Data Communication for Future Experiments

Andy Tiankuan Liu
tliu@mail.smu.edu
Southern Methodist University

Instrumentation Frontier Community Meeting
Argonne National Laboratory
January 11, 2013

Outline

- Requirements of future experiments
- Data communication for future accelerator-based experiments
  - Direct modulation
    - Component level: fibers, lasers, laser drivers, serializers, photodiodes, TIA, deserializers
    - Module level: optical transmitters and optical receivers
    - System level: power budget and jitter budget
  - Optical modulation
- Data communication for future applications involving large volume liquid argon
- Wireless data communication
- Summary

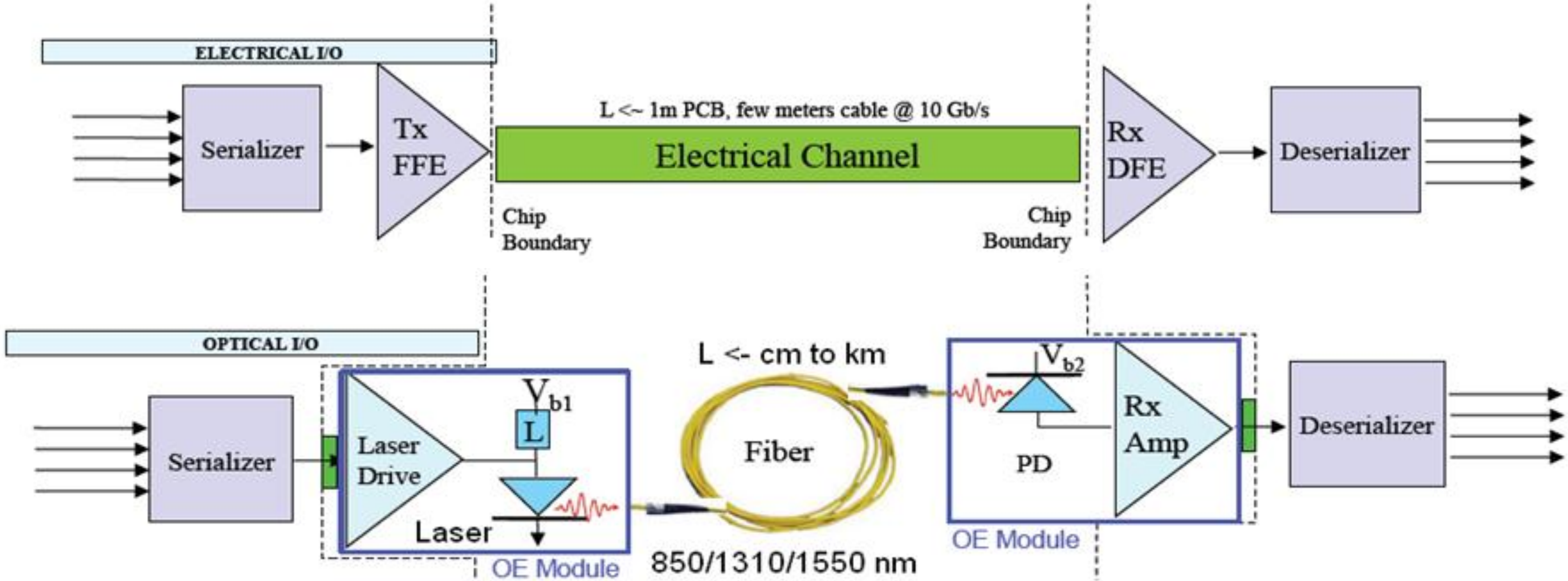
Requirements of future experiments

Requirements of future experiments

- Large volume data
- Low power consumption
- Radiation, temperature, size, mass
- …

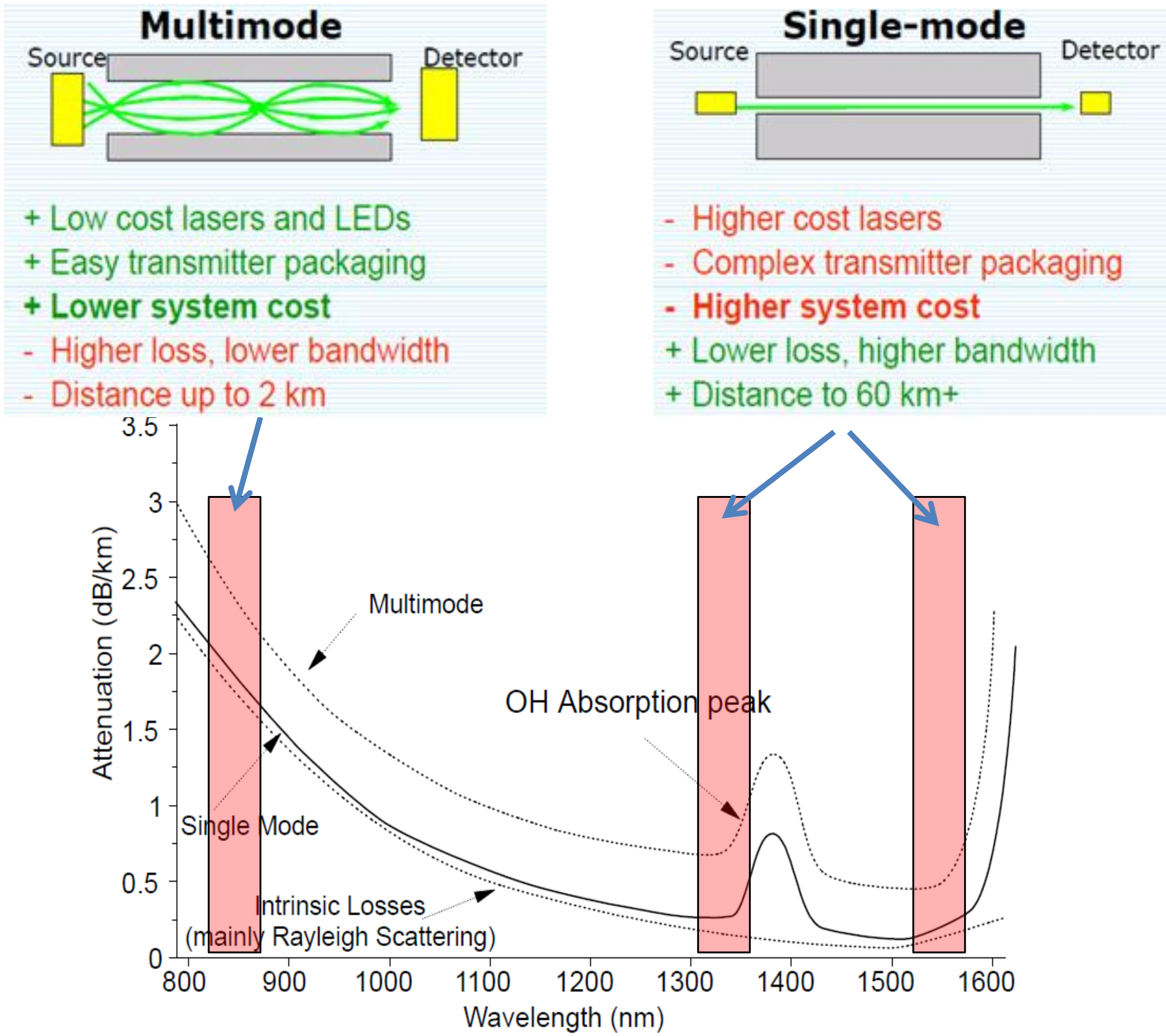
Advantage of optical links:

- High bandwidth and long distance
- Low mass and high density
- No ground loop
- …



