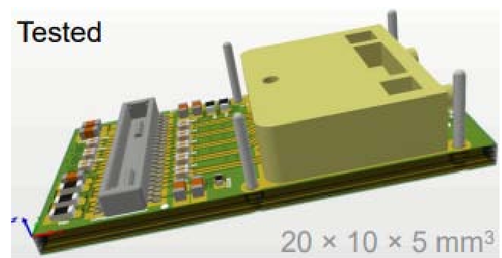
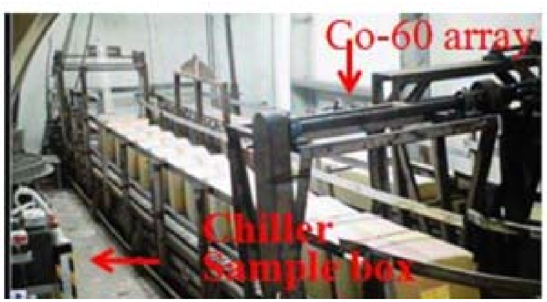
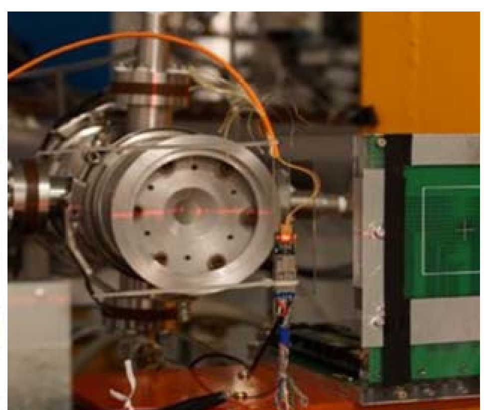
High speed Fiber-Optics for the EIC and future rad-hard applications

TIDC EIC workshop
NCKU, Tainan
2022.08.18-19

S. Hou
Academia Sinica







Proposal to EIC

- DAQ and data links will be totally Fiber-optics
- Taiwan opto-electronics IT is the primer production choice
  LHC upgrade electronics are TW made

- Join EIC, take up data-link duty for DAQ or a sub-det.
- ***Goal →***
  small funding on RD
  stay on Rad-hard Opto-electronics
  TW as the production site

Opto-fiber RD items

- **Fiber Rad-hard**

  MM Ge-doped @INER Co60 TID study is finishing
  COTS, Fluorine-dope, pure Silica fiber Rad-hard study

- **Rad-hard Active opto-electronics**

  850 nm VCSEL, PD characteristics, COTS 光環, II-VI, ..
  NIEL @INER 30 MeV protons

- **ASICs, laser driver, PD TIA ← deadly issue!**

  lack of expertise!!
  Collab. with HEP groups, acquire known chips
  check on COTS

- Transceiver >10 Gbps

  fabrication vs speed: PCB, passive, connectors, design, 前鼎, 源傑, ..
  coupling: active, lens, to fiber-ends
  NIEL, Ageing to Bit-Error-Rate

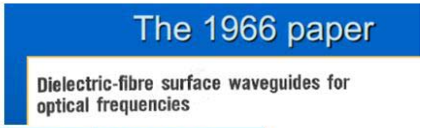
- **Facilitate INER proton beam**

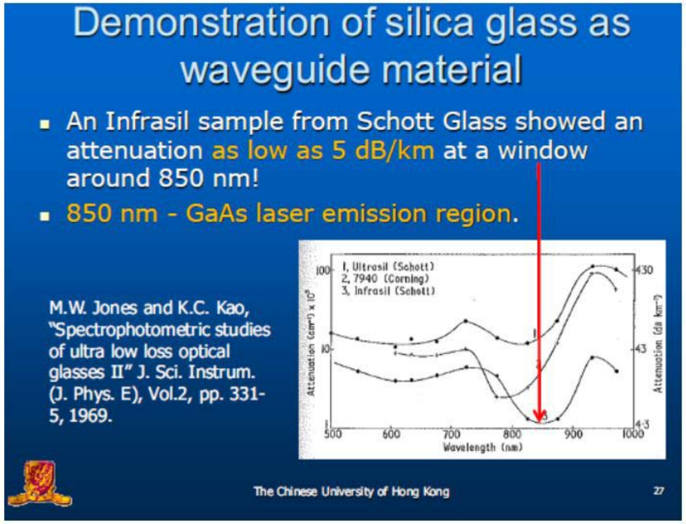
  for Rad-hard studies

Fiber as wave guide

Fiber-optics: innovation →IT

COTS: opto-electronics and fibers

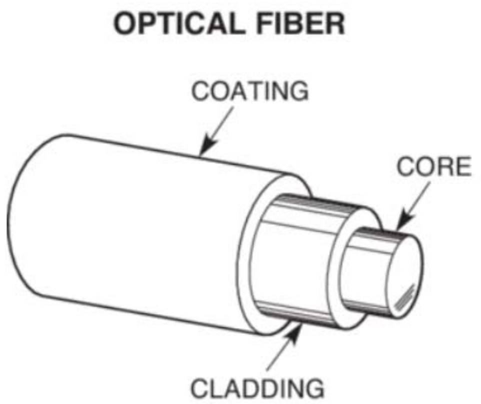


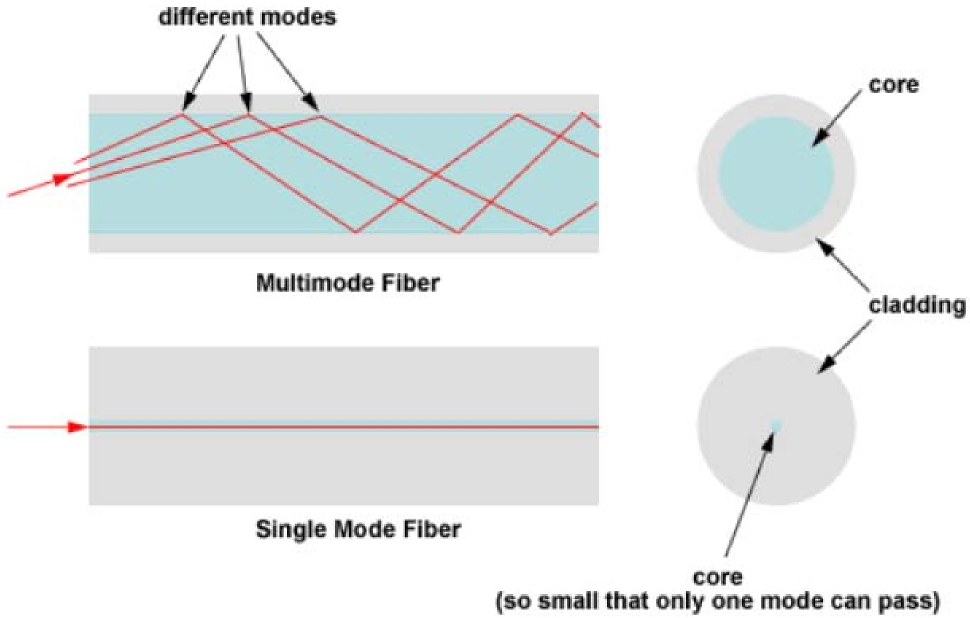


Nobel Prize '09 lecture

Optical fiber basics

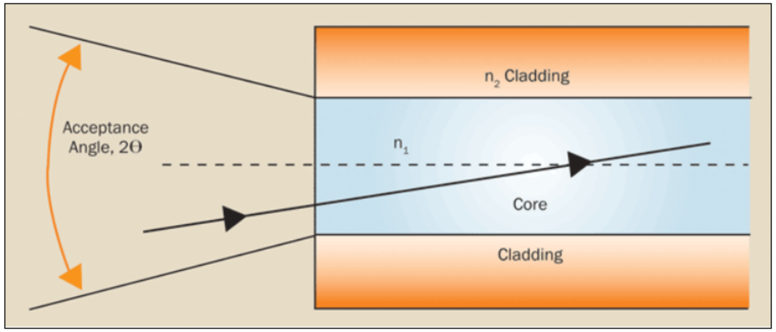
Fiber Modes :
Multi-guided modes: pathways grouped
Single mode fiber: 0th mode no reflection



