A versatile link for high-speed, radiation resistant optical transmission in LHC upgrades

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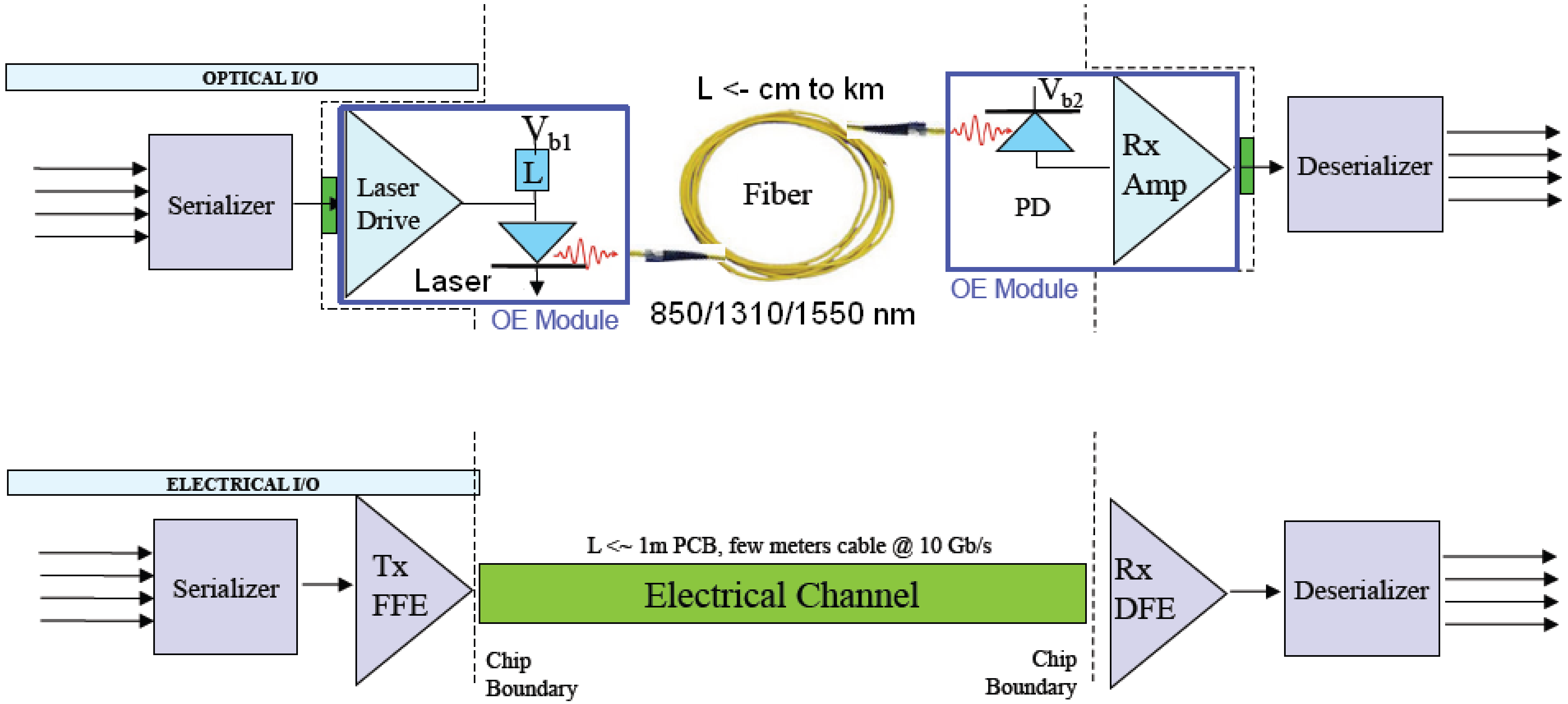
Outline

- Overview of optical links
- Versatile Link project introduction
- Work package progress
  - WP 2.1 front end (CERN)
  - WP 2.2 passive (Oxford)
  - WP 2.3 backend (Fermilab)
  - WP 1.1 system (SMU)
- Versatile Link project status
- Summary

From copper to fiber links



- Fiber link has advantages over copper link in power consumption, density, data rate, distance, EMI, cable management.

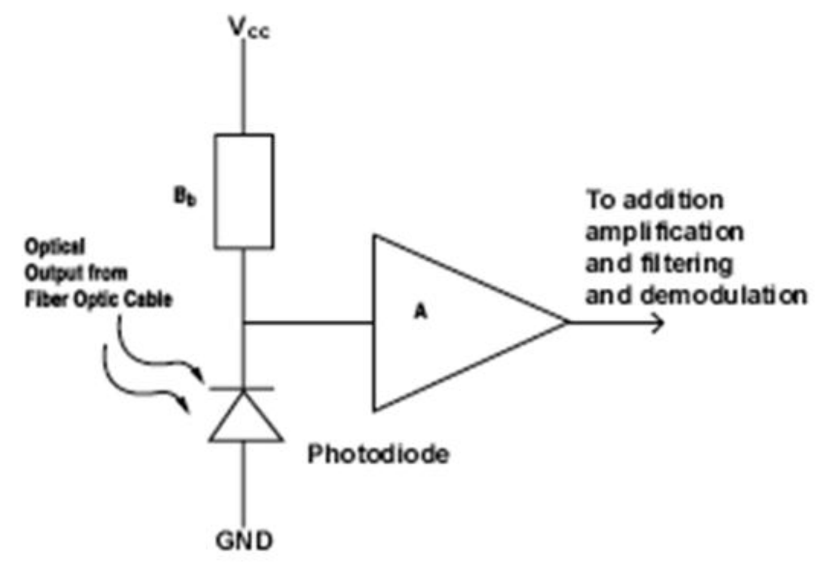
Courtesy of M. Ritter, IBM research, invited talk at TWEPP2010.

Technology options - lasers

Source type	Operating λ (nm)	Suitable fiber	Launch power	Data rate	cost	application
FP	1300	MMF SMF	10 dBm	10Gbps	Med	Metro, access, LANs
DFB	1310 1550	SMF	20 dBm	>10Gbps	High	Long haul, metro WANs
VCSEL	850 1310	MMF SMF	-3 dBm	10Gbps	Low	Access, LANs, premises

- Laser diodes are direct bandgap pn-junctions used under forward bias.
- Laser lasing wavelength depends on the material of the active layer. In the 850 nm-band AlGaAs/GaAs and in the 1300/1550 nm-bands InGaAsP/InP are commonly used.
- Lasers are usually radiation tolerant, but different type of laser changes differently when irradiated.

Technology options - photodiodes



Receiver block diagram

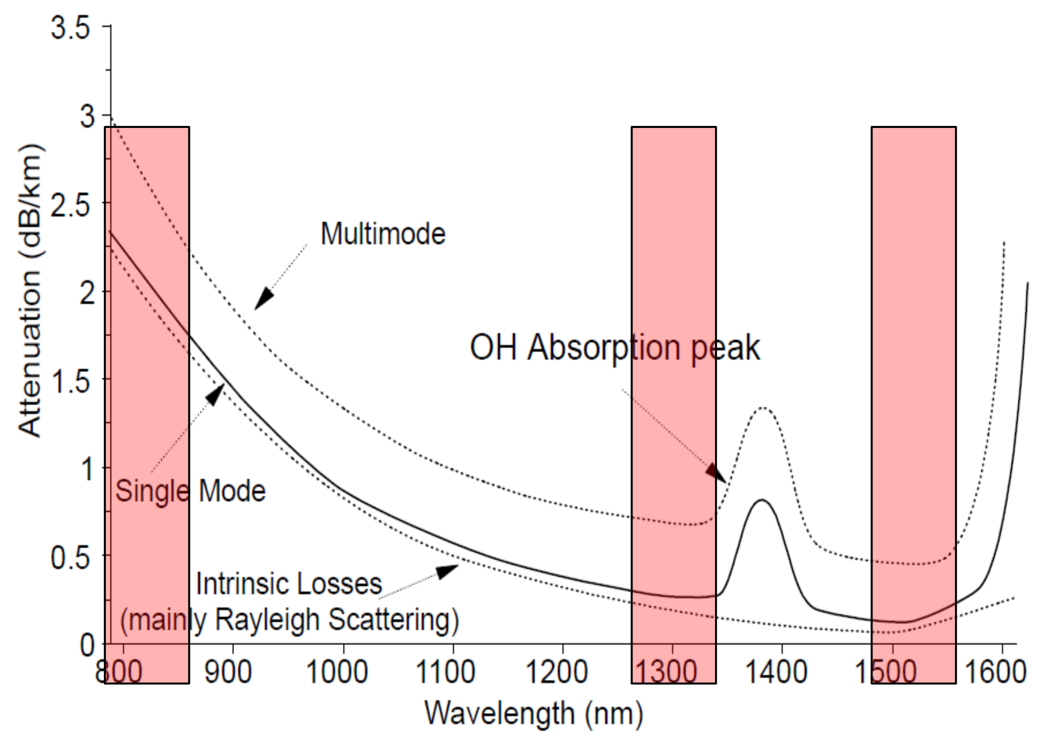
Available receivers:

- The p-i-n Photodiodes
    - Si, Ge, GaAs for shorter λ's (eg 850nm)
    - InGaAs for longer λ's (eg 1310/1550nm)
    - Good optical sensitivity

- Avalanche Photodiodes (APD's)
    - Up to 50% more sensitivity than p-i-n diodes
    - Operates at much higher voltage
    - Much higher cost than p-i-n diodes

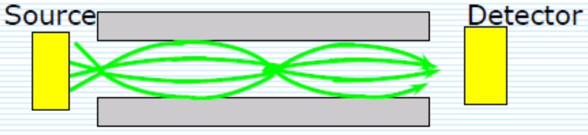
Technology options - fibers

- Single-mode fiber support one mode of transmission at 1310 or 1550nm
- Laser optimized multi-mode fiber designed to support laser-based 850 system



Typical Fibre Infrared Absorption Spectrum.