M. Ritter, TWEPP, Aachen, German, Sept. 2010

Optical fibers - Technology options

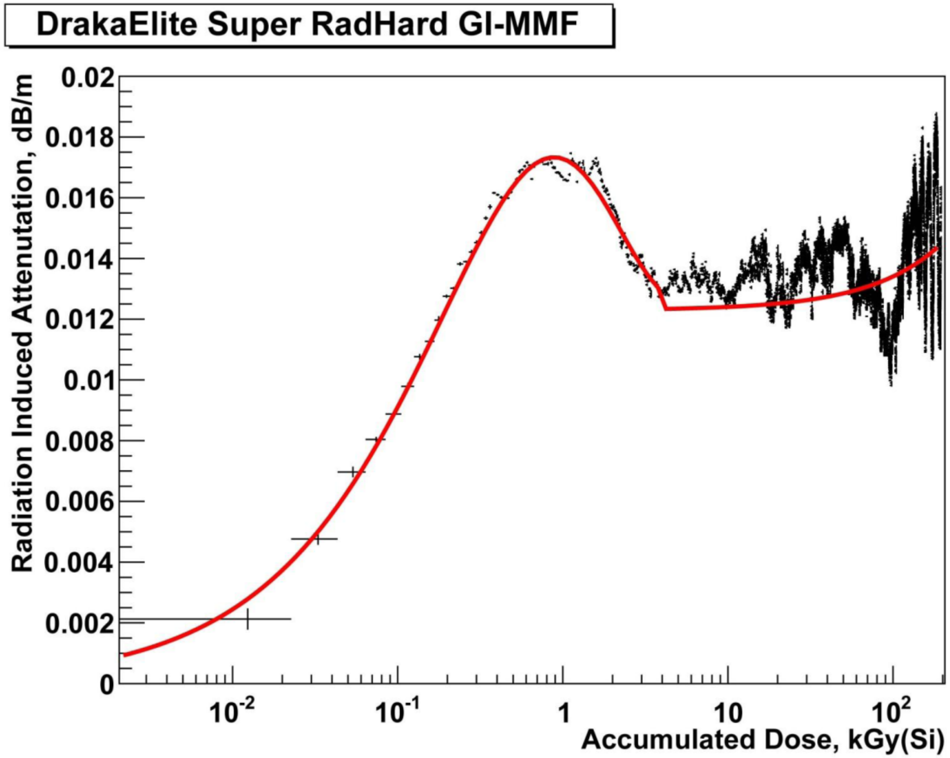


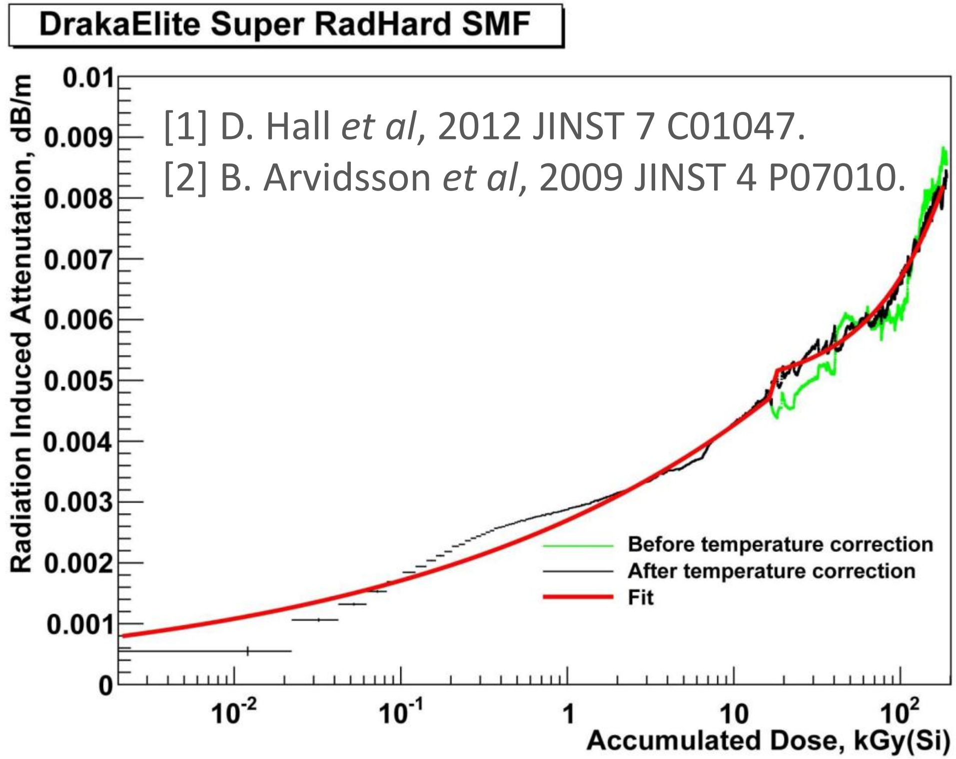
Typical Fibre Infrared Absorption Spectrum.

A. Xiang *et al*, TIPP, Chicago, IL, USA, June, 2011.

Optical fibers

- Radiation induced attenuation is temperature-dependent and dose rate dependent.
- In general, germanium or fluorine doped fibers are radiation tolerant, whereas phosphorous doped fibers are not. fluorine doped fibers have better radiation performance than germanium doped fibers.
- Two single-mode and two multi-mode fibers have been qualified for use at HL-LHC detectors.

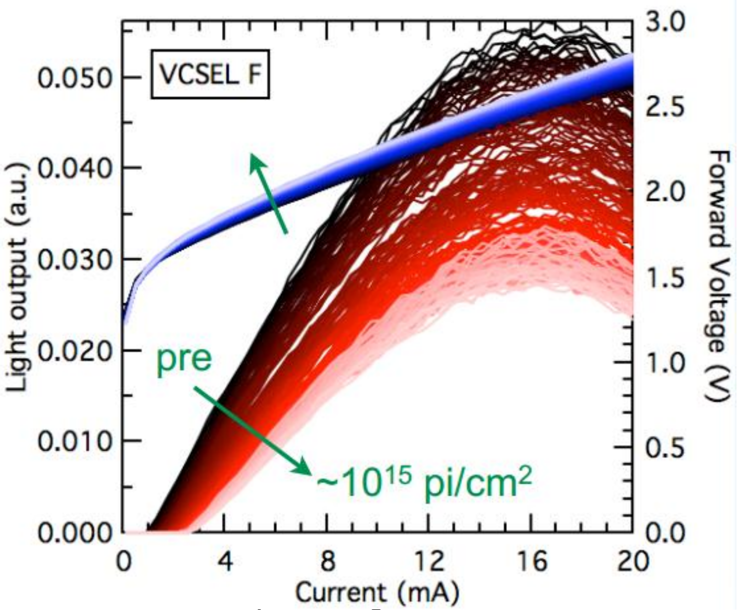




Laser diodes

Laser type	Wavelength (nm)	Fiber type	Photo-diode type	Data rate (Gb/s)	Launching power	cost	Distance
VCSEL	850 1310	MM SM	GaAs InGaAs	10	Low	Low	< 300 m
FP	1300	MM SM	InGaAs	10	Med	Med	< 2 km
DFB	1310 1550	SM	InGaAs	>10	High	High	> 10km

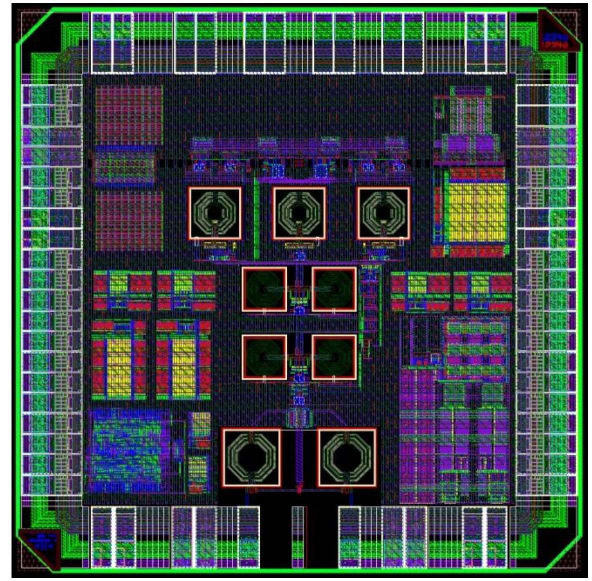
- 850 nm VCSELs and 1300 nm FP lasers are sufficiently rad-tol for LH-LHC tracker applications. 1300 nm VCSELs not as rad-tol as 850 nm counterparts.
- Lasers could survive a few 10^{15} n/cm^2.
- Jan Troska *et al, IEEE TNS* 58 (6), Dec. 2011