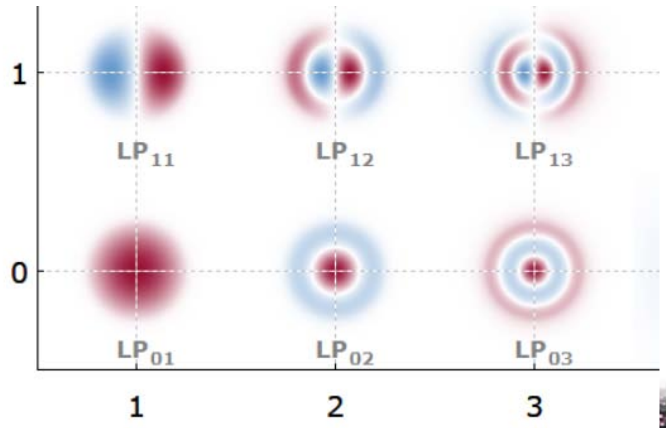


Numerical Aperture (NA)

$$NA = \sqrt{(n^2_{core} - n^2_{cladding})} = \sin\theta$$

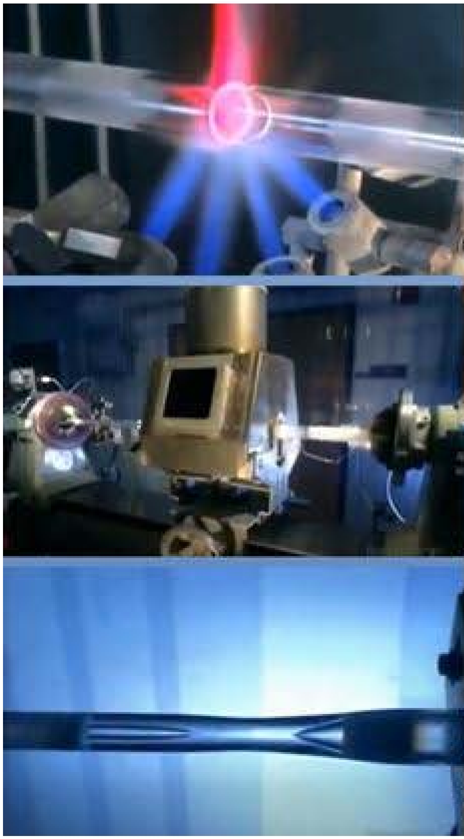


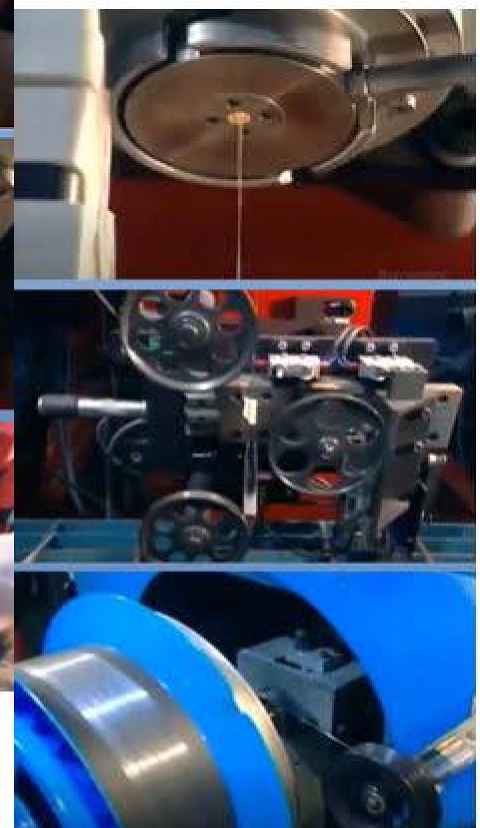
linearly polarized (LP) modes



Optical fiber making

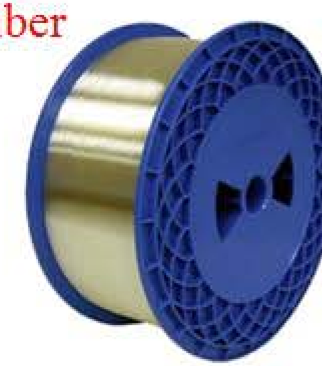
PCVD plasma chemical vapor Deposition
MCVD modified chemical vapor deposition
OVD outside vapor deposition
VAD vapor axial deposition





Fused Silica Tubes,
pure SiO_2
for Fiber Optics,

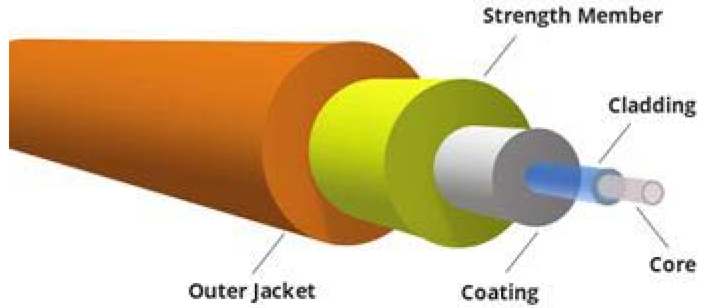
Bare Fiber Reel



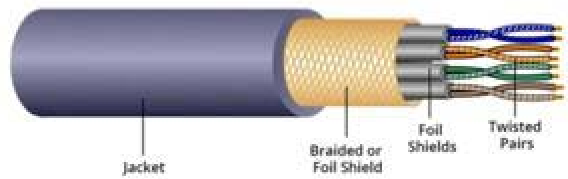
Fiber Cable

Copper wires vs Fiber cable

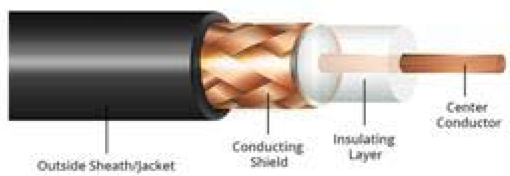
Fiber Optic Cable
1 Gbps → 10 Gbps → 25 Gbps
OM2 OM3
MM <500m SM~1km



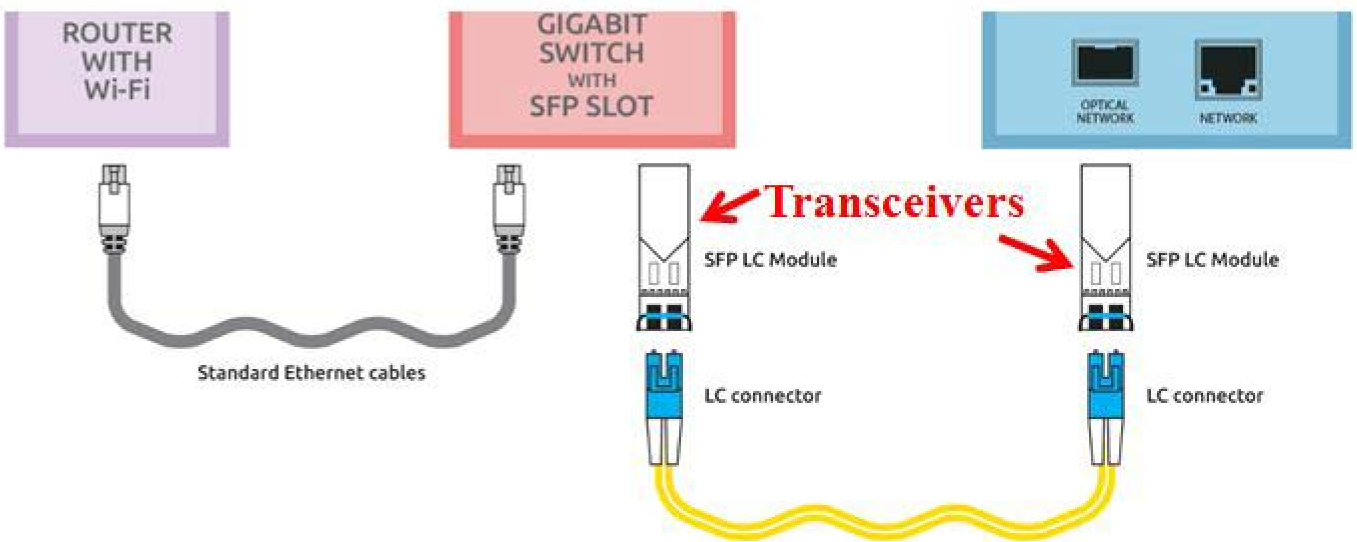
Twisted Pair Cable
e.g. RJ45 CAT6 10 Gbps <5m