Multimode

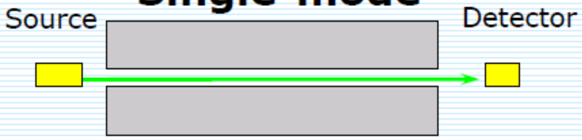


+ Low cost lasers and LEDs
+ Easy transmitter packaging
+ Lower system cost
- Higher loss, lower bandwidth
- Distance up to 2 km

Best for:

- ***Premises, Data Center, CO***

Single-mode



- Higher cost lasers
- Complex transmitter packaging
- Higher system cost
+ Lower loss, higher bandwidth
+ Distance to 60 km+

Best for:

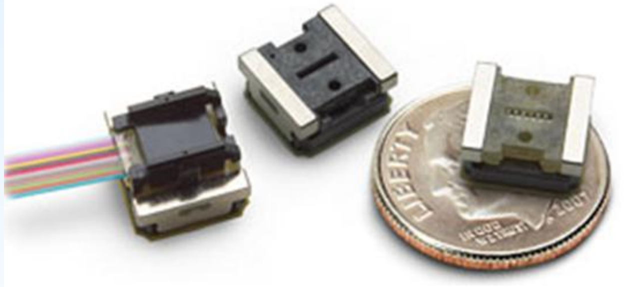
- ***WAN, MAN, Access, Campus***

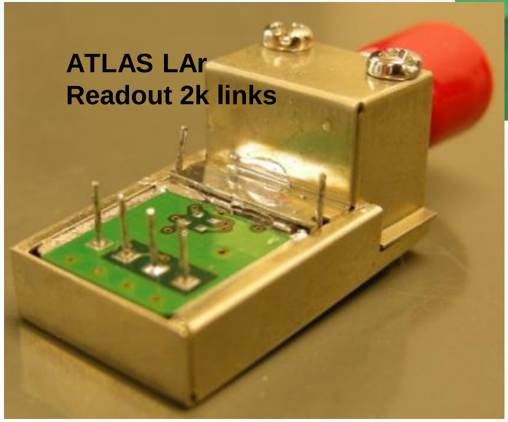
LHC -> High Lumi LHC Migration Path

0.1G

5/10G

40/100G





1.6G

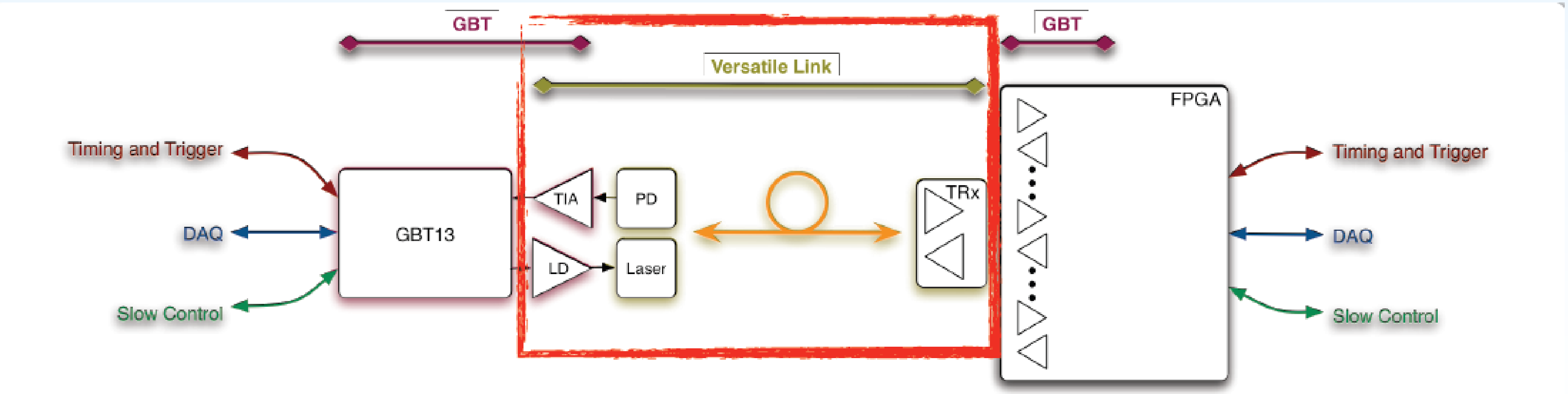
Highly demanding in R&D projecst:

- Expertise in optics, EE and physics.
- Test Equipment
- Technology
  - Rad and Mag tolerance
  - Low mass, low power
- Joint Project

VL project introduction – an ATLAS-CMS common project

- Optical layer linking front-end to back-end up to 150 m distant.
- Bi-directional @ 5 Gbps
- Two Point-to-point solutions
  - 850 nm Multimode
  - 1310 nm Single-mode
- Electro-optical pluggable module
- Radiation tolerent front-end

- Commercial off the shelf back-end
- Customer radiation tolerence qualified passive components
- In tandem with the GBT project
- Joint project endorsed by ATLAS & CMS upgrade steering group
  - Phase I: proof of concept (18 months)
  - Phase II: feasibility study (18 months)
  - Phase III: pre-prodn. readiness (18 months)



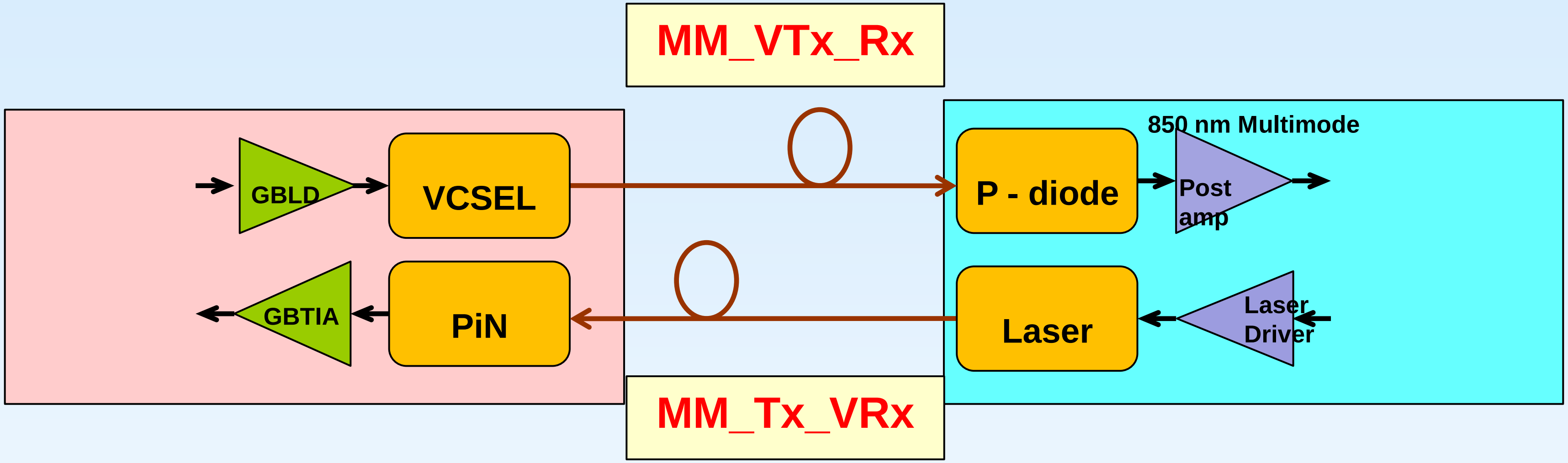
On-Detector
Custom Electronics & Packaging
Radiation Hard

Off-Detector
Commercial Off-The-Shelf (COTS)
Custom Protocol

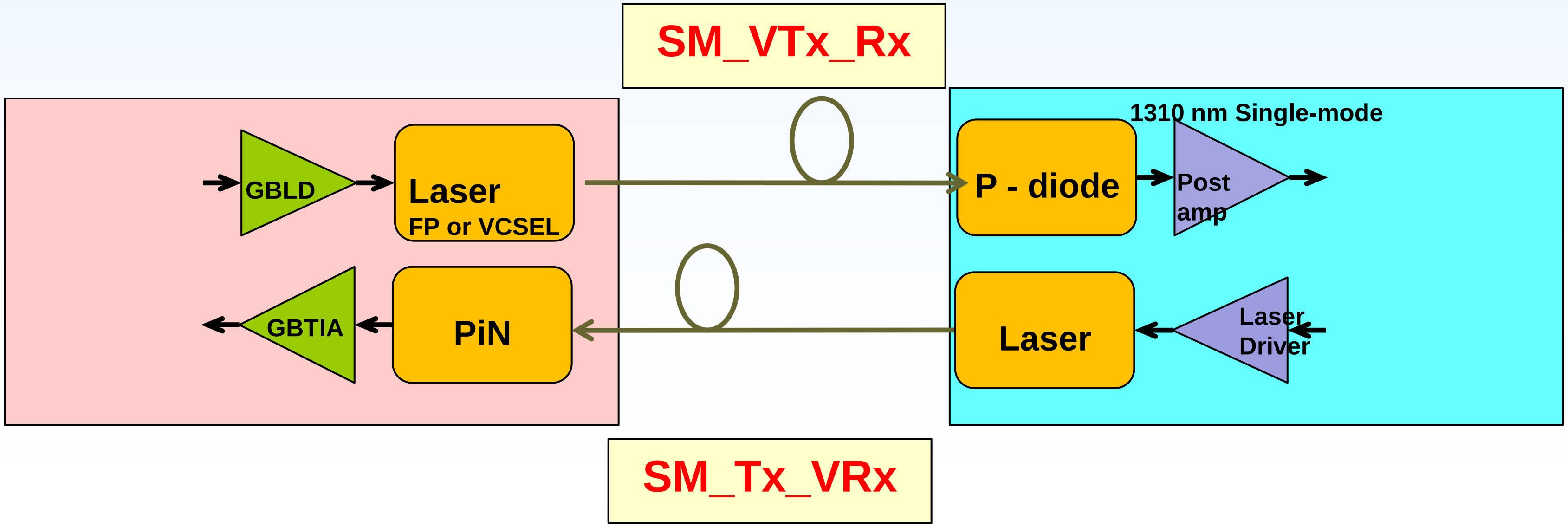
Nomenclature for the Versatility

Front End

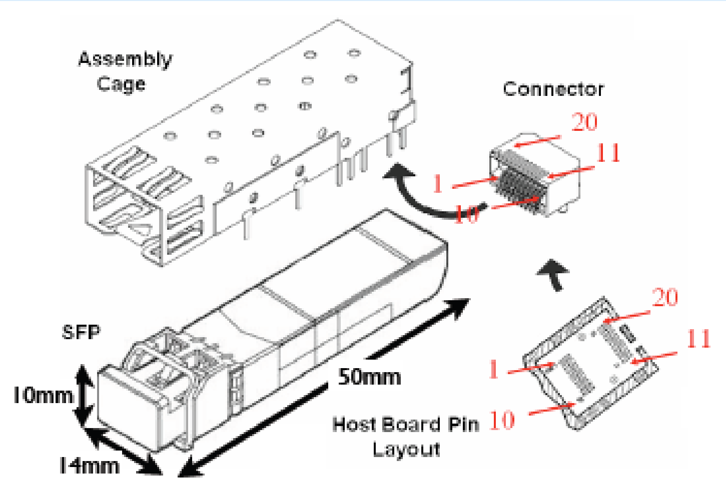
Back end – Off detector

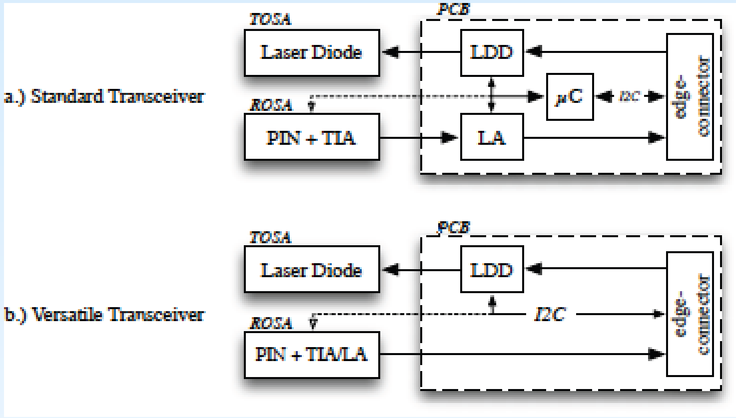


2 wavelengths and 2 data flow directions
4 device families and 2 type fibers



Front end concept (CERN)