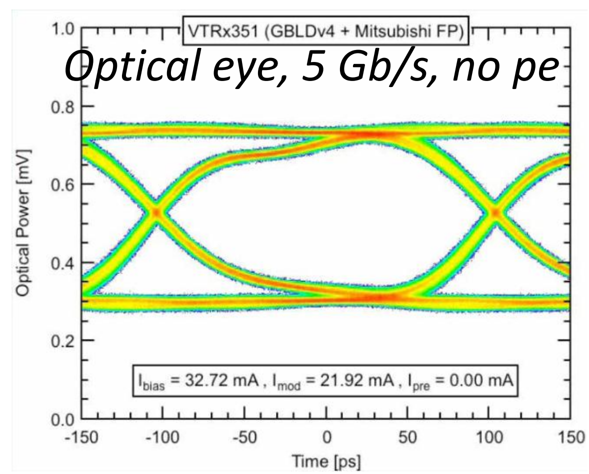


Laser diode driver 1: GBLD

COTS laser drivers cannot meet HL-LHC upgrade rad-tol requirements. Slow control is the most sensitive part.

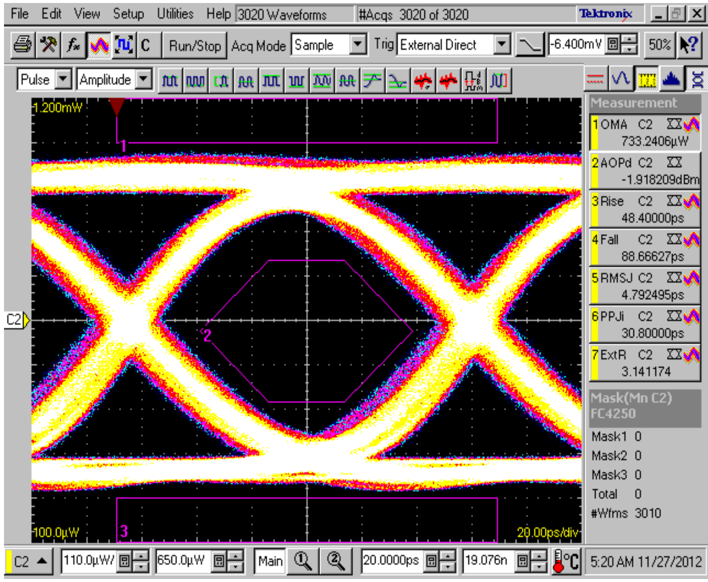
- **130 nm** CMOS technology
- **5 Gb/s**
- **Drive both VCSEL and FP lasers**
- **Pre-emphasis/de-emphasis**
- Survive up to **100 Mrad**.
- SEU immune (previous version SEU tested)
- Ref: G. MAZZA *et al*, , TWEPP, Oxford, UK, Sept. 2012.





Laser diode driver 2: LOCld

- SMU is developing a **single channel VCSEL driver ASIC (LOCld1)** and a **multi-channel VCSEL driver ASIC (LOCld4 and LOCld12**), all at **8 Gbps**, based on a **0.25 μm silicon-on-sapphire (SoS)** CMOS technology.
- LOCld1 was prototyped and **successfully tested up to 10 Gb/s with BER <10^{-12}**. LOCld1 will be submitted I2C and DAC in Feb. 2013.
- LOCld4, a four-channel VCSEL driver array, has been designed and prototyped. Design speed 8 Gb/s. The test is ongoing.
- LOCld12 will be designed and submitted in 2013.

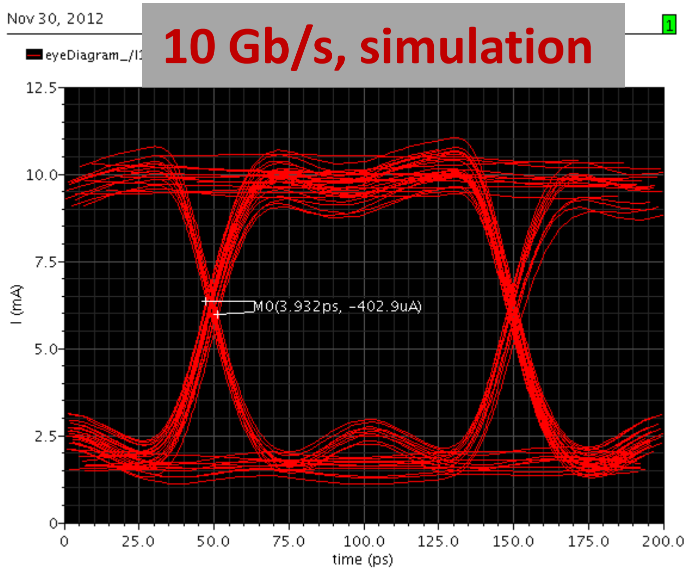


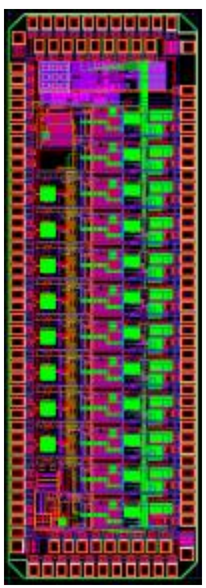
LOCld1 Optical eye at 8 Gb/s

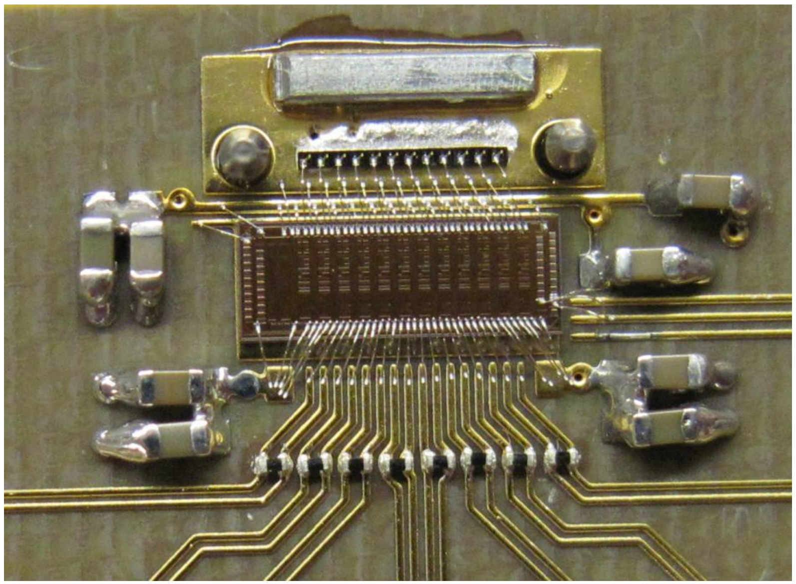
Futian Liang *et al*, TWEPP, Oxford, UK, Sept. 2012.

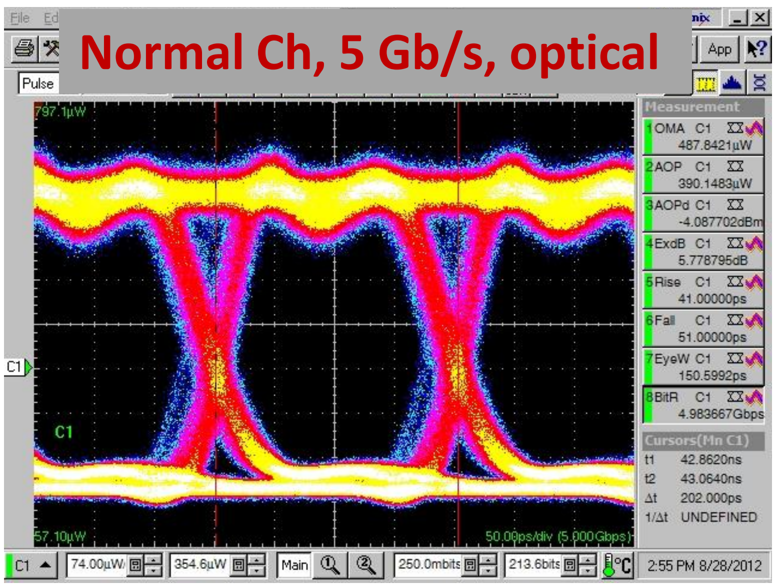
Laser diode drivers 3

- The **Ohio State Univ. (OSU)** group has prototyped and tested a VCSEL driver array based on **130 nm CMOS** technology. **8 channel + 4 spare channels.** All channels operates **5 Gb/s**. Waiting for irradiation test results.
- The OSU group is designing a **10-Gb/s** VCSEL driver array based on the same technology.