Coaxial cable
e.g. RF, BNC 10 Gbps <5m



Network with fiber cable:
Need Transceivers



Commercial opto-electronics

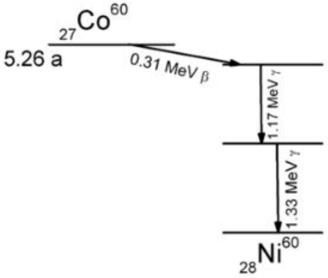
- **Transceivers:**
  - **Laser diodes** as light source
  - **PIN diodes** as photo detector
  - **Laser Driver chip** convert electrical signals to optical
  - **Transimpedance amplifier TIA** on PD current to electrical signals
  - **Control IC** for the application protocols

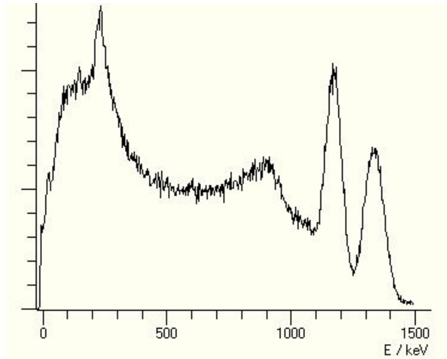
Laser type	Wavelength (nm)	Fiber type	Photo-diode type	Data rate (Gb/s)	Launching power	cost	Distance
VCSEL	850 1310	MM SM	GaAs InGaAs	10	Low	Low	< 300 m
FP	1300	MM SM	InGaAs	10	Med	Med	< 2 km
DFB	1310 1550	SM	InGaAs	>10	High	High	> 10km

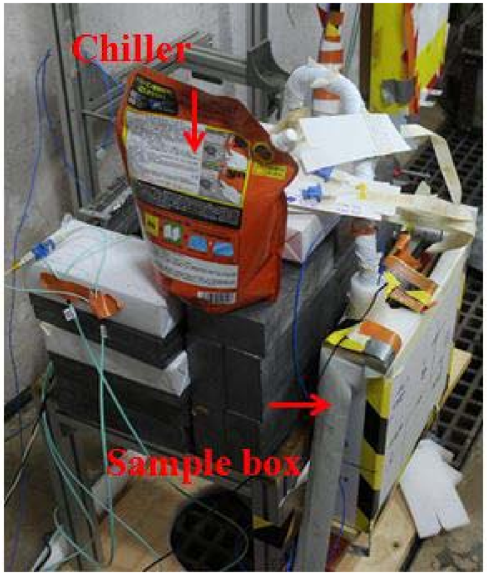
850-nm VCSELs - for short-distance over multimode fiber
1300-nm VCSELs - for longer-distance communication over single-mode fiber
1550-nm VCSELs - tunable sources for DWDM multiple transmissions over one fiber

FIBER

Radiation Induced Attenuation (RIA) by Total Ionization Dose (TID) at INER Co60 facility







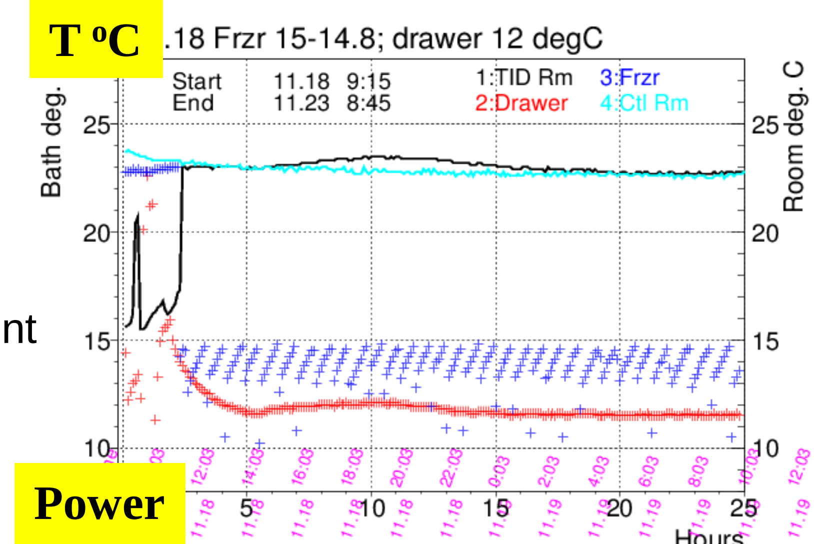
Ge-doped MM fiber test, day-1

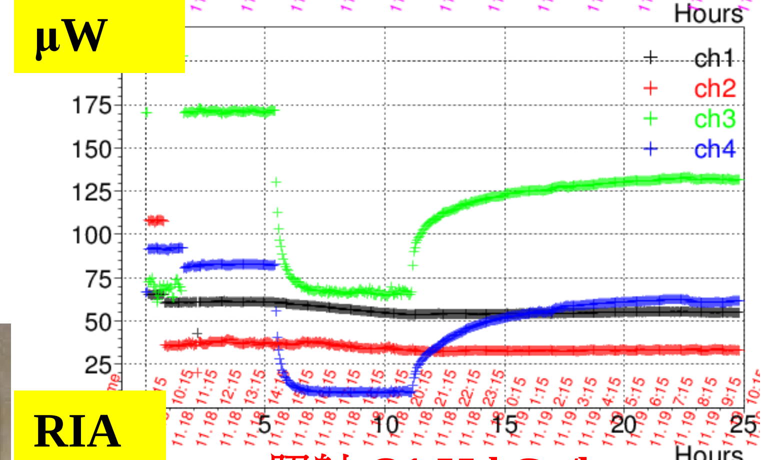
Ge-doped multi-mode fiber
50/125 µm M3,OM4 >10 Gbps

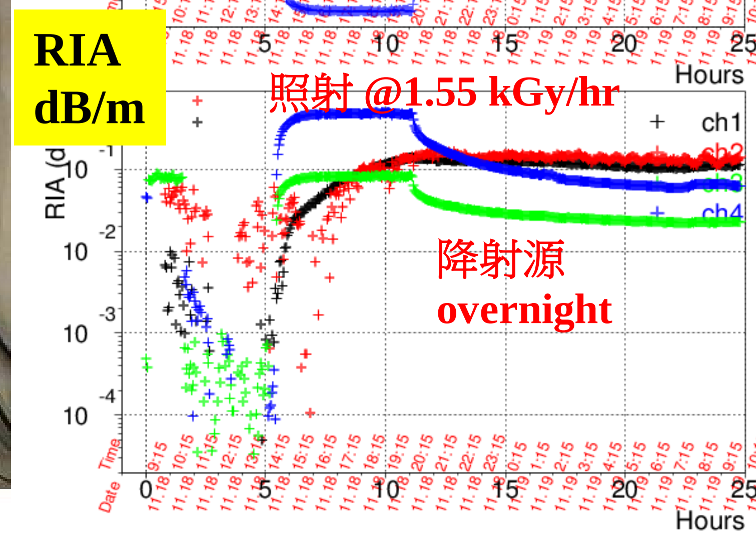
- water bath, constant temperature, online measuremnt
- 50 nm source → sample → power meter
- Gamma dose calibration, Alanine capsule