- Based on industry standard SFP+
- Progressive modifications on
  - Lower mass, non-magnetic
  - Radiation tolerant chip sets

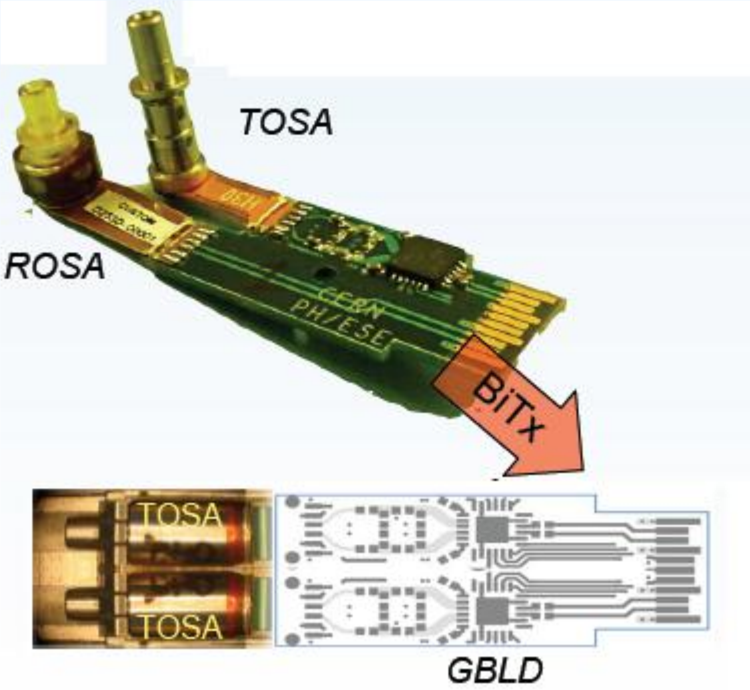
VTRx

Components

GBLD
GBTIA
Commercial LDD
Commercial TIA/LA
ROSAs
TOSAs
Device modelling

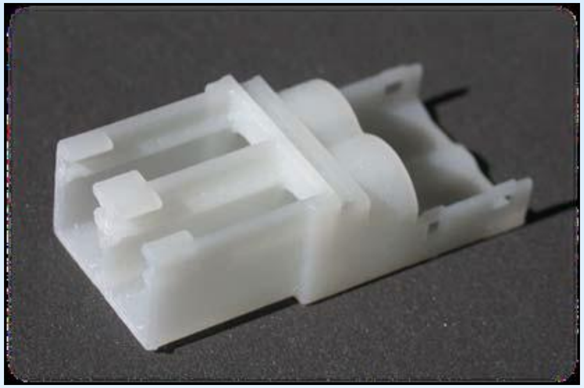
Pkg know-how

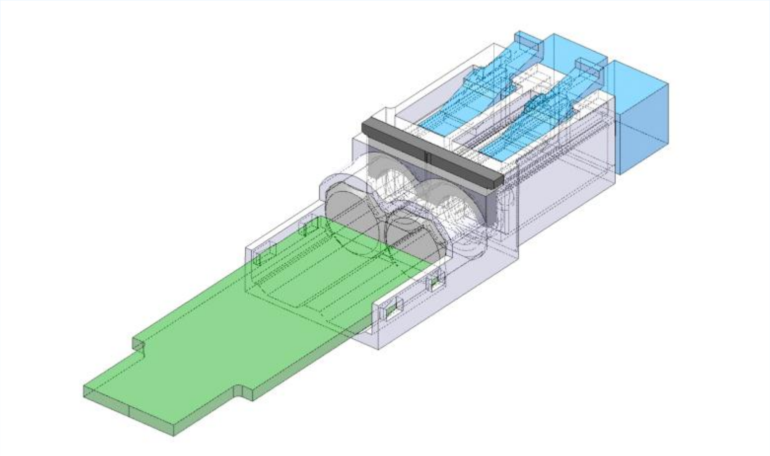
Commercial Eval Boards
In-house Test boards
Industrial partnership

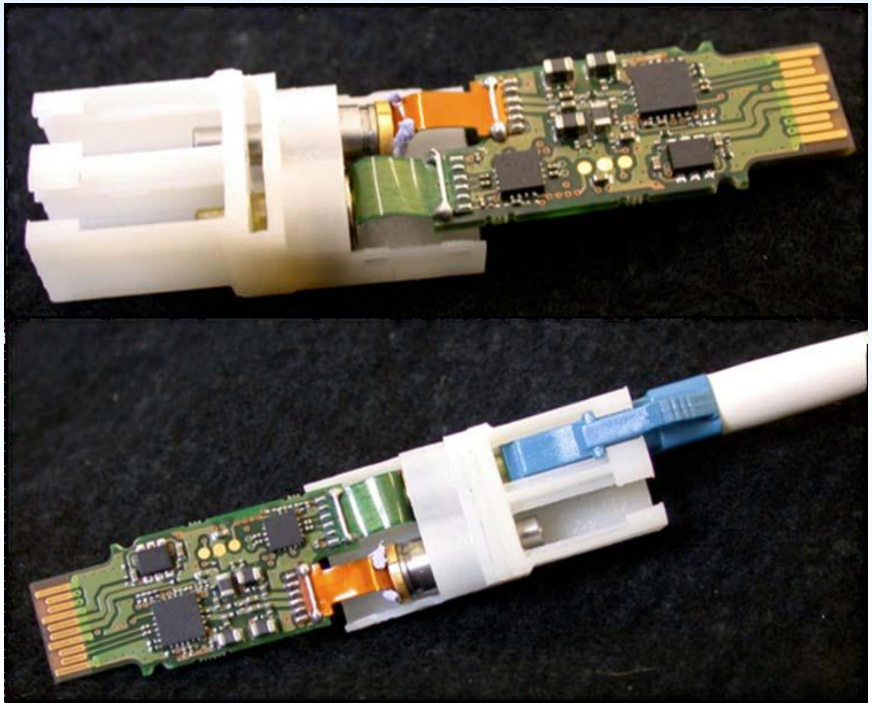


Front end packaging (CERN)

- Replace metal housing with low mass plastic latch
- Part mechanically associates LC connector, TOSA/ROSA and PCB
- Rapid prototype successfully tested

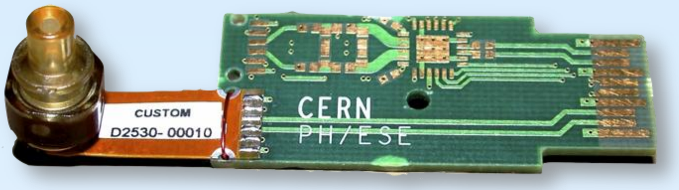


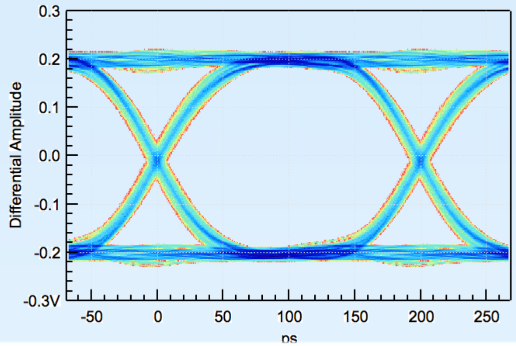




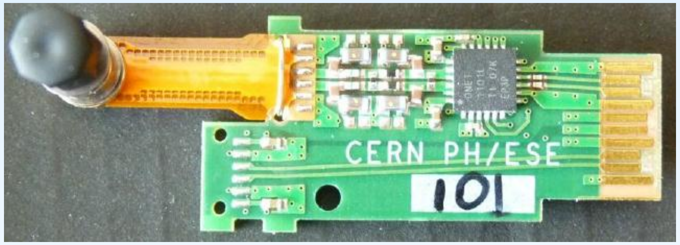
Front end opto-electrical design (CERN)

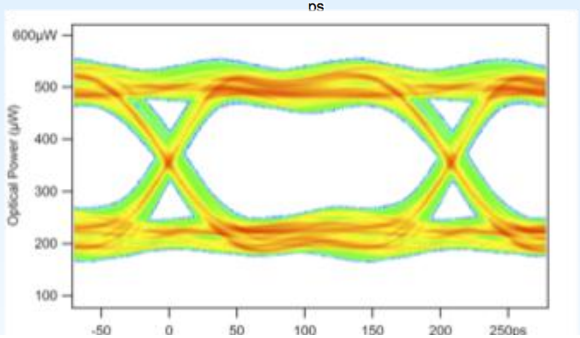
- **GBTIA-ROSA on prototype VTRx PCB**
  - **Favorable sensitivity test results**



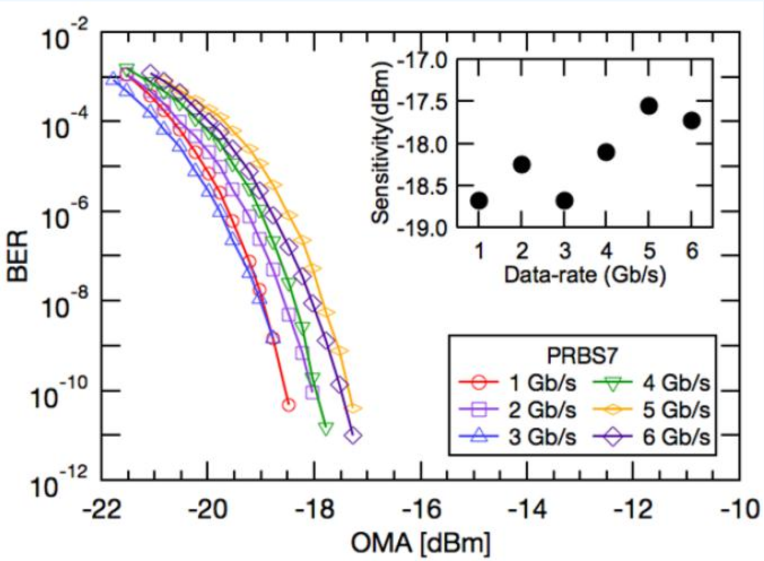


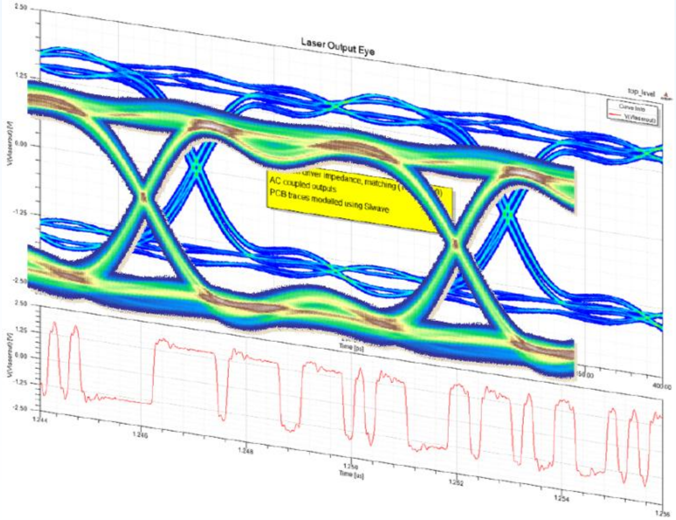
- **COTS Laser driver and TOSA on prototype VTRx PCB**
  - **Simulation and signal integrity assurance practice implemented**