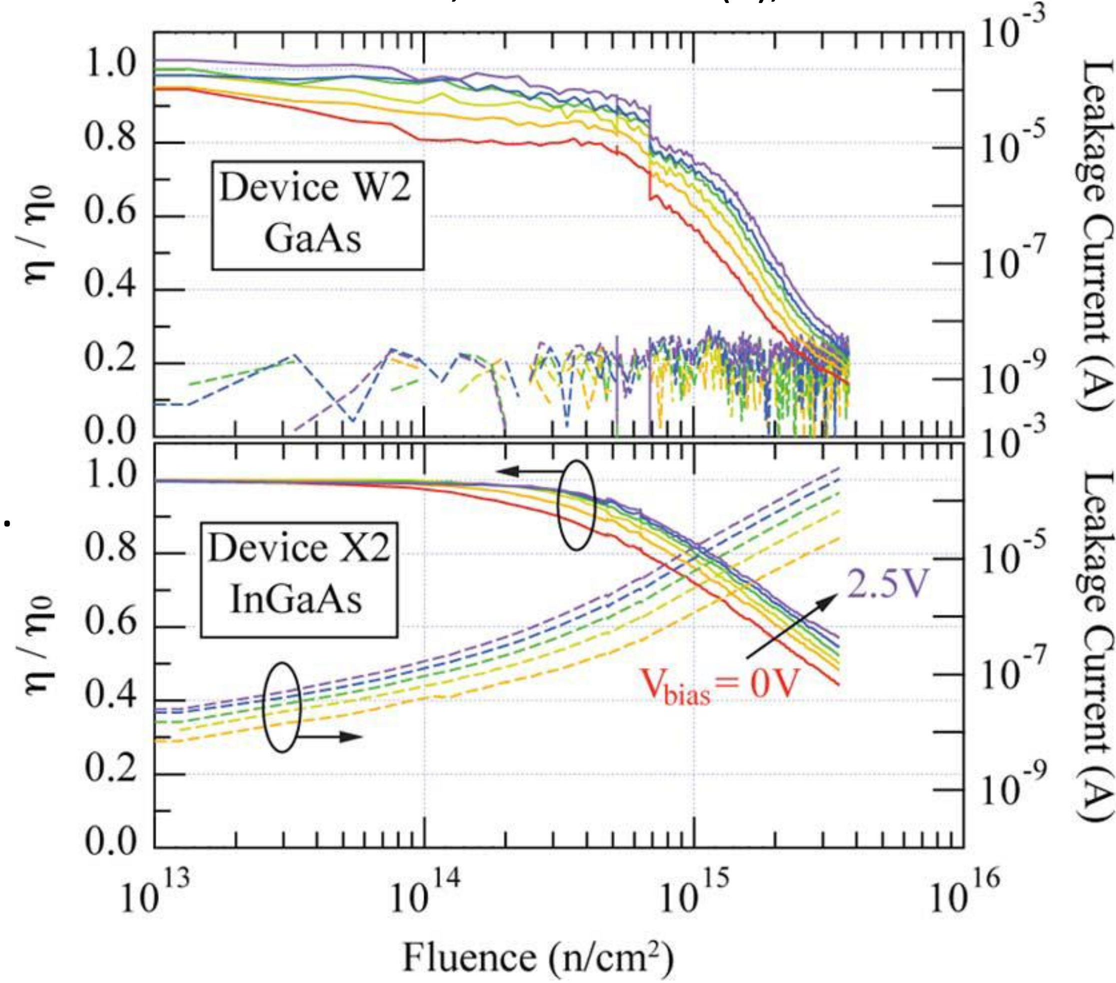


KK Gan *et al*, TWEPP, Oxford, UK, Sept. 2012

Photodiodes

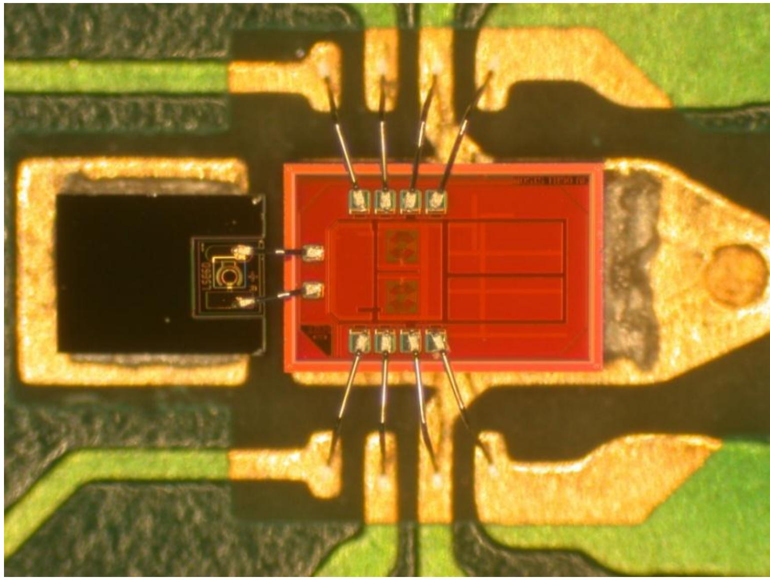
- Technology options: usually GaAs at 850 nm and InGaAs 1310/1550 at nm.
- In responsibility, InGaAs devices are less affected than GaAs ones.
- In leakage, InGaAs devices show large increase, while GaAs devices show no increase.
- InGaAs & GaAs responsibility heads to zero at several 10^{15} n/cm^2. Use InGaAs for Trackers even at 850 nm.
- No significant annealing.

Jan Troska *et al, IEEE TNS* 58 (6), Dec. 2011



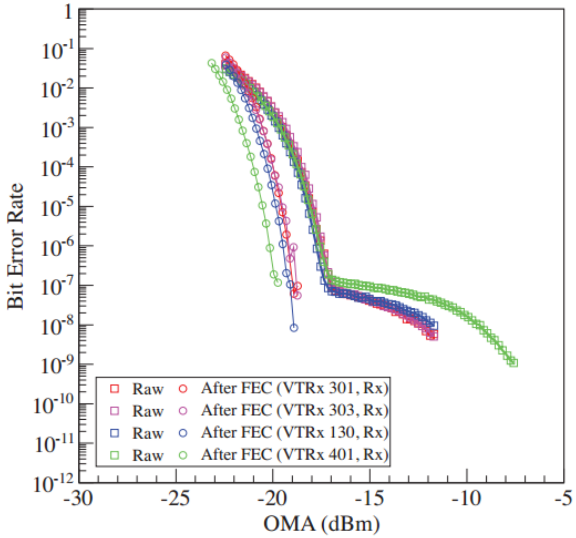
Transimpedance amplifiers: GBTIA

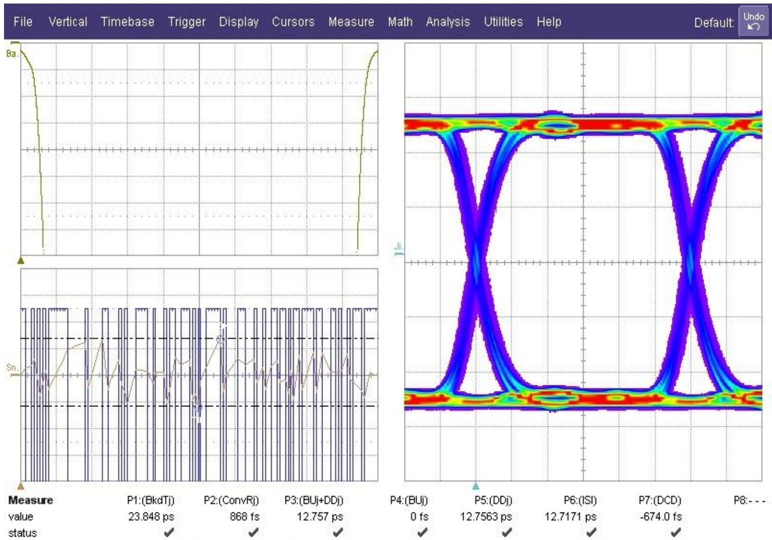
COTS TIA cannot meet HL-LHC upgrade rad-tol requirements because of SEU rate.



