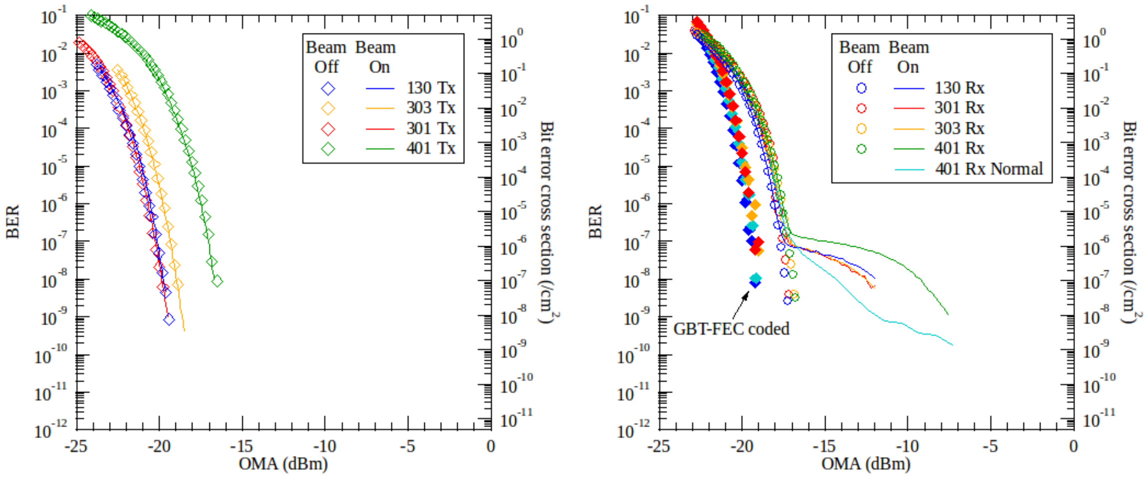

Figure 5. Bit Error Rate performance of VTx (left) and VRx (right) paths of several complete VTRx prototypes in a beam (VTRx 130, 301 and 303 are SM devices, VTRx 401 is MM) at grazing or normal beam incidence [9].

3.2 Single-event upset testing of the VTRx

Figure 5 shows the bit error rate test results of the transmit (VTx) and receive (VRx) path of several VTRx prototype devices tested in a 70 MeV proton beam ($\Phi = 10^8 \mathrm{p/cm^2/s}$) in August 2011 [9]. The data demonstrates that the transmitter remains unaffected by beam presence. In contrast, the receiver shows single event upsets (SEU) in the pin diode, a feature expected from a device optimized to collect charge. The only way to mitigate SEUs at these elevated data rates is by implementing Forward Error Correction (FEC), a functionality available from the GBT chip.

These results, even though still incomplete, indicate that it is possible to build a low mass, magnetic field tolerant transceiver device which will resist HL-LHC radiation environments.

4 Conclusion and outlook

In conclusion of the second phase of the Versatile Link project, the feasibility of a bi-directional 4.8 Gbps optical link for HL-LHC applications can be considered as demonstrated. Two radiation tolerance grades have been defined for calorimeter and tracker-grade applications. Suitable lasers, pin photodiodes and fibres have been identified, also for operation in cooled detectors. MM and

SM VTRx prototypes have been built and tested in system and in beam. A full set of specifications is available at [19].

To complete the Versatile Link development program, more results are expected on the tracker-grade VTRx (MM InGaAs ROSA, SM VCSEL TOSA), on the multi-fiber cabling options (ribbon and micro-tube cables), on the back-end tracker-grade transceivers (MM transmitter OMA, SM transmitter arrays), and at the system level (interoperability checks, components stress tests).

After completion of the common R&D work, phase III of the Versatile Link project will consist of two parts: i) a production oriented part for medium-term upgrades (2017–2018), where the Versatile Link will be customized for specific applications and corresponding tendering actions will be launched, and ii) a detector-specific R&D part for long-term upgrades (2020–2022), where new concepts will be explored for tracker-type applications (low power and small footprint) and calorimeter-type applications (high speed and parallelism).

The Versatile Link project is nearing the end of its generic program and detector-specific developments are about to take over. The joint ATLAS and CMS R&D project team has not only demonstrated technical feasibility of a Versatile Link for HL-LHC experiments, but has also proven that well-focused work across collaborations is possible and effective.

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