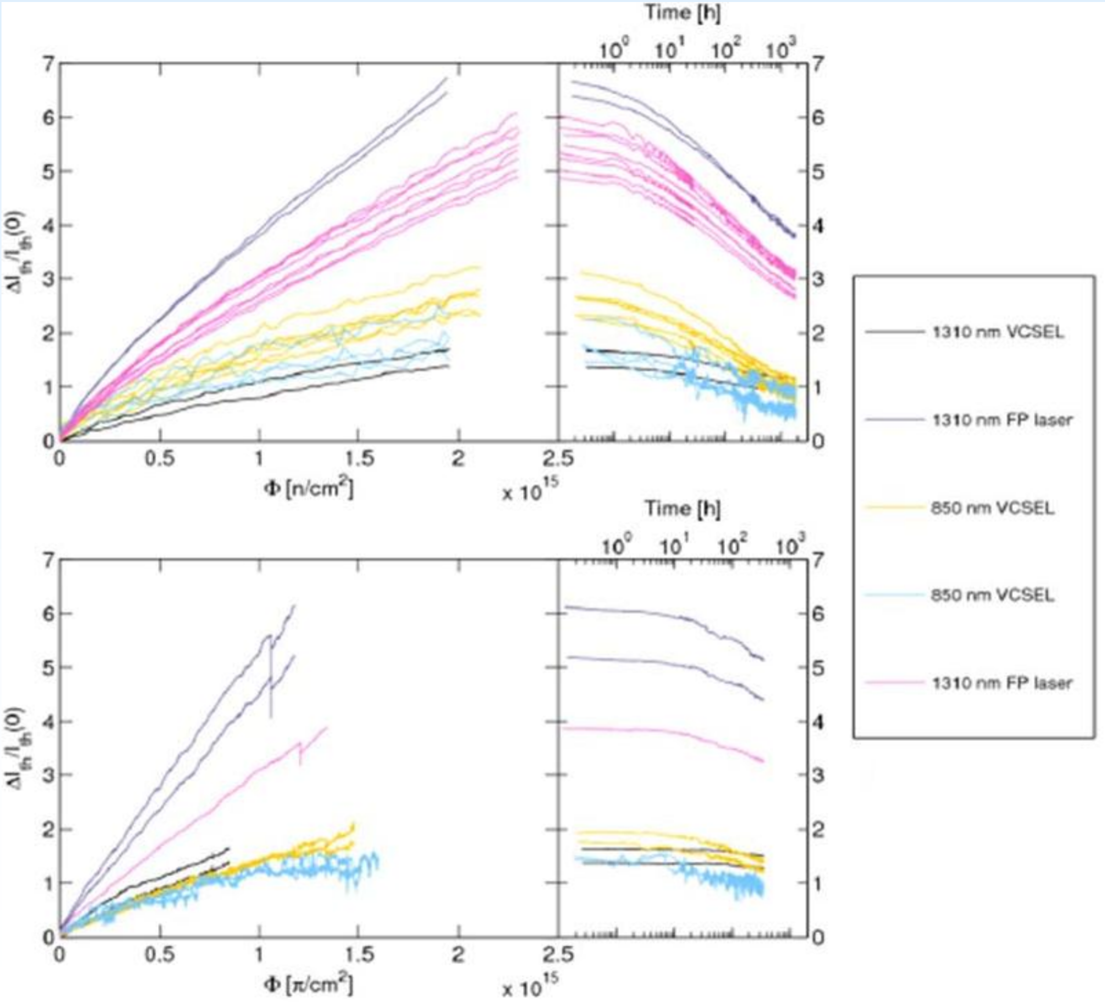
- **GBLD on prototype VTRx PCB is in the pipeline**

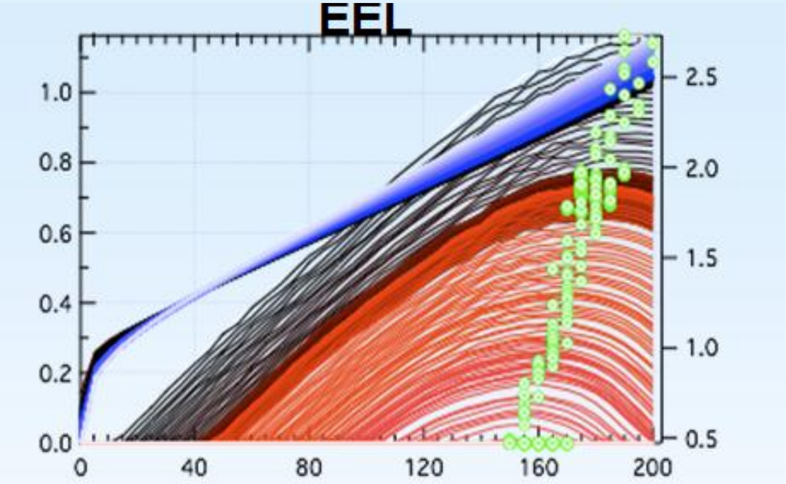


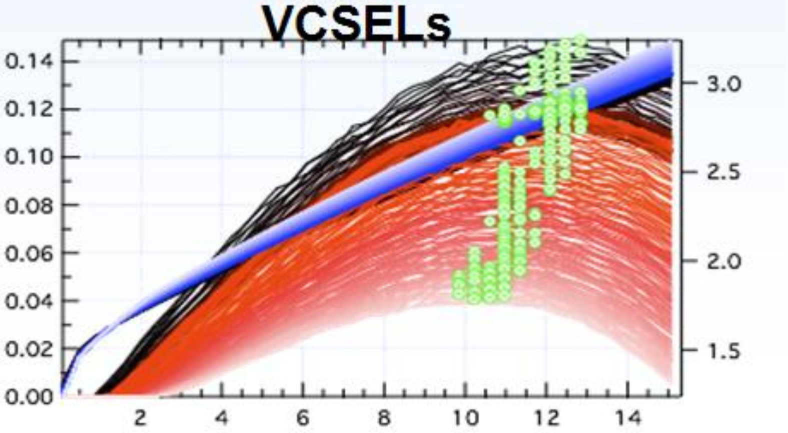


Irradiation test on lasers (CERN)

- 850nm VCSELs appear to be most radiation resistant
- Newer edge-emitters (EELs) are significantly more resistant than older designs
- A full source comparison taking annealing into account is in progress

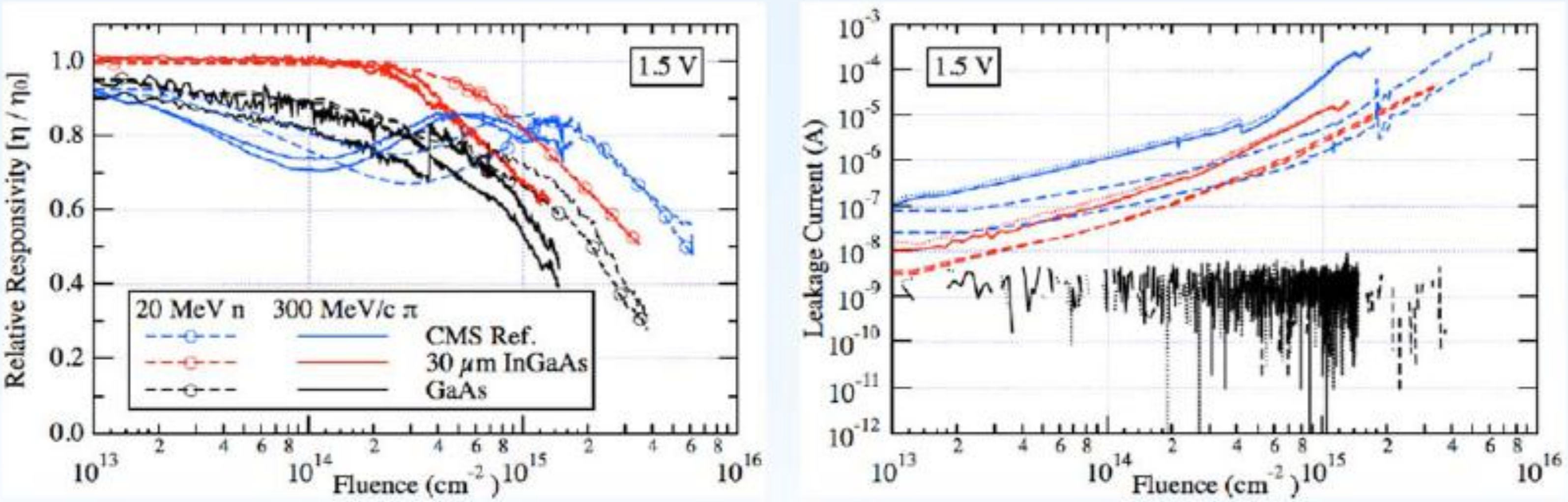






Irradiation test on p-i-n diodes (CERN)