- **130 nm CMOS** technology
- **4.8 Gb/s**
- Radiation tolerance is proven up to **200 Mrad**. No **burst errors** longer than 3 bits long occur, **fully corrected by the GBT protocol**
- Power consumption: 250 mW at 2.5 V
- **Die packaged in a** Receiver Optical Sub-Assembly **(ROSA)**

M. Menouni *et al*, TWEPP, Paris, France, Sept. 2009.

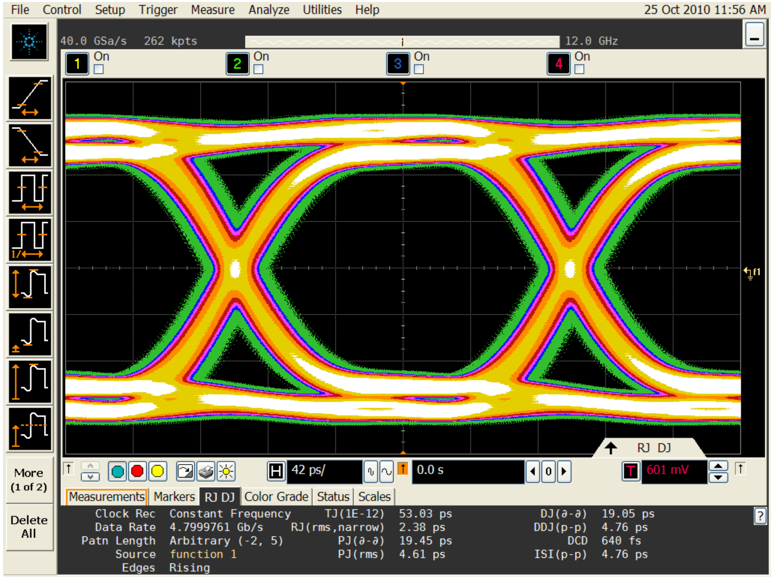


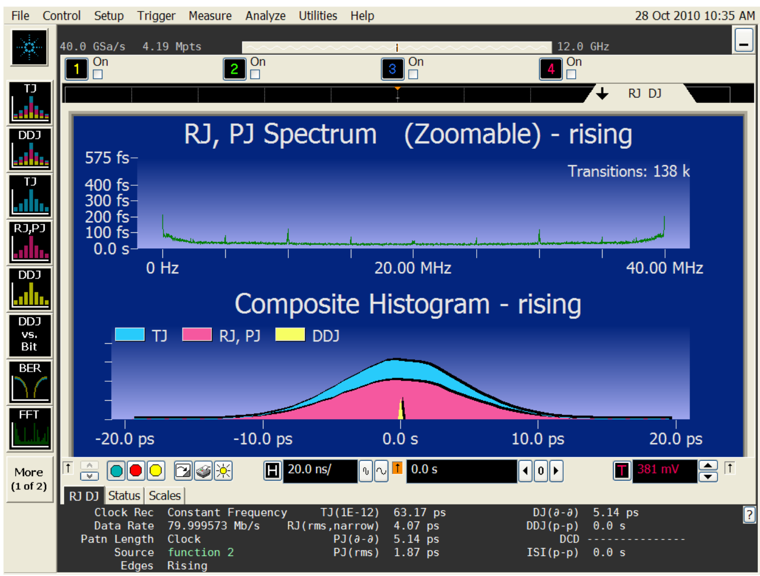


Serializer/deserializer 1: GBTx

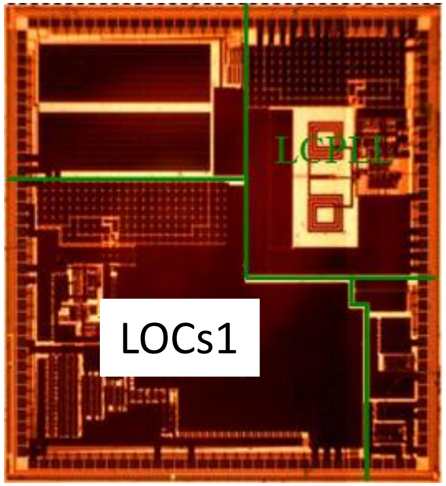
COTS serializers (FPGAs) cannot meet HL-LHC upgrade rad-tol requirements because of single-event upset (SEU) rate.

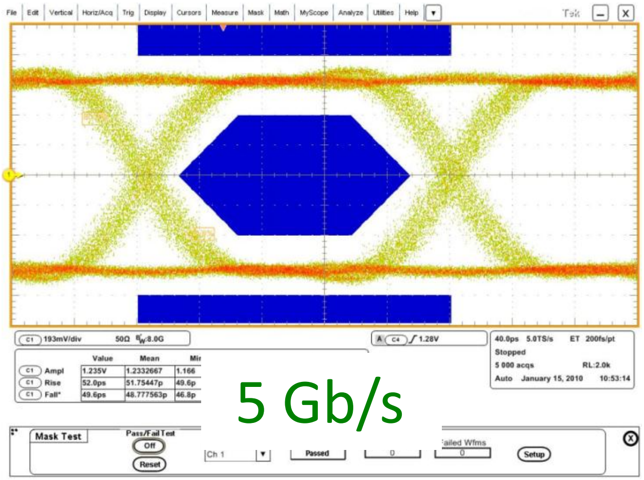
- **130 nm** CMOS technology
- **Bi-directional**: TX for data readout. RX for trigger, timing and slow control (TTC).
- Data rate **4.8 Gb/s**
- Custom **GBT protocol** to handle SEUs (**payload rate 3.3 Gb/s**)
- Radiation tolerance
- Power dissipation: **3 W**
- **Latency: 100 ns for TX. 112.5 ns RX.**
- Status: first prototype tested in 2011. Second prototype submitted Nov. 2012.
- CERN will start designing a low power GBT ASIC family in a **65 nm CMOS** technology: **10 Gb/s, ¼ power of GBTx**, …
- GBTx homepage: https://espace.cern.ch/GBT-Project/GBTX/default.aspx

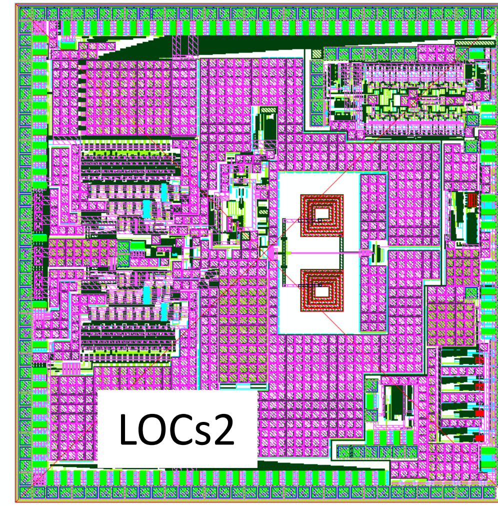




Serializer option 2: LOC







- **0.25 µm silicon-on-sapphire (SoS)** technology
- LOCls1: **5 Gb/s x 1 ch**, 0.46 W, latency: 12.8 ns (no encoding), rad-tol tested
- LOCs2: **8 Gb/s x 2-ch**, 1.2 W, latency: 8 ns, under test
- LOCx2: under development, **5.44 Gb/s x 2 ch**, **custom encoding protocol** with **embedded bunch crossing counter**. Low **overload: 6.25%**. Low **latency: < 80 ns** (TX + RX, including encoding and decoding). Quick resynchronization recovery on the receiver side.