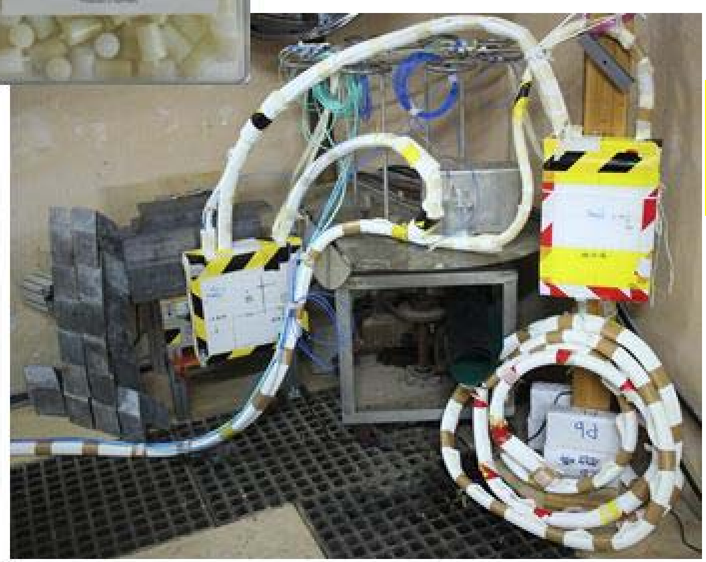
Co60 irradiation:

- ON   daily working hours ~10hr **RIA**
- OFF overnight **Annealing**









Ge-doped MM fiber, Co-60 test

Fiber Radiation Induced Attenuation (RIA)

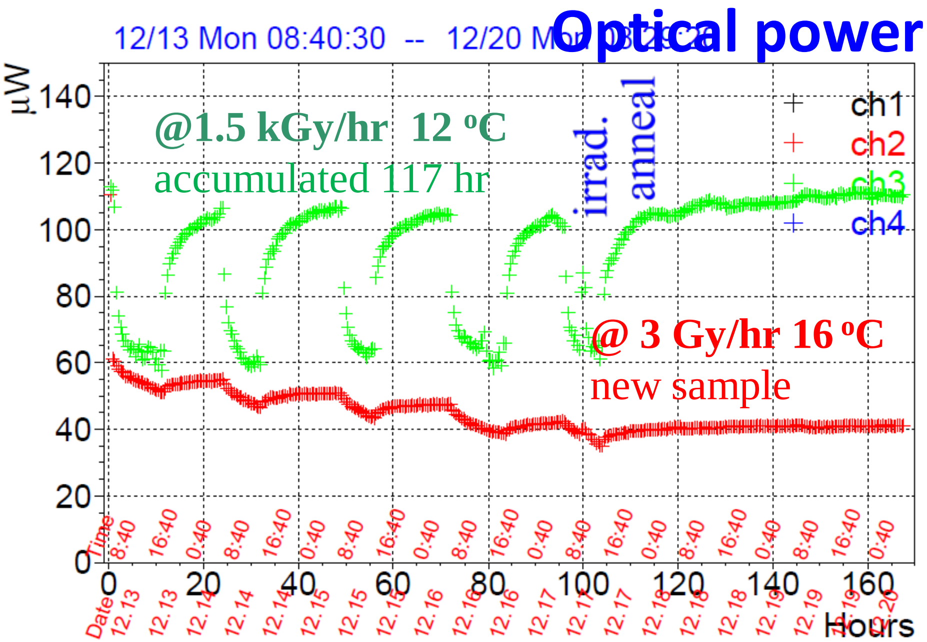
$$RIA = (IL(0) - IL(t))/Length$$ IL insertion loss

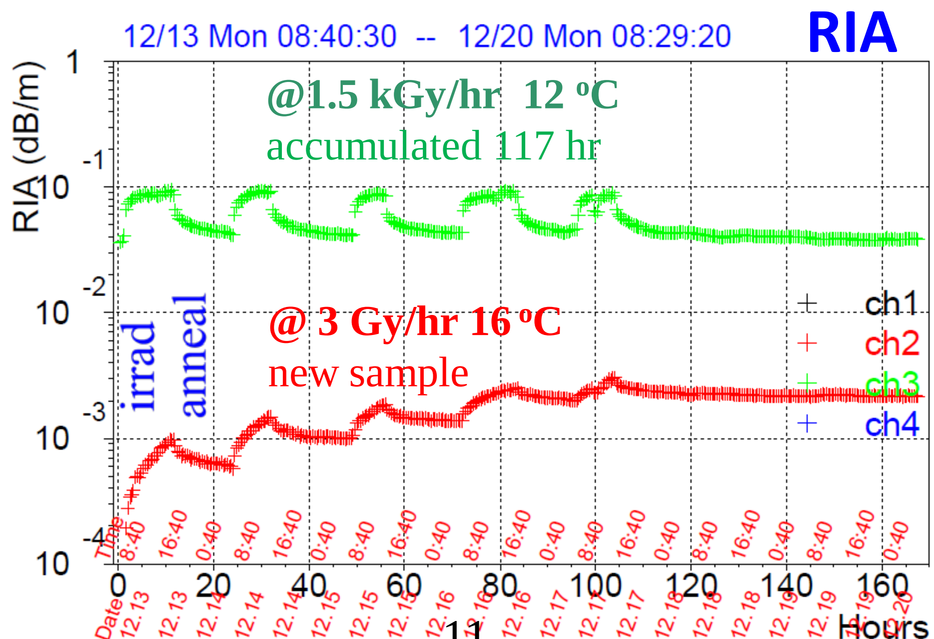
$$IL(dB) = 10 \times \log10 (P_T/P_R)$$ P_T transmitter, P_R received

Dependences : **Dose rate, Temperature**

Fibers tested at Dose rate 3.0 Gy/hr, 1.5kGy/hr

Irrad ~8hr daytime, anneal overnight, over 1 week



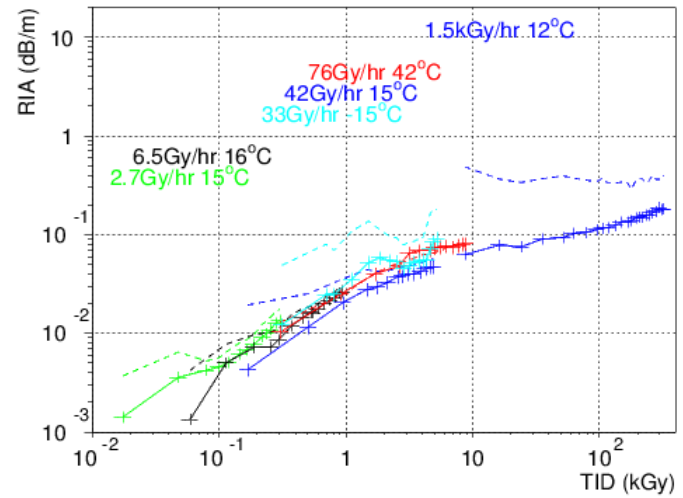


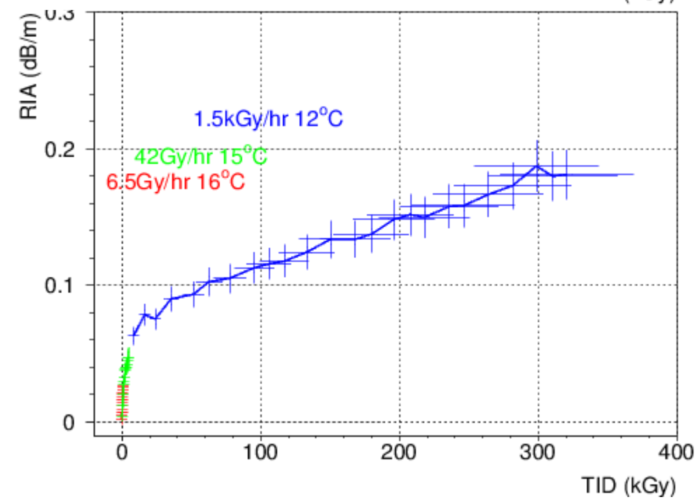
台廠 Ge-doped MM fiber RIA instant vs annealed

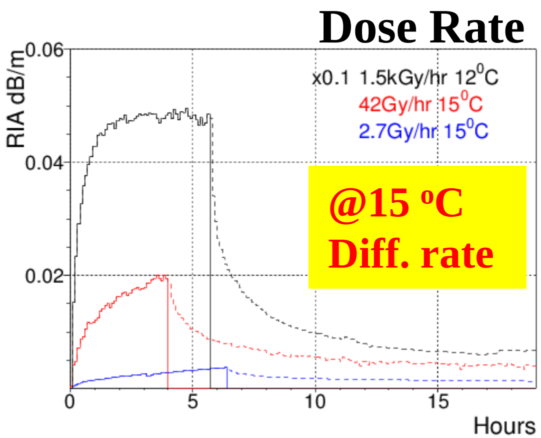
Plot Instant RIA, at daily max dose,
Plot RIA after 10 hr annealing