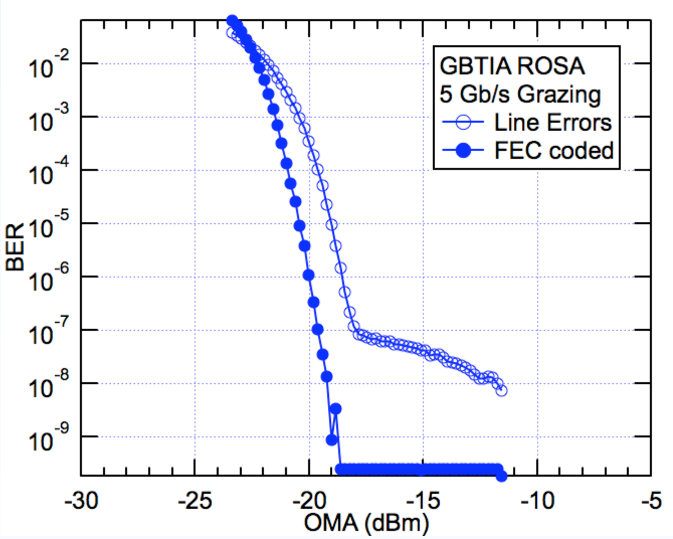
- PIN total fluence resistance test

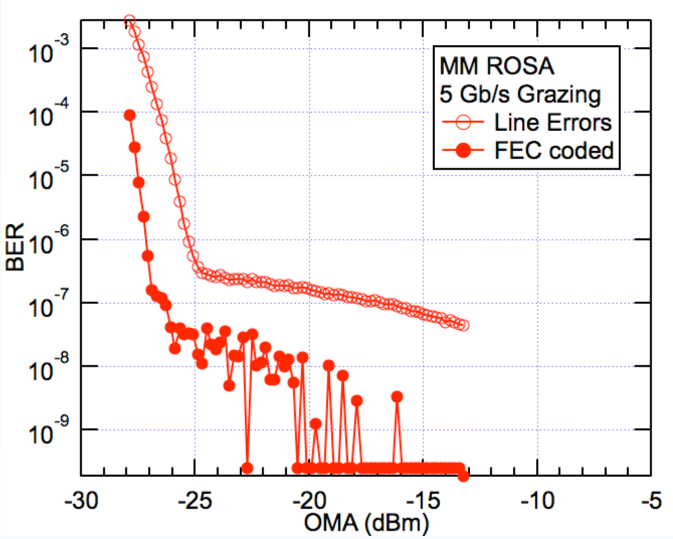


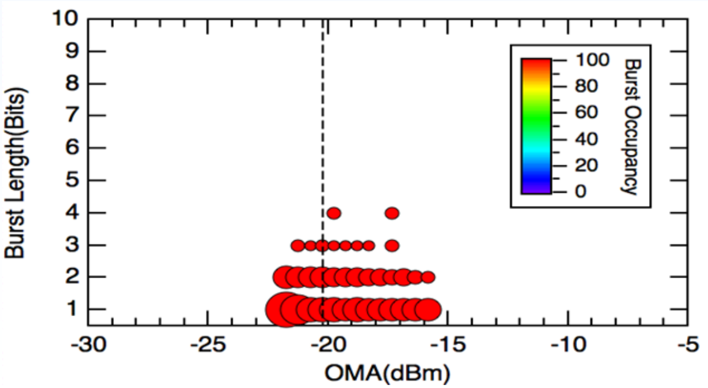
- Approximate damage factors indicate that 300 MeV/c pions are around twice as damaging as 20 MeV neutrons
  - Smaller relative factor for newer devices w.r.t. CMS reference parts
- InGaAs devices’ responsivity less affected than GaAs devices
- GaAs devices show no increase in leakage current

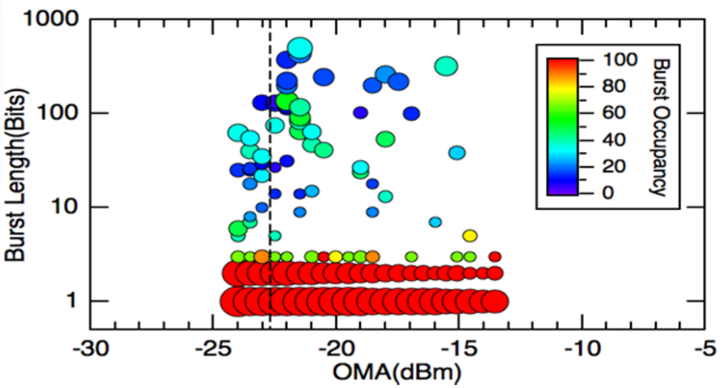
Irradiation test on ROSA (CERN)

- **GBTIA ROSA robust against SEU**
  - **BER due to single bit flips similar for all devices**
  - **GBT-FEC effective in correcting SEUs from PIN**
  - **Longer bursts limited in GBTIA ROSA**



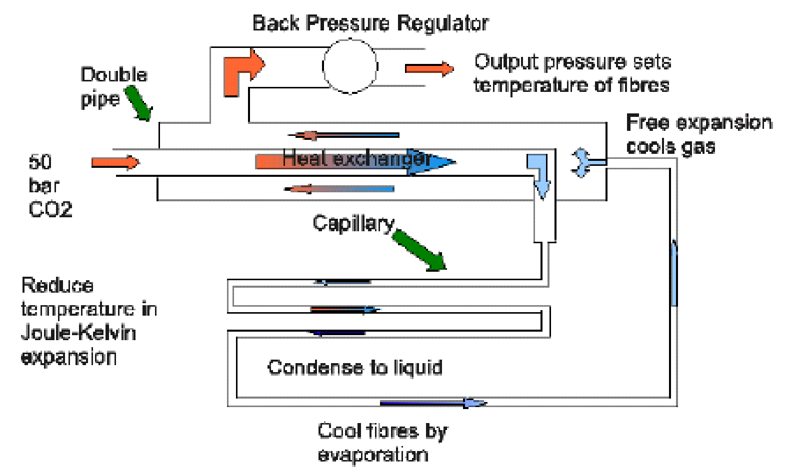






Passive Components (Oxford)

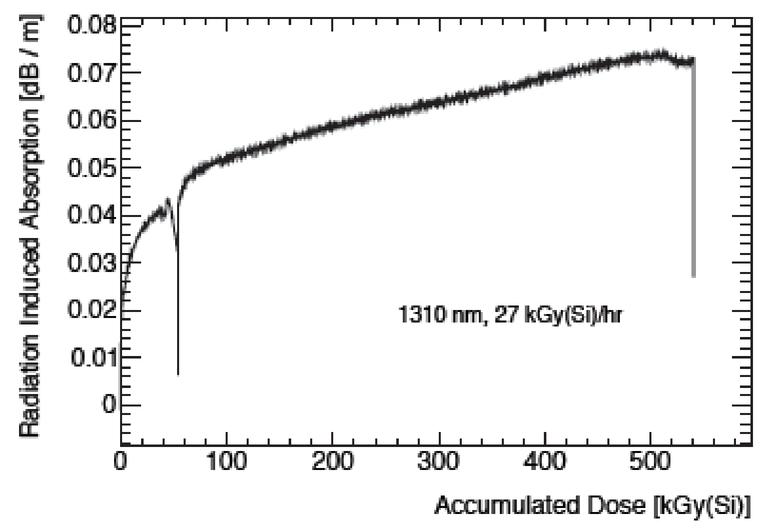
- Commercial LOMMF for 850nm and SMF for 1310nm operations
- Radiation Induced Absorption (RIA) in fibers is highly temperature dependent.
- Oxford has developed a CO2 cooling system capable of keeping fiber samples cold (-26 deg C) during irradiation.



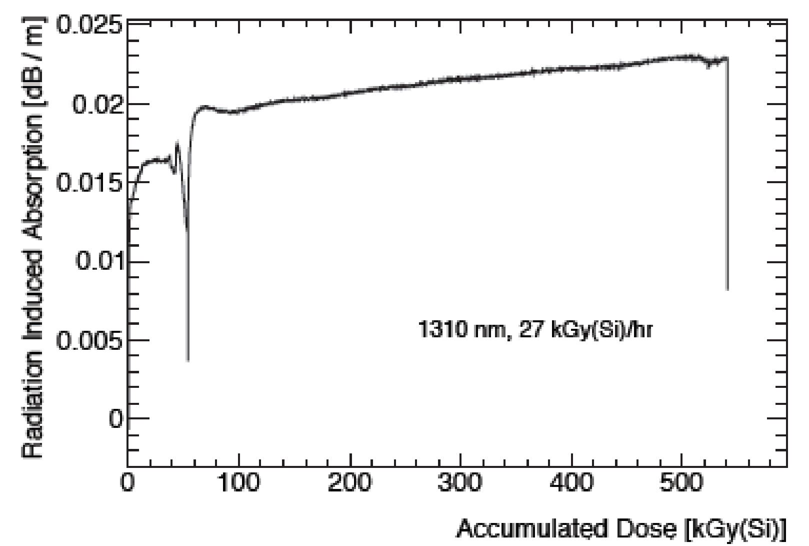
Passive Components (Oxford)

Versatile Link

Temperature of exposure = -26 deg. C



Draka SM fibre



Product X

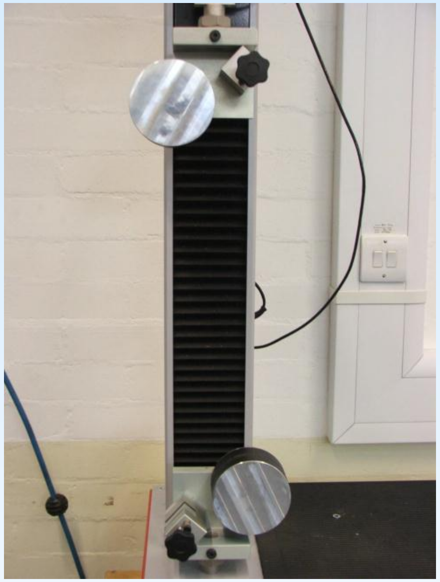
Both of these SM fibres have small attenuation for a typical cable run
For ATLAS or CMS inner detectors. ~0.1 dB from RIA.

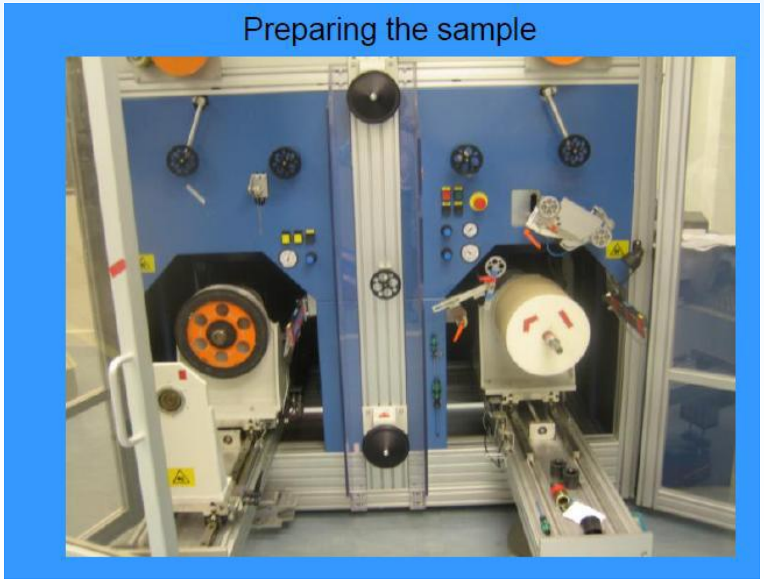
The MM fibres did not fare so well at these very high dose rates.
We are planning a run at a lower dose rate up to a full SLHC integrated dose.