[1] D. Gong, 2010 *JINST* 5 C12009
[2] D. Gong *et al*, TWEPP, Oxford, UK, Sept. 2012
[3] T. Liu *et al*, TWEPP, Oxford, UK, Sept. 2012

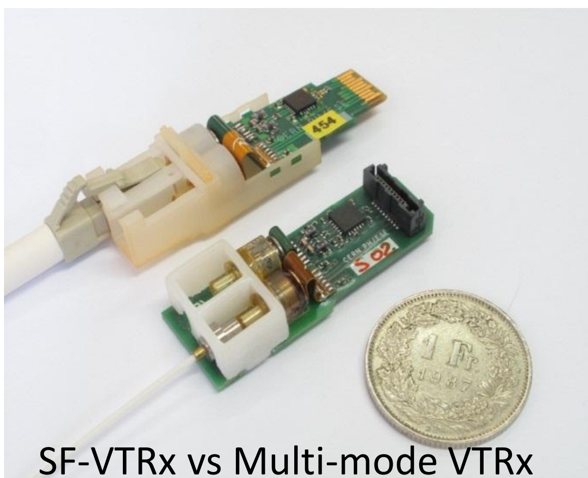
Module development 1: VTRx/sf-VTRx

COTS optical transceivers cannot meet HL-LHC upgrade rad-tol requirements.

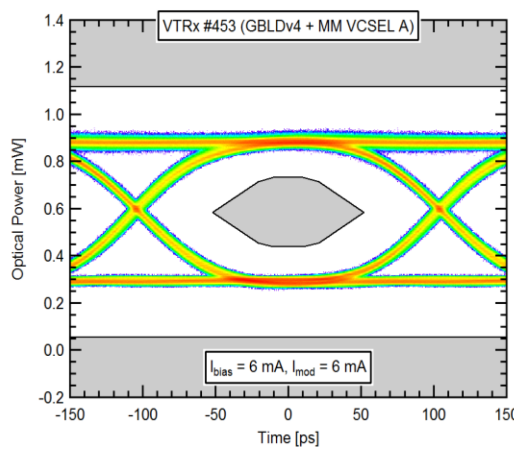
- Developed by CERN
- ATLAS/CMS joint Versatile Link project
- Unidirectional (VTTx) or bidirectional (VTRx)
- 850 nm MM or 1310 nm SF

- 150 meter
- 5 Gb/s
- Pluggable
- Radiation tolerance
- Status: Pre-production readiness

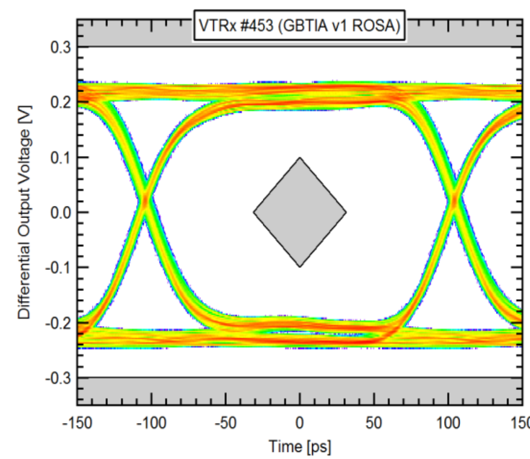
C. Soos *et al*, TWEPP, Oxford, UK, Sept. 2012


SF-VTRx vs Multi-mode VTRx

TX Eye

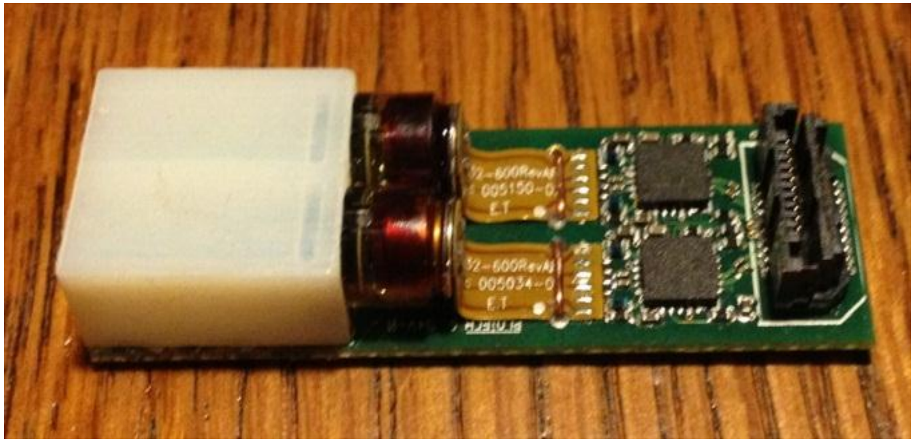


RX Eye

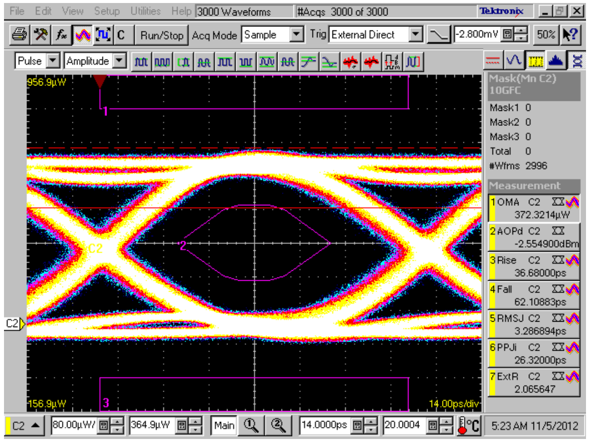


Module development 2: MTx

- SMU collaborated with CERN, ideas from sf-VTRx.
- 2 channels
- Unidirectional (transmitters only)
- 8 Gb/s
- 850 nm
- First prototype demonstrated with COTS VCSEL driver. Production will use LOCld