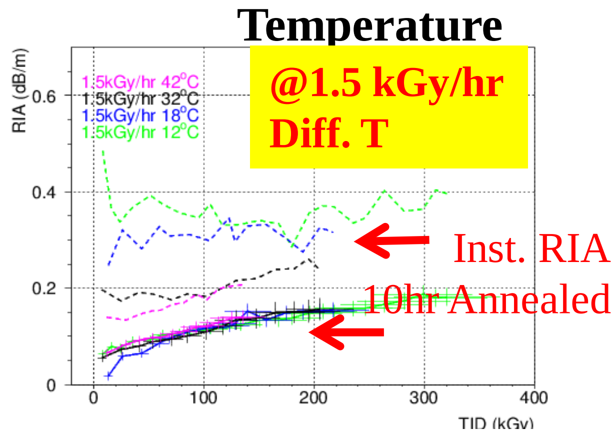
- **Dose Rate dependence:**
  higher rate higher instant RIA
- **Temperature dependence:**
  lower T, higher instant RIA

Annealed RIA:
smooth logarithmic curve toward high TID





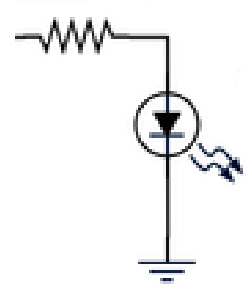




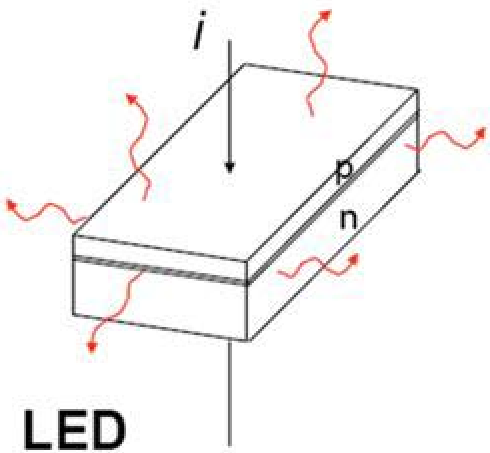
Rad-hardness of opto-electronics, COTS

USB, SFP+ devices >5 Gbps
Light-coupling material
VCSEL, Control IC, BER

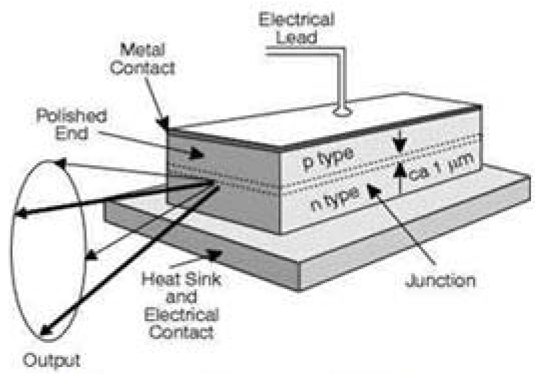
Laser diodes, light sources



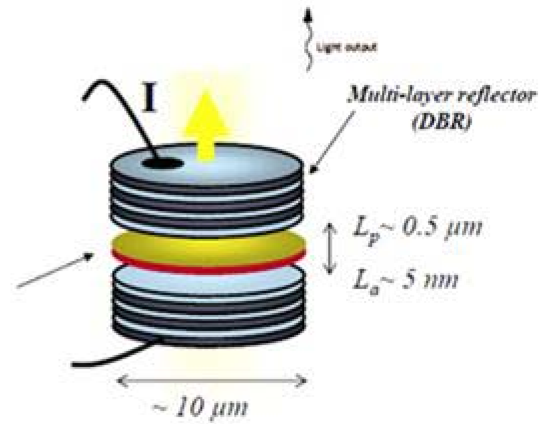
Spontaneous light emission
Laser Diodes (LD), Light Emitting Diodes (LED) LED
LD has an optical cavity for stimulated emission.
Light Amplification by Stimulated Emission of Radiation (LASER)



LED

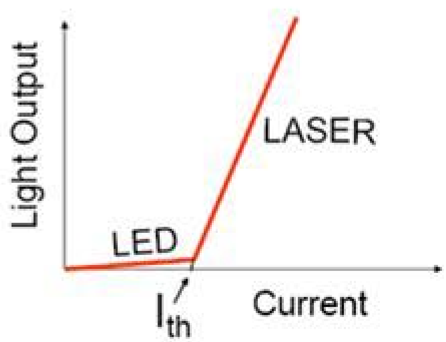


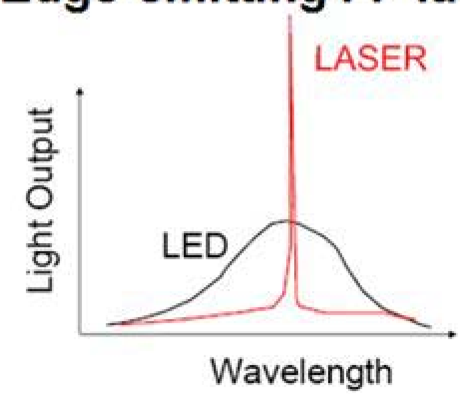
Edge-emitting FP laser



VCSEL

(Vertical Cavity Surface Emitting Lasers)





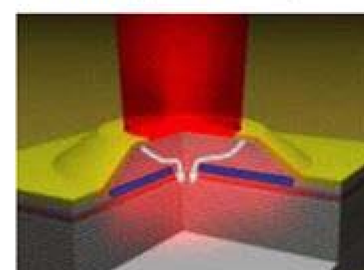
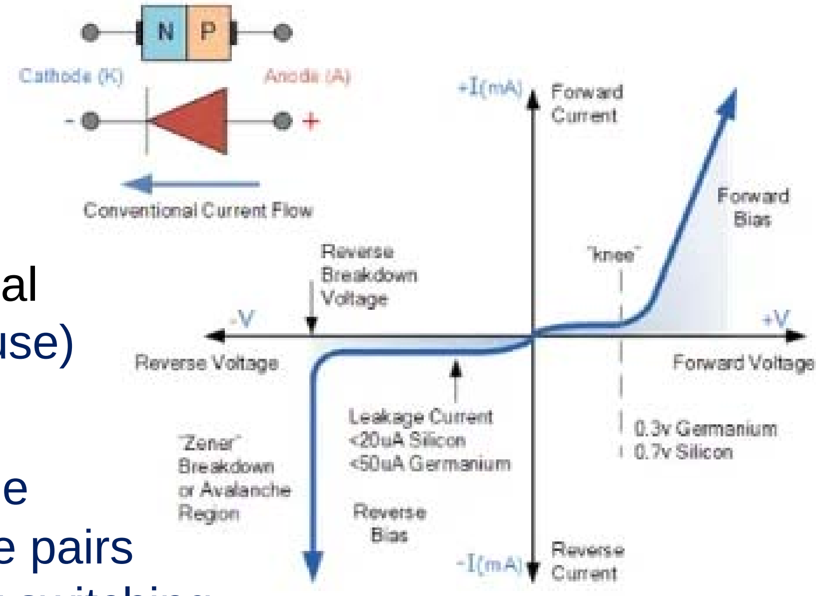
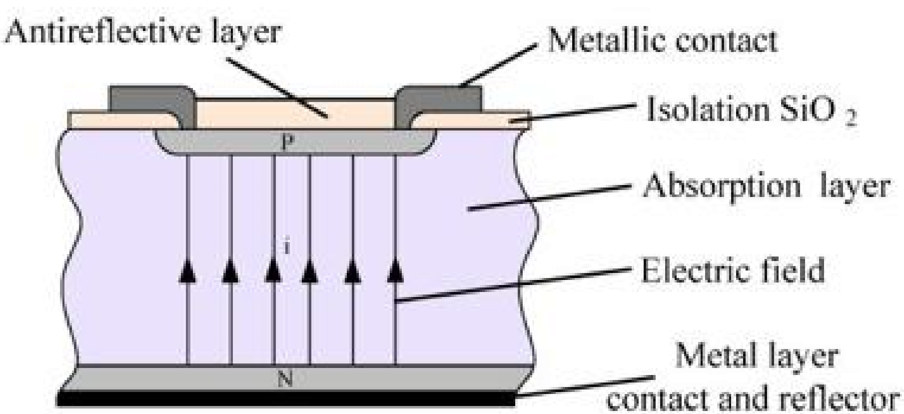