2:50pm, J. Aramovitch et al
“The cryogenic performances of specific optical and electrical components for a liquid argon time projection chamber”

Passive Components (Oxford)

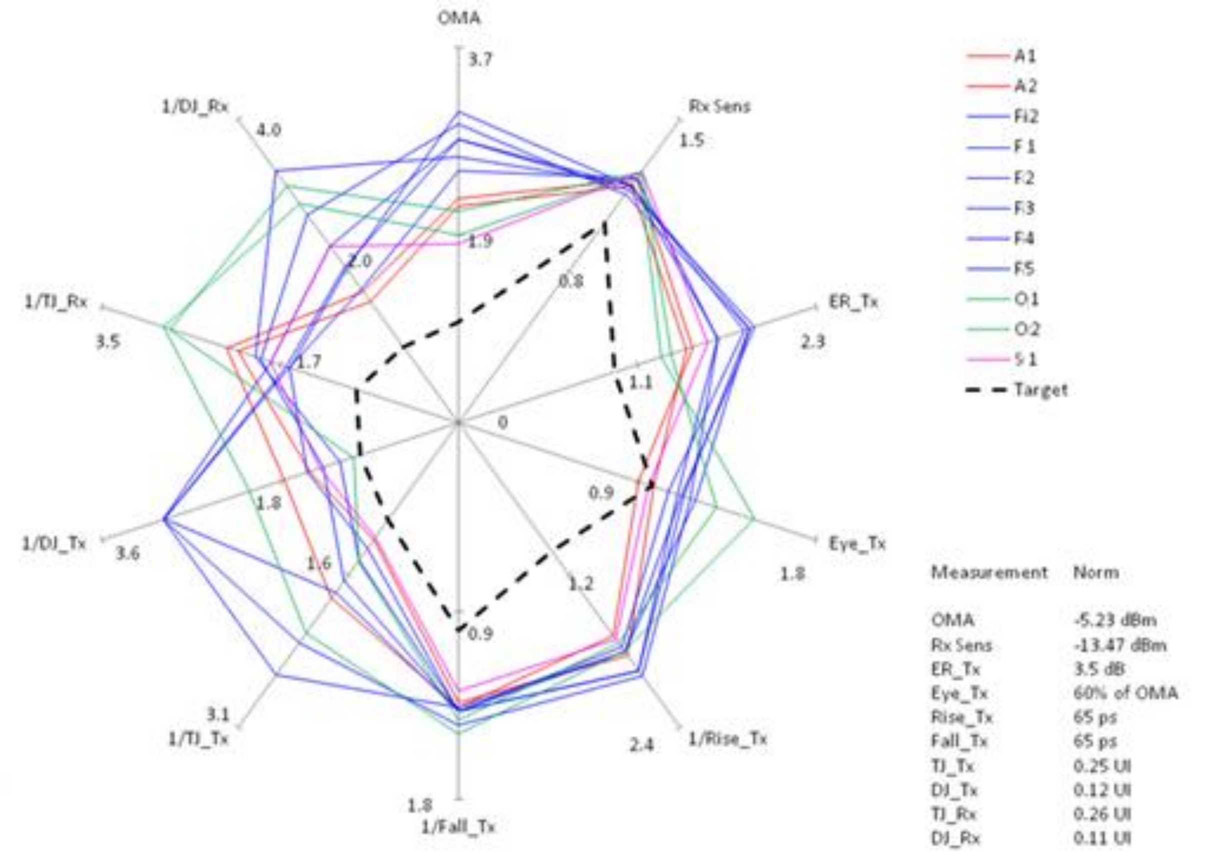
- Mechanical and cabling properties under radiation are studied (pull test and micro-bending)
- Commercial MT/MPO connector for ribbons and LC connector for single fibers are studied (coupling efficiency)
- Irradiate to the HL-LHC dose and check form significant changes before and after
- Reasonable results for SMF28e





Preparing the sample

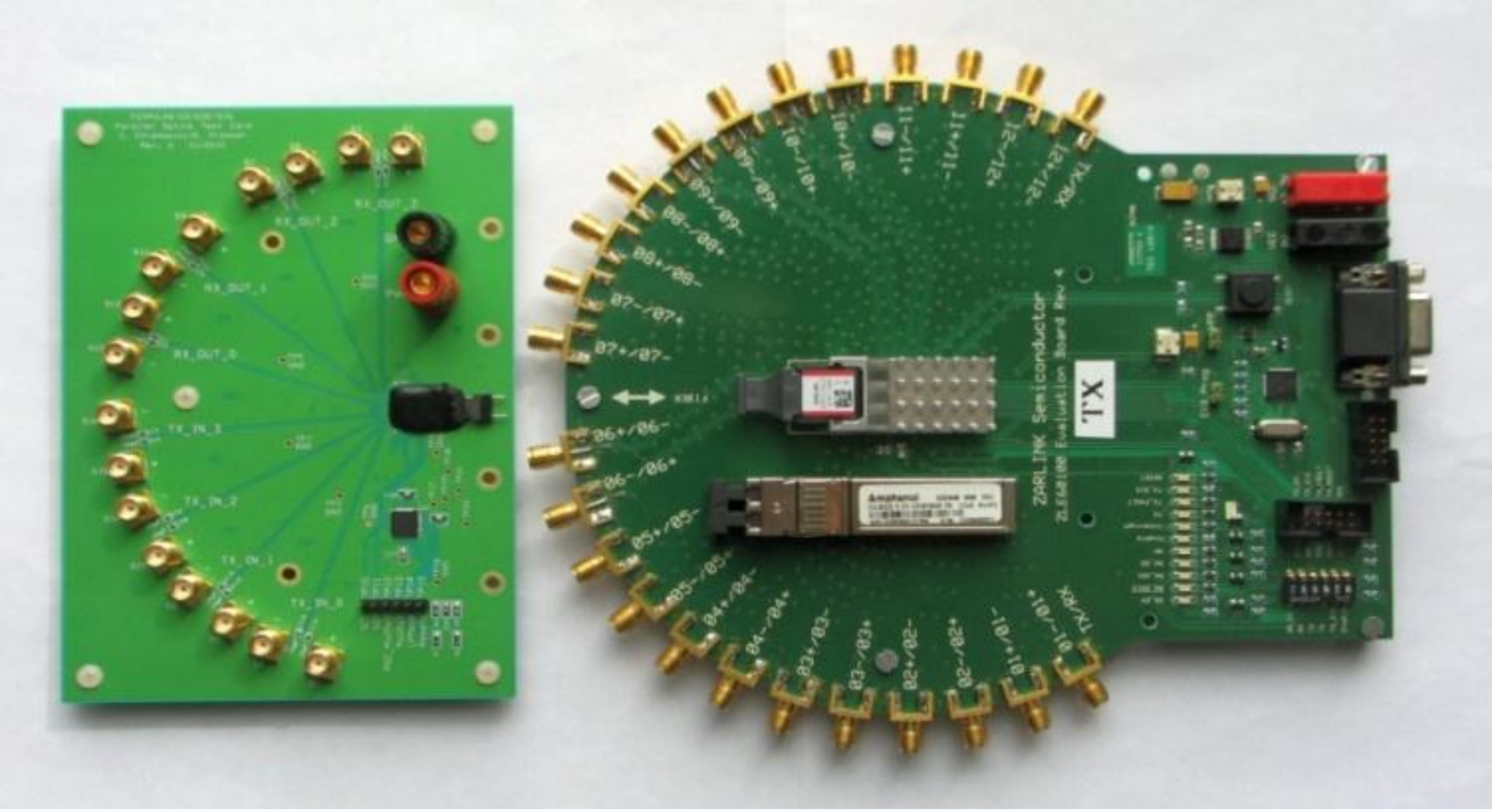
Back end single channel (Fermilab)



Measurement	Norm
OMA	-5.23 dBm
Rx Sens	-13.47 dBm
ER_Tx	3.5 dB
Eye_Tx	60% of OMA
Rise_Tx	65 ps
Fall_Tx	65 ps
TJ_Tx	0.25 UI
DJ_Tx	0.12 UI
TJ_Rx	0.26 UI
DJ_Rx	0.11 UI

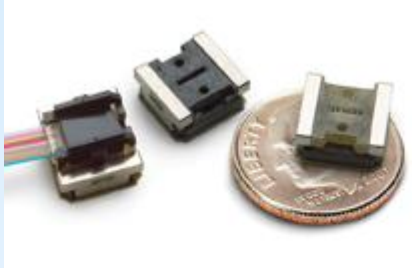
- Test reference components at 4.8Gbps and up to 10Gbps
- High power variant under investigation to meet system margin

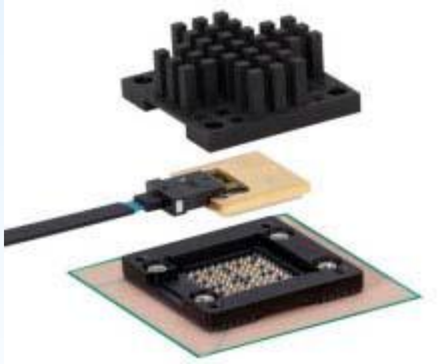
Back end parallel (Fermilab)

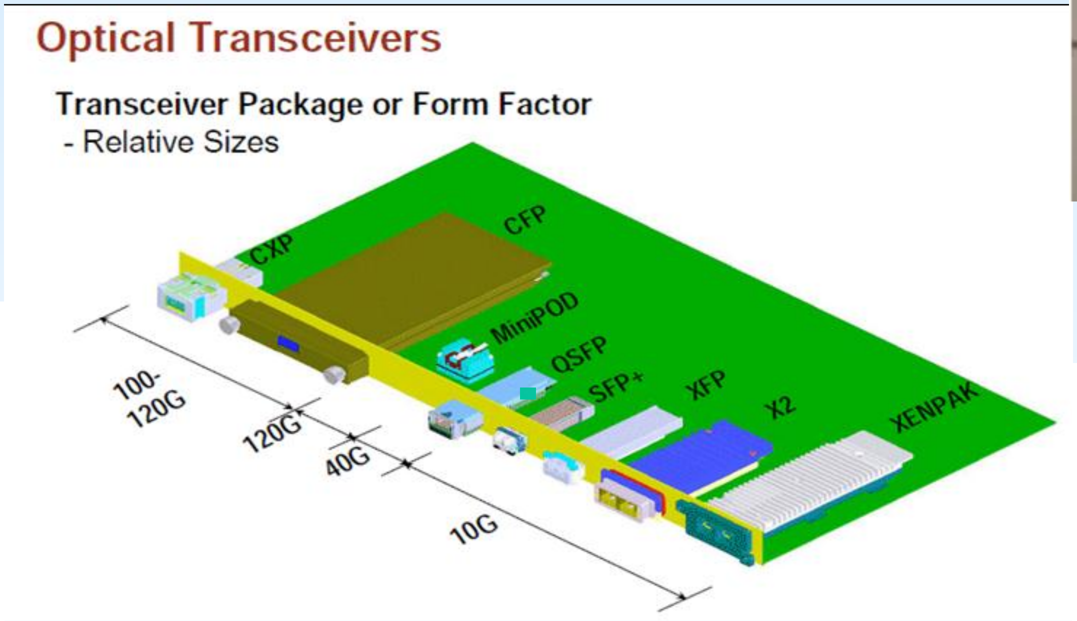


- Parallel modules provide higher density, easier cable management and lower power consumption
- 4-channel engine at 6.25Gbps/channel and 12-channel TRx at 5 Gbps/channel are tested
- 40/100GbE transceiver parts are being ordered.