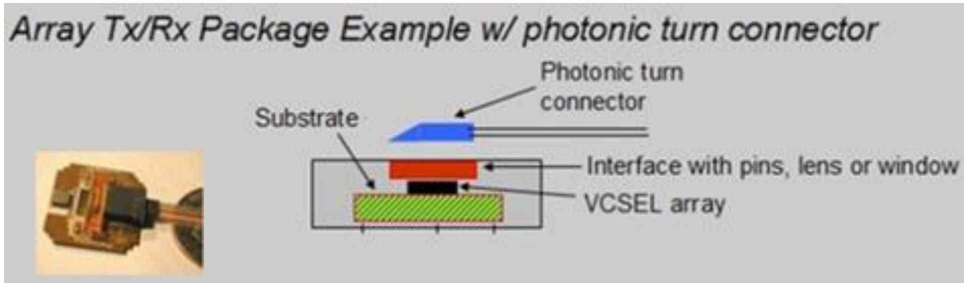
Optical eye at 10 Gb/s

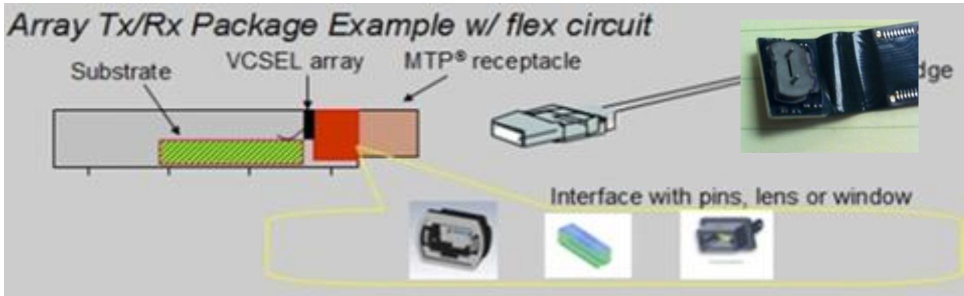


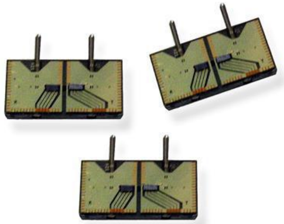
T. Liu, TWEPP, Oxford, UK, Sept. 2012

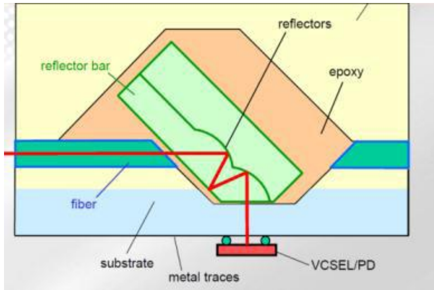
Module development 3 – ATx

- ATx: VCSEL array based parallel transmitter module
- Under development by SMU & FNAL
- 12 channels x 10Gb/s
- MPO optical connection
- ULM and Finisar VCSEL arrays
- Driver arrays being designed by SMU and OSU
- Three module designs adapted from miniPOD, QSFP and iFlame transceivers are investigated.





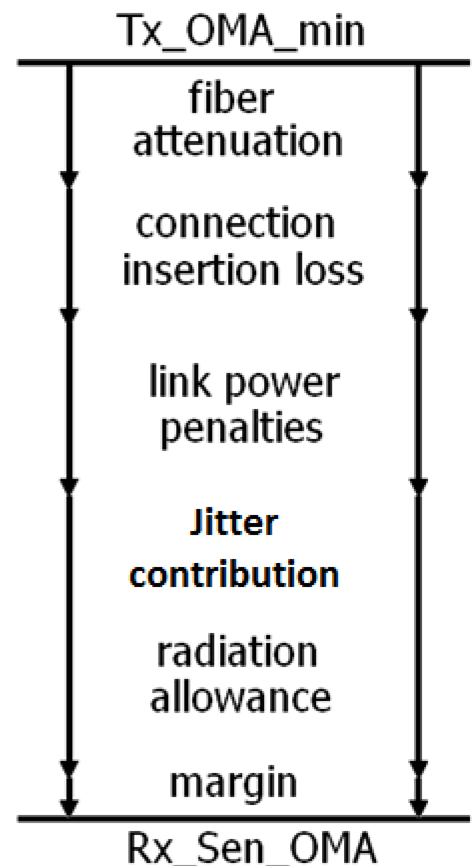




A.C. Xiang *et al*, TWEPP, Oxford, UK, Sept. 2012

Power budget based on MTx - microPOD

Parameter	Spec	Note
Min Tx Optical modulation amplitude	**-5.2 dBm**	Conservative value taken from triple tradeoff curve (RMS spectral width, center wavelength, Tx OMA)
Max unstressed Rx sensitivity	-10.4 dBm	Spec'd at 10G, can be better at 5 Gb/s
Power budget	5.2 dB	
Fiber attenuation	0.3 dB	70 meter, OM3, 3.5dB/km
Connector loss	**1.5 dB**	3 connections if 0.5dB per insertion loss, 4 if 0.375dB/connector some vendors start to ship 0.2dB low loss connectors
Link penalties	1.0 dB	Fiber bandwidth limit not reached, most contribution from noise rather than closure (ISI, etc.)
Jitter contribution	0.4 dB	Array based receiver. To be verified.
Radiation penalties	0.1 dB	Calorimeter grade, mostly from fiber
Margin	**1.9 dB**	

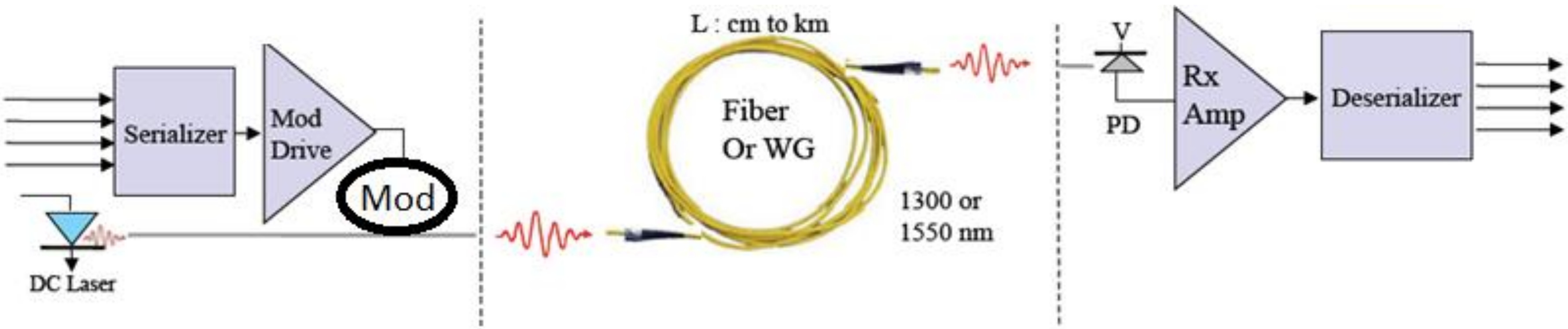


D Gong *et al* 2011
JINST 6 C01088

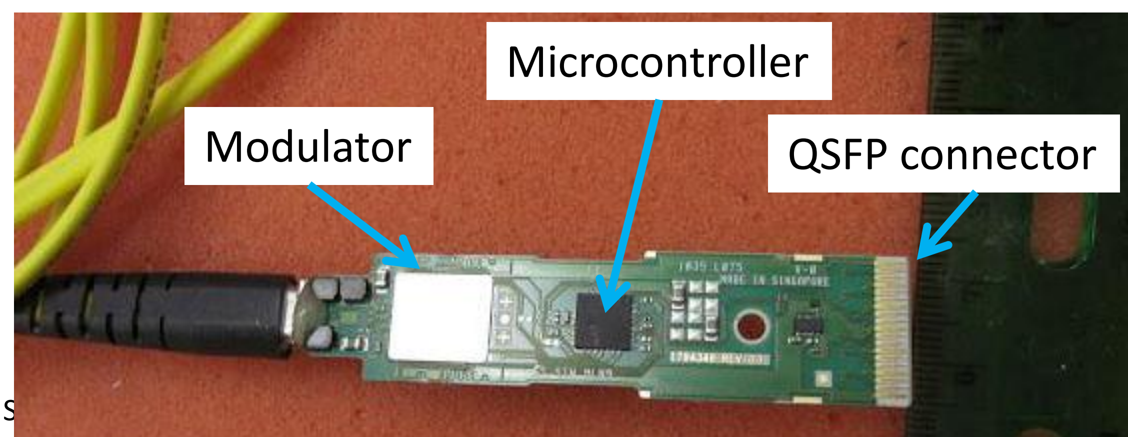
Outline

- Requirements of future experiments
- Data communication for future accelerator-based experiments
  - Direct modulation
    - Component level: fibers, lasers, laser drivers, serializers, photodiodes, TIA, deserializers
    - Module level: optical transmitters and optical receivers
    - System level: power budget and jitter budget
  - **Optical modulation**
- Data communication for future applications involving large volume liquid argon
- Wireless data communication
- Summary

Optical modulation



- Advantages: higher bandwidth (>10 Gb/s), longer distance, lower power, CW lasers off-detector and more reliable, …
- ANL group tested 3 different types of modulators. No SEU observed, but microcontroller using flash memory failed during tests. Working with external **I2C and monitor links** through QSFP connector to emulate non-rad-tol microcontroller.