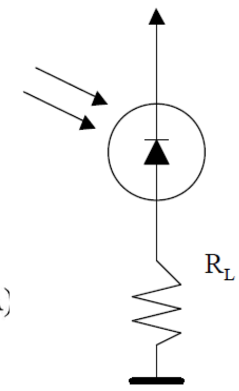
Photo-detectors

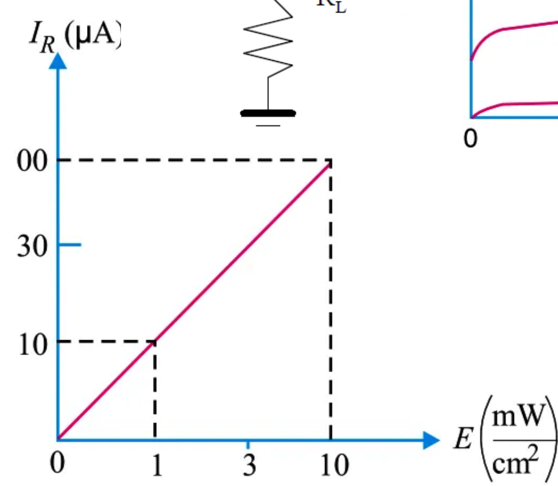


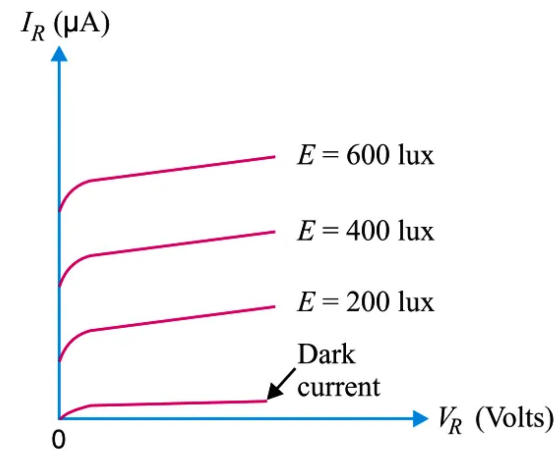
- **Photo-detector (PD)**
  converts incident light pulse into electrical signal
  - **PIN Photo-detector** (most common PD in use)
  - Avalanche Photo-diode (APD)

- **PIN** diode is operated in the reverse-bias mode
  - wide depletion region to create electron-hole pairs
  - low junction capacitance allows for very fast switching









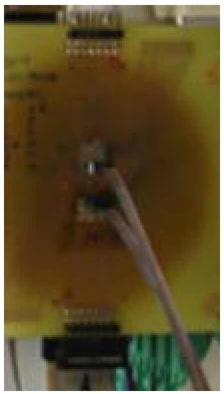
VCSEL degradation, annealing

VCSEL light degradation ➔ linear to fluence

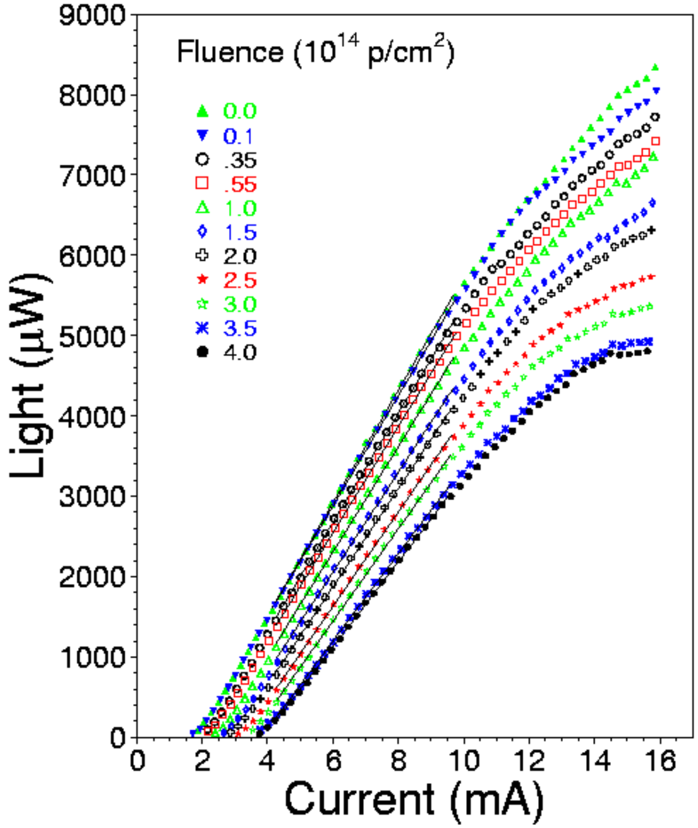
rad-hard fiber connected to readout, independent of flux rate