Back end emerging (Fermilab)

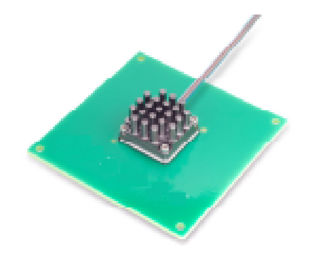






Optical Transceivers

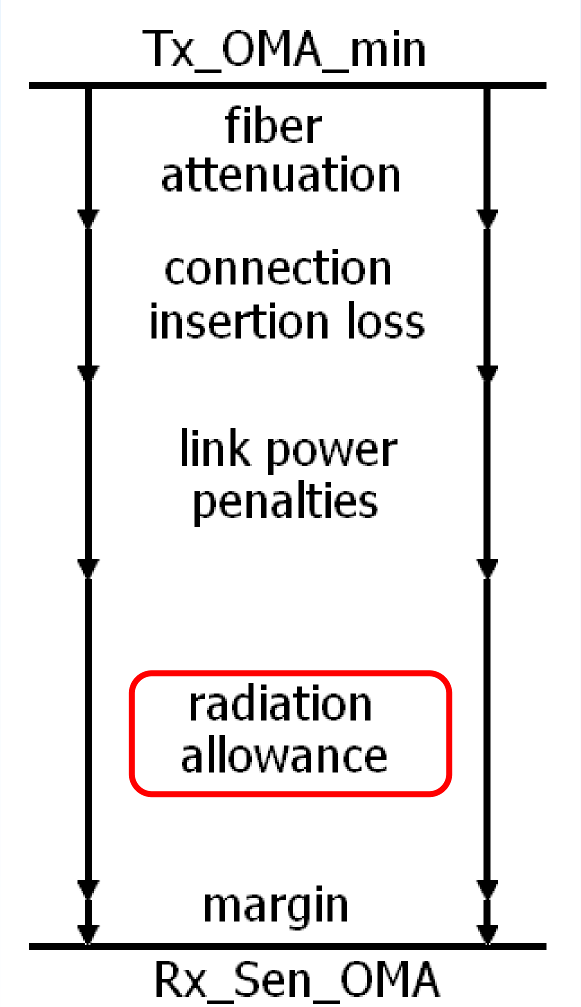
Transceiver Package or Form Factor
- Relative Sizes



- Further evaluation continues on emerging products such as board mount optical engine (closer to chip, not limited to edge)
- FMC module card is designed for one proprietary package

Versatile Link Power Budget (SMU)

- The amount of available optical power in a link is capped by Tx power and Rx sensitivity, settled by vendor consensus and available technologies.
- Link penalties are simulated using 10GbE link model http://www.ieee802.org/3/ae/public/adhoc/serial_pmd/documents/
- Link penalties of 1.0 dB for MM and 1.5 dB for SM are allocated based on simulation and verified by measurements on commercial modules.
- VL is specifically constrained by radiation degradation of front-end components.
  - Degradation is categorized by application: tracker and calorimeter
  - For tracker, high power transmitters needed for adequate safety margin


Tx_OMA_min

fiber attenuation

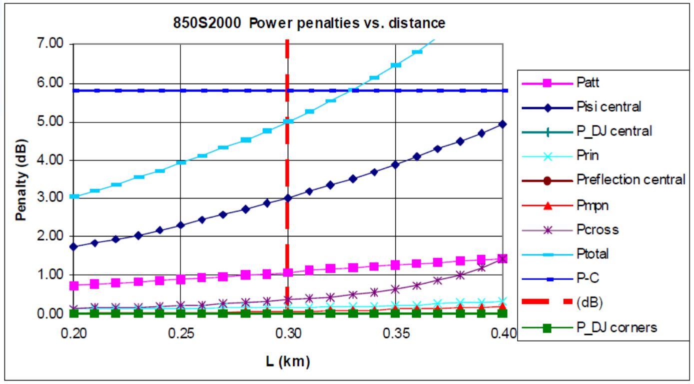
connection insertion loss

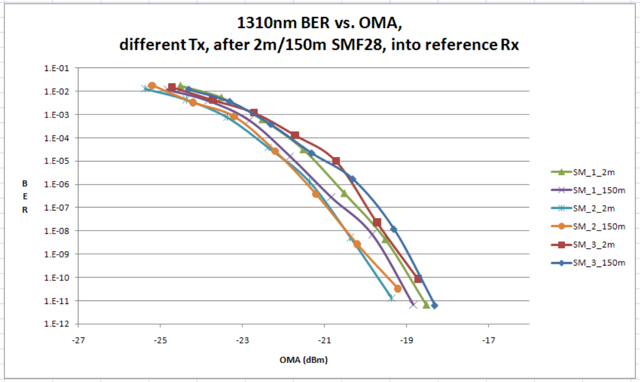
link power penalties

radiation allowance

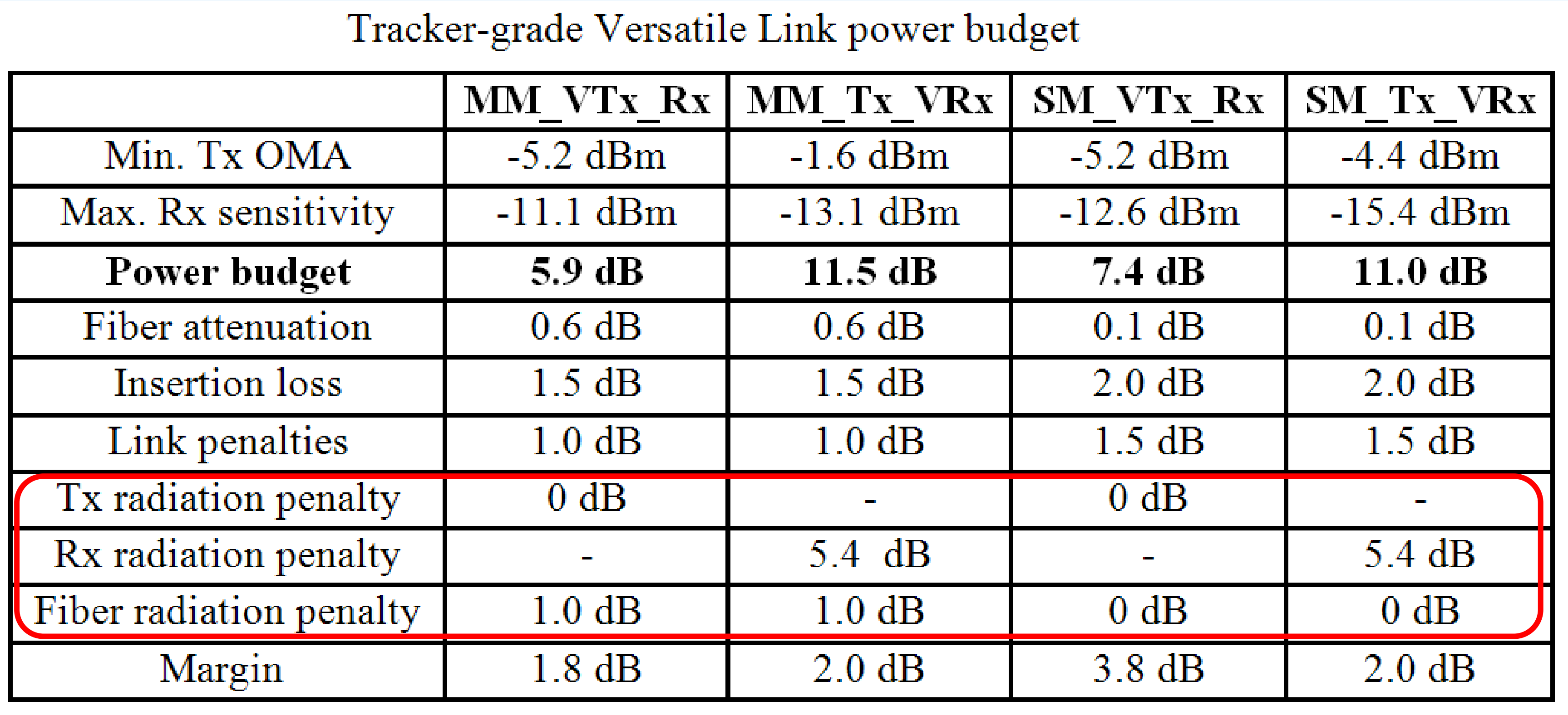
margin

Rx_Sen_OMA





Versatile Link Power Budget (SMU)