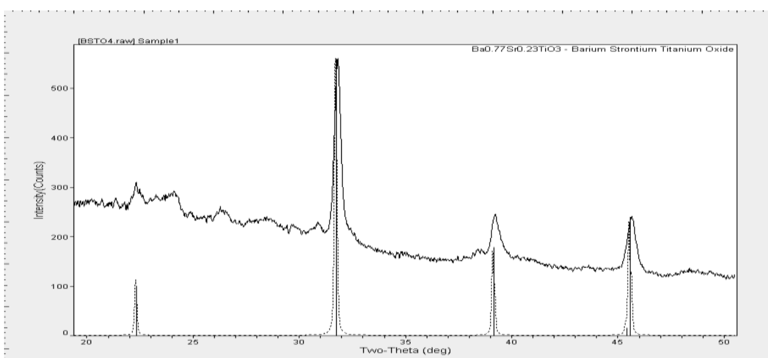


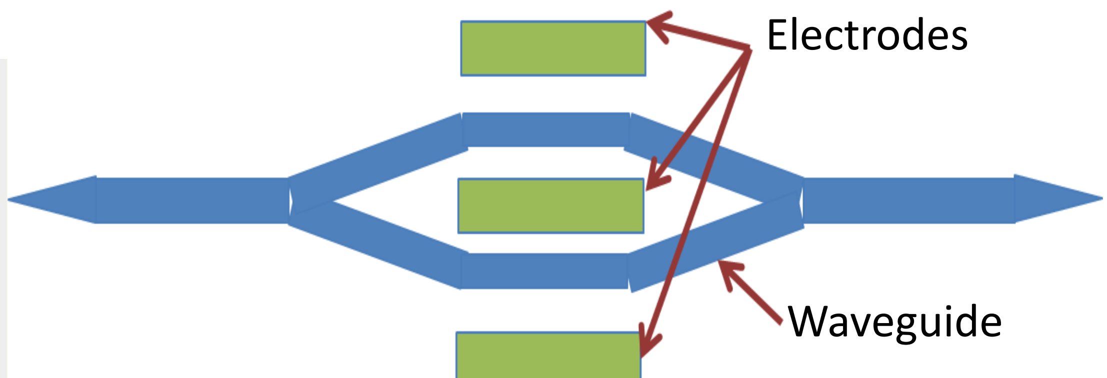
G. Drake *et al*, TWEPP, Oxford, UK, Sept. 2012.

External modulation (cont'd)

- The University of Minnesota group led by Prof. Roger Rusack is developing a low-profile, low operating voltage Mach-Zehnder (MZ) modulator based on a novel electro-optic material, Barium-Strontium Titanate (Ba-SrTiO3, BSTO).
- Have successfully demonstrated deposition of a uniform layer of BSTO.
- This year will make prototype with different parameters to optimize the modulation properties.
- Next year will prototype packaged module.

X-ray scatter compared against a standard spectrum

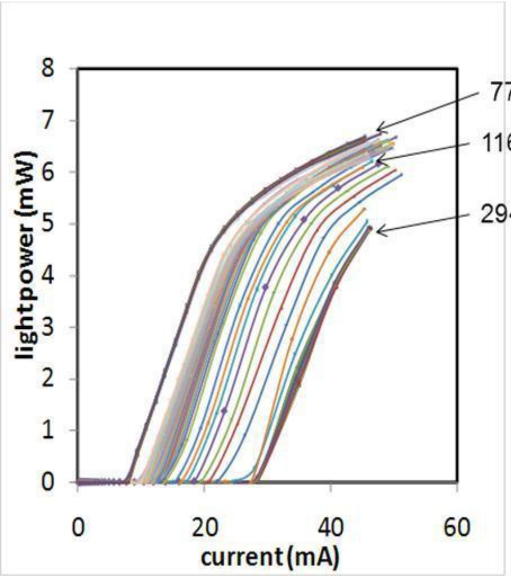


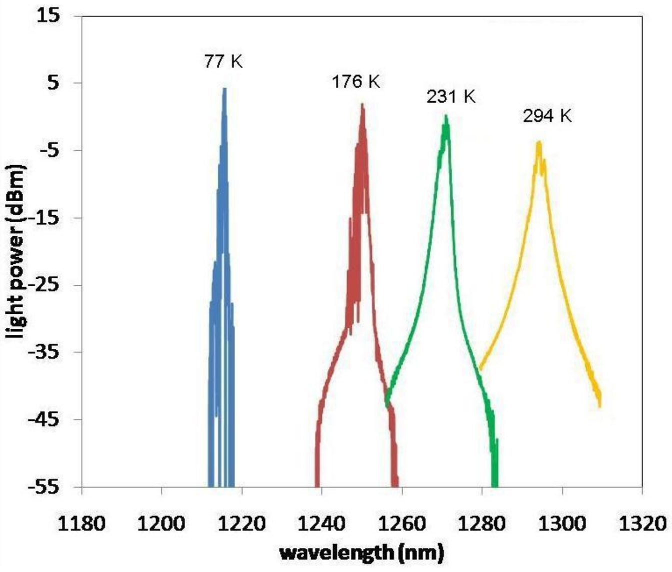


Data communication for applications involving large volume liquid argon

- Advantages of optical data communication for a large volume Liquid Argon Large time projection chamber (LArTPC): **high bandwidth** (no zero suppression needed), **small number of cables**, **low thermal load**, **low out gassing**.
- SMU group have confirmed that serializers (FPGAs), laser drivers, laser diodes, fibers, optical connectors can still operate at 77 K.

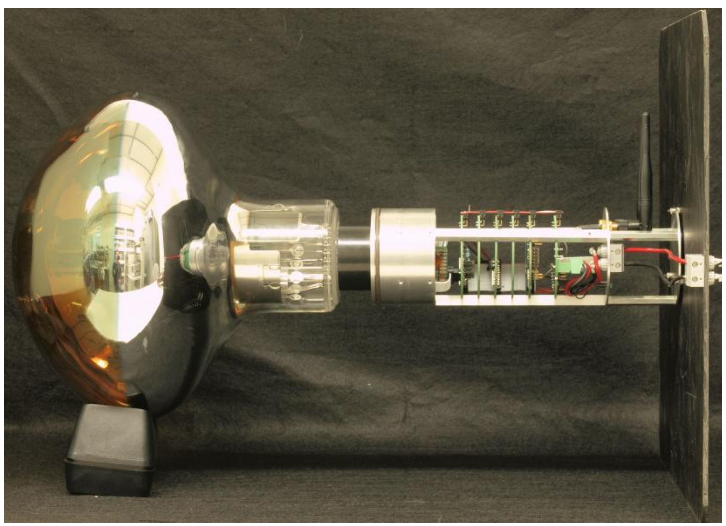
T Liu *et al,* 2012 *JINST* 7 C01091

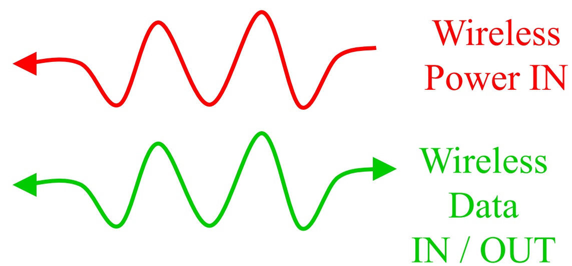




Wireless data communication for future experiments

- Motivation: Eliminate cables for movability, flexibility, low cost, and low mass, low latency, ….
- Wireless data transfer
  - RF: [1]
  - Free-space optical [2]
- Wireless power transfer [1]
  - Laser diode or LED with Collimator
  - RF Power Transmitter





The ANL group led by Dr. Zelimir Djurcic is building a detector module that operates from wireless power and sends data wirelessly.

[1] P. De Lurgio *et al*, IEEE NSS/MIC, Anaheim, CA, USA, Oct. 31, 2012
[2] J. Chramowicz *et al*, 2010 *JINST* 5 C12038

Summary

- Optical data communication with high data rate, high density, and critical environmental requirements is being extensively studied and will be widely used in the future experiments.
- Optical fibers, laser diodes, and photodiodes needed for the future accelerator-based experiments have been identified.
- ASICs such as Laser drivers, TIAs, serializers and deserializers are being developed. Custom optical transceiver modules are being developed.
- On the system level, link power budget and jitter budget have been researched.
- Optical modulation , cryogenic applications of optical data communication and wireless data communication are being studied.