Fast annealing by charge injection

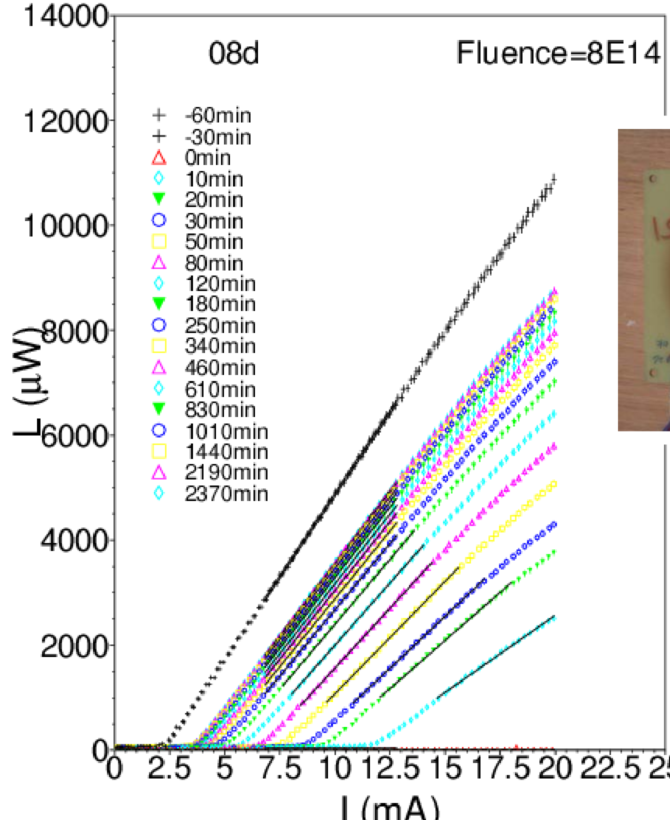
at operation current (10 nA) applied

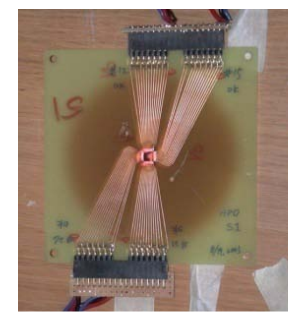


L-I of VCSEL (oxide) vs. **online** Fluence



L-I of VCSEL (oxide) vs. **Annealing** time



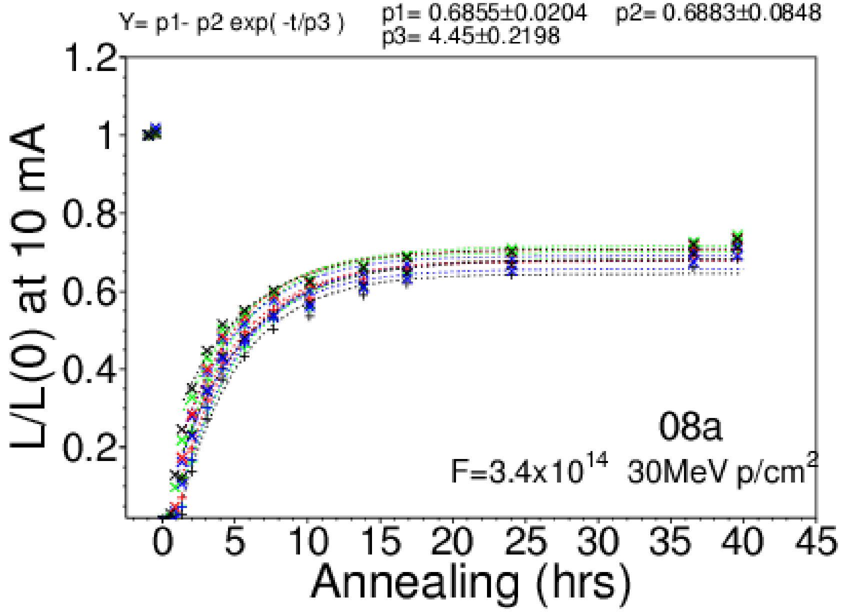


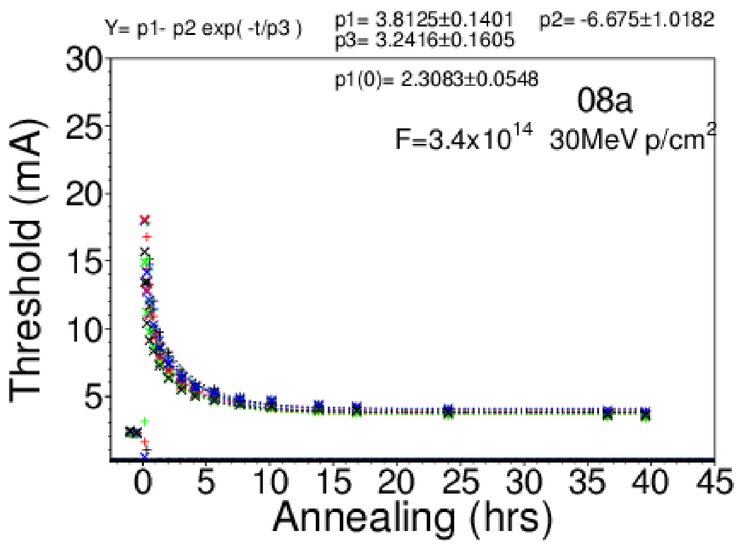
VCSEL annealing in time

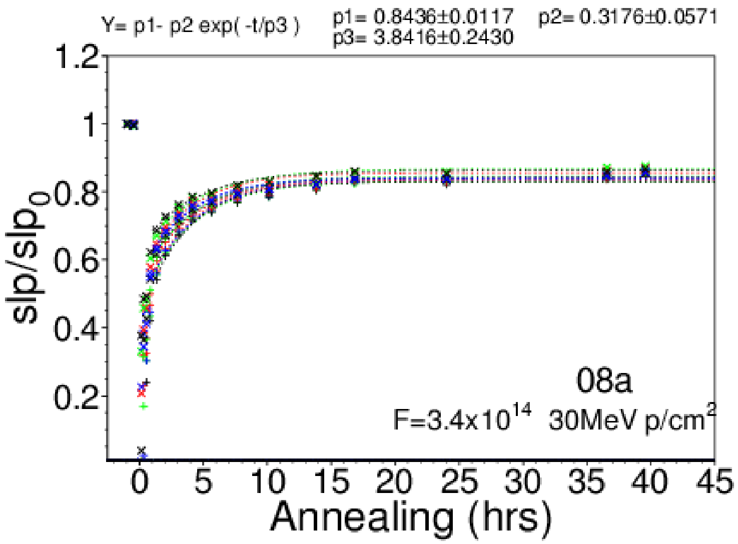
- Charge injection at
  at the operation 10 nA

$f(t)= f_{\infty} - a\cdot \exp(-t/ \tau)$

➔ recovery time
τ ~ 5 hours

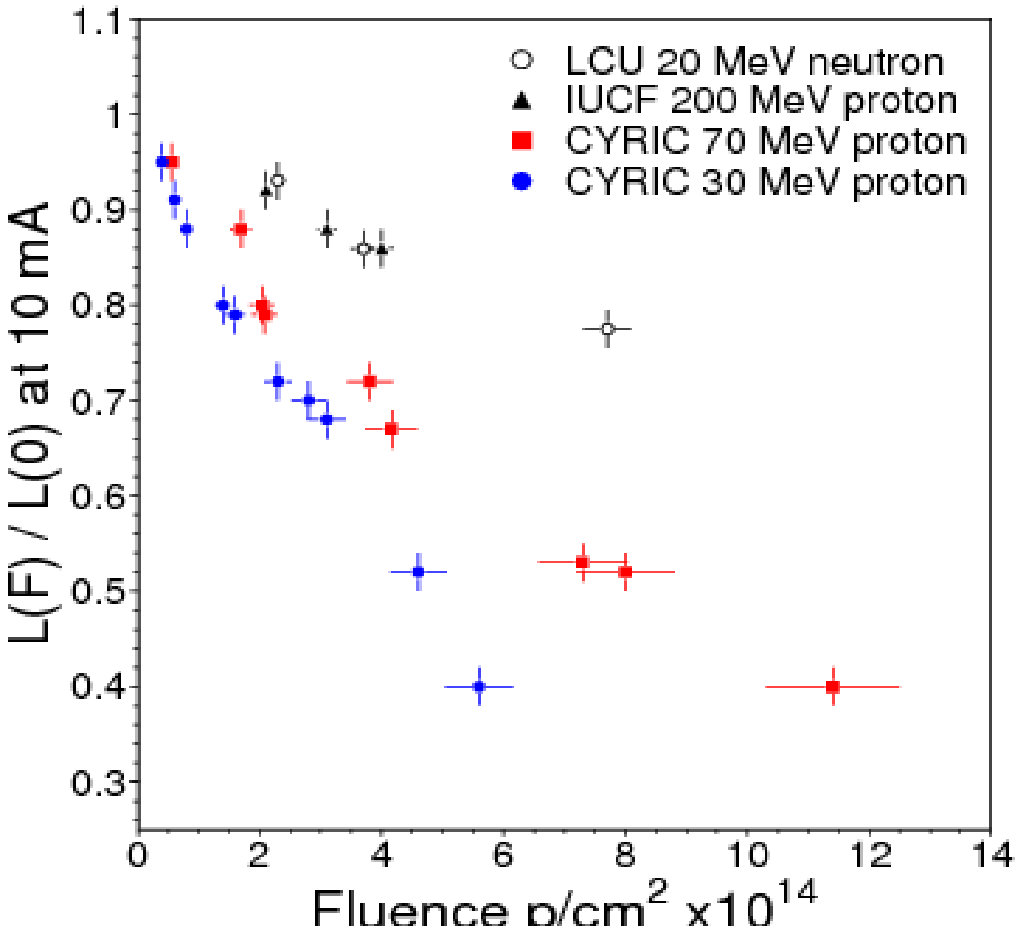


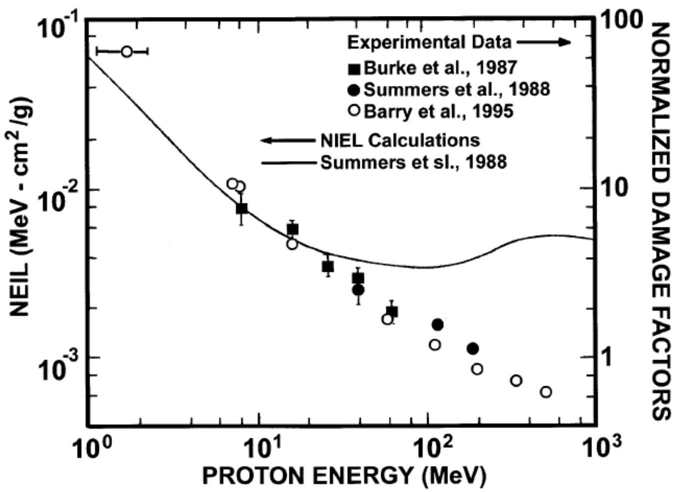




VCSEL rad-hardness summary

- VCSEL light degradation in proton radiation (ATLAS Oxide confined) deviates from the NIEL calculation