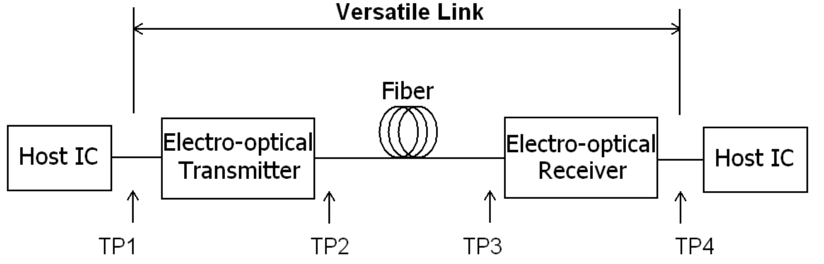


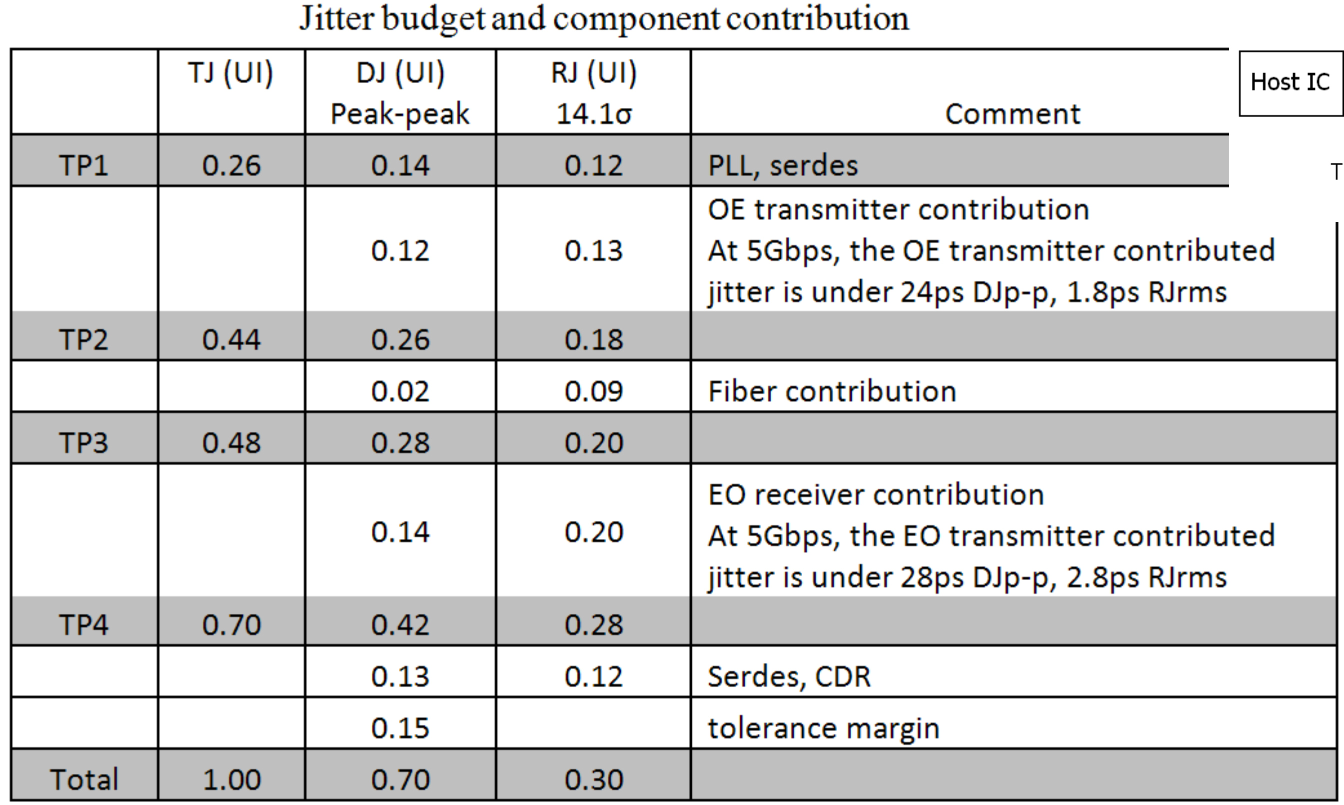
Tracker-grade Versatile Link power budget

	MM_VTx_Rx	MM_Tx_VRx	SM_VTx_Rx	SM_Tx_VRx
Min. Tx OMA	-5.2 dBm	-1.6 dBm	-5.2 dBm	-4.4 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**	**11.0 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	0 dB	0 dB
Margin	1.8 dB	2.0 dB	3.8 dB	2.0 dB

- Only rad-hard downlink (back-end to detector) needs customization
  - Increased transmitter power request QA with vendor
  - Apply FEC help to gain extra margin

Versatile Link Jitter Budget (SMU)



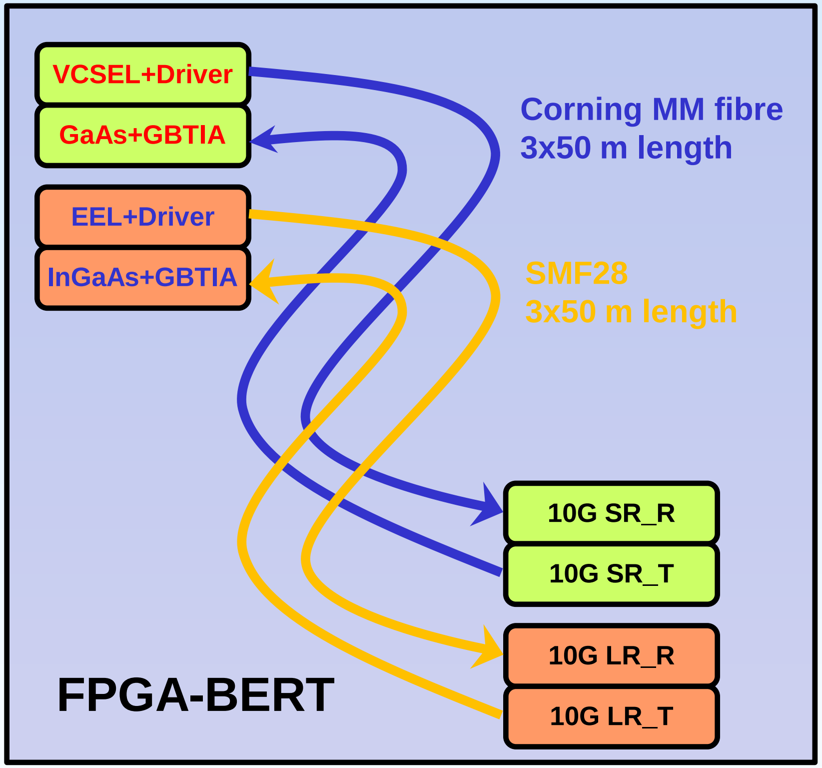


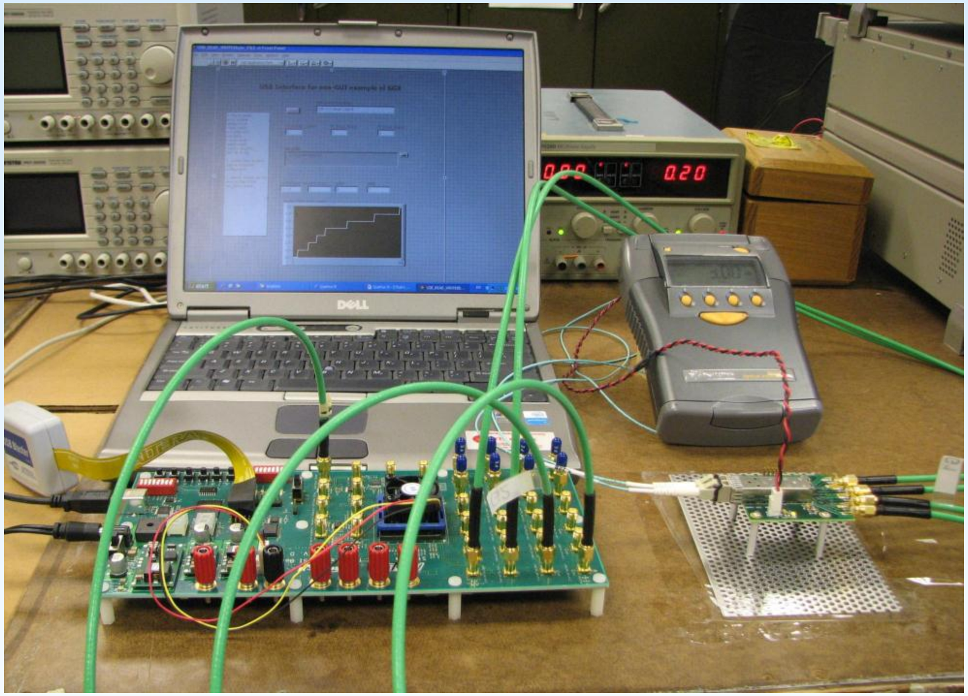
Jitter budget and component contribution

	TJ (UI)	DJ (UI) Peak-peak	RJ (UI) 14.1σ	Comment
TP1	0.26	0.14	0.12	PLL, serdes
		0.12	0.13	OE transmitter contribution At 5Gbps, the OE transmitter contributed jitter is under 24ps DJp-p, 1.8ps RJrms
TP2	0.44	0.26	0.18	
		0.02	0.09	Fiber contribution
TP3	0.48	0.28	0.20	
		0.14	0.20	EO receiver contribution At 5Gbps, the EO transmitter contributed jitter is under 28ps DJp-p, 2.8ps RJrms
TP4	0.70	0.42	0.28	
		0.13	0.12	Serdes, CDR
		0.15		tolerance margin
Total	1.00	0.70	0.30	

- Jitter allocation is specified at interfaces along the link. Component contributions can be derived.
- Industry standard is adapted. Test results on demonstration links are compliant.

System demonstrator (all hands)





- Full system tests on all link options
- BER vs. OMA with additional environmental stresses
- Parts are being ordered/made now

9:50am, A.Xiang et al.
"Design and verification of an FPGA based bit error rate tester"

VL project status

Front-End VL TRx	Fibre	Back-End TRx
EE laser, 1310nm Drive current	SM	LR-SFP+ SNAP12 Opto Engine Tx or TRx Array availability Tx-OMA
VCSEL, 1310nm Compliance voltage, Availability, Reliability		
InGaAs PIN, 1310nm Radiation induced leakage		
VCSEL, 850nm Compliance voltage, Reliability	MM Radiation Induced Attenuation in the cold	SR-SFP+ SNAP12 Opto Engine Tx-OMA
GaAs PIN, 850nm Rad-induced Responsitivity drop		
GBLD Availability		

Summary

- Establishing system and components specifications based on simulation and testing is a good practice to follow. It gives us confidence that the system will work on a large scale.
- Front-end low mass package successfully validated. Integration of optoelectronics show good results.
- Set of irradiation test results for front-end and passive components render lists of qualified parts.
- Both single and parallel options are evaluated for backend.
- System demonstrators to be released by Phase II consolidation (Sept, 2011).
- We thank supports from ATLAS, CMS, and from various funding agencies to make this important project happen, it'll be up to us to make it successful.

Credits

- CERN
  - Jan Troska, François Vasey, Csaba Soos, Christophe Sigaud, Pavel Stejskal and Sarah Storey
- Fermilab
  - Jeff Andresen, John Chramowicz, Alan Prosser, Simon Kwan et al.
- Oxford
  - Nick Ryder, Todd Huffman, Tony Weidberg et al.
- Southern Methodist University
  - Annie Xiang, Jingbo Ye, Andy Liu, Kent Liu, Datao Gong

Thank you!

Back up

Component	Type	FIT
VTRx	On detector transceiver laser with driver PIN with amplifier both 850nm and 1310nm	250
TRx	Off detector transceiver Both 850nm and 1310nm	200
Other component	Connector Fiber cable	25 25
Link total	**Full duplex**	**500**

- System reliability early consideration
- Failure is defined as link BER exceeding 10^{-12}
- FIT is one failure in billion (10^9) device hours
- TRx FIT of 200 is allocated after Telcordia SR-332, issue 2, 2006
- VTRx FIT is allocated assuming similar sub-device reliability and part count, with extra margin for customized assembly
- For 10 years of detector operation, 200 FIT is equivalent to 2% channel failure.