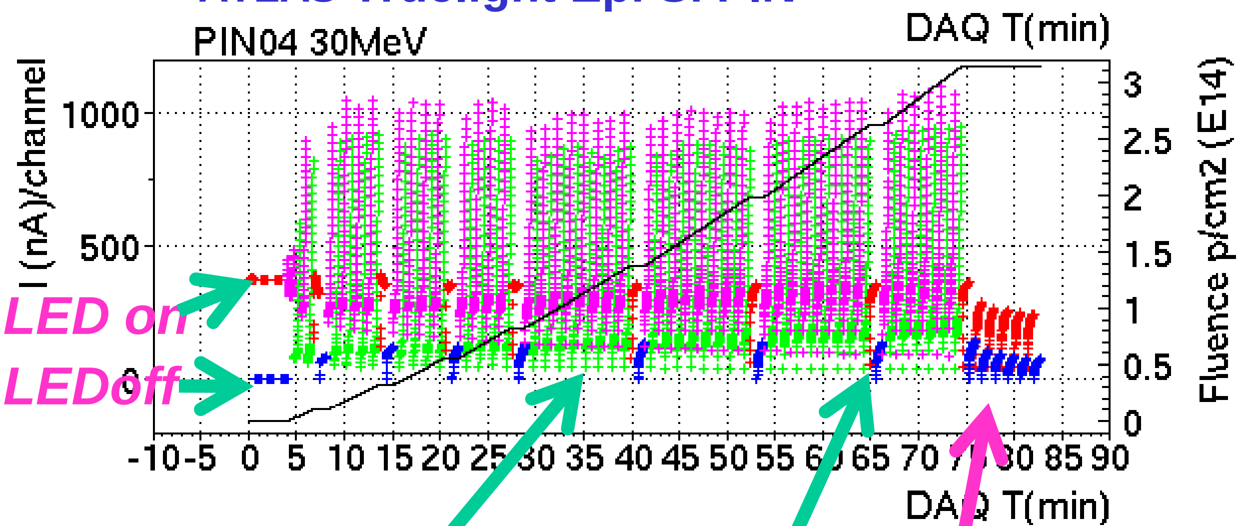
GaAs solar cell

Srour, IEEE TNS 50, 653 (2003)

PIN responsivity, dark current

- Tohoku 30 MeV proton
- Control beam on/off
  LED light on/off
- Online PIN V_R scan

ATLAS Truelight Epi Si PIN



beam on, *beam off*

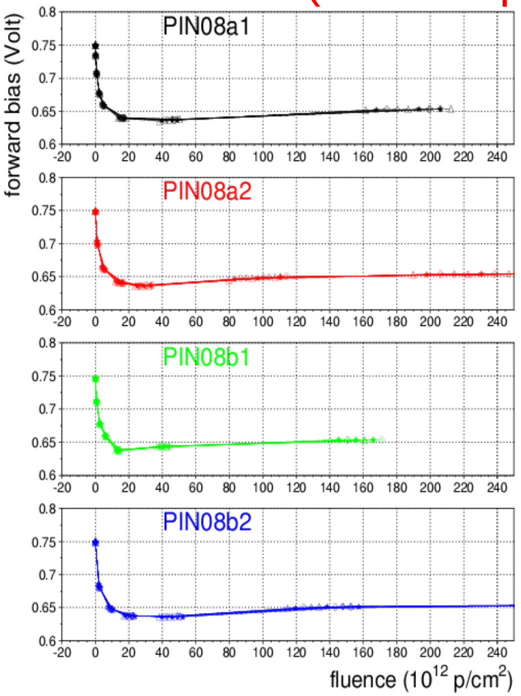
Each strip is a 0-20V scan

Beam off: + LED on + LED off

Beam on: + LED on + LED off

Quick recovery
expelling dark current

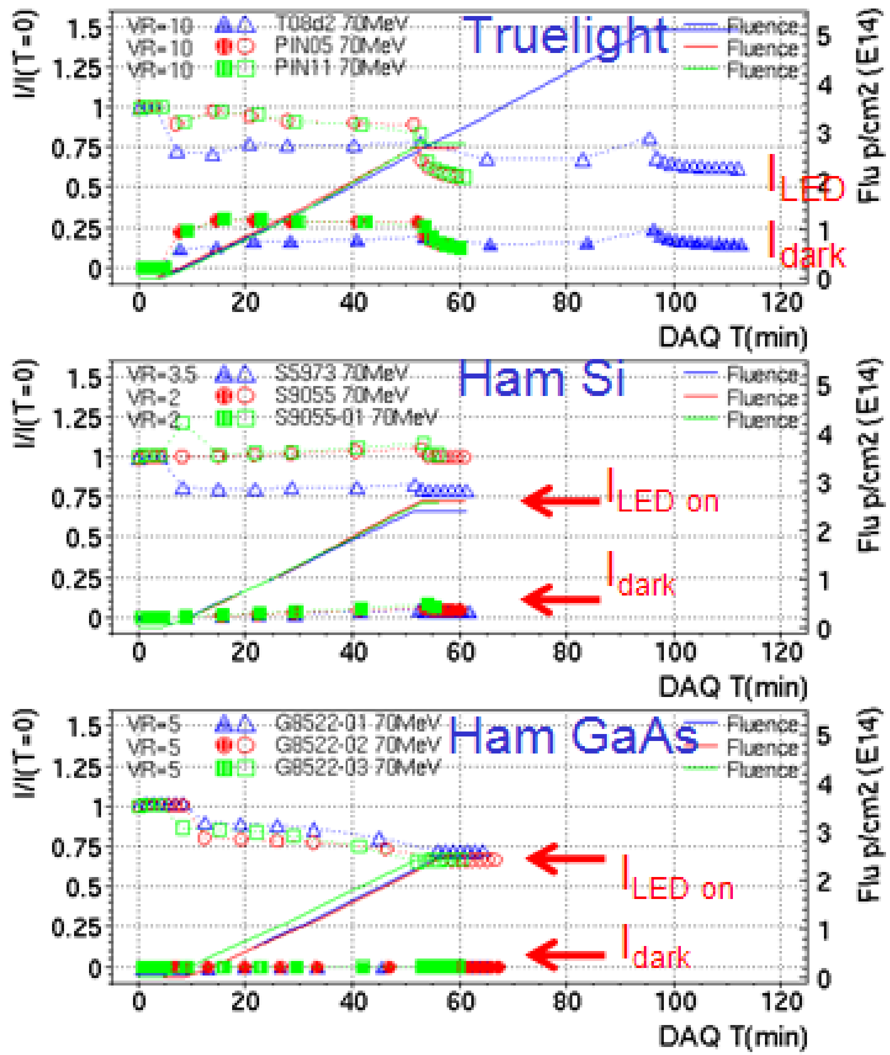
Forward bias (30 MeV p)



PIN proton damage, summary

Degradation of responsivity (I/L) proton 2E14								
					30 MeV		70 MeV	
	V_R Vol	fc GHz	diam. µm	I/L A/W	I/L ratio	Dark nA	I/L ratio	Dark nA
Truelight	**-10**		**100**	**0.55**	**45%**	**70**	**45%**	**50**
S9055	-2	1.5	200	0.32	100%	40	100%	20
S9055-01	-2	2.0	100	0.20	100%	15	100%	10
S5973	-3	1.5	400	0.53	70%	100	80%	50
G8500-01	-5	3.0	40	0.11	45%	0	80%	0
G8500-02	-5	1.9	80	0.25	40%	0	72%	0
G8500-03	-5	1.5	120	0.40	35%	0	72%	0

70 MeV proton



- PIN rad-hardness
  diameter, thickness ➔
  A/W, speed & rad-hard
- Proton energy dependence
  Si PIN : compatible with
  30 MeV and 70 MeV protons
  GaAs PIN : twice damage by 30 MeV
  than 70 MeV protons

Total Ionizing Dose to Commercial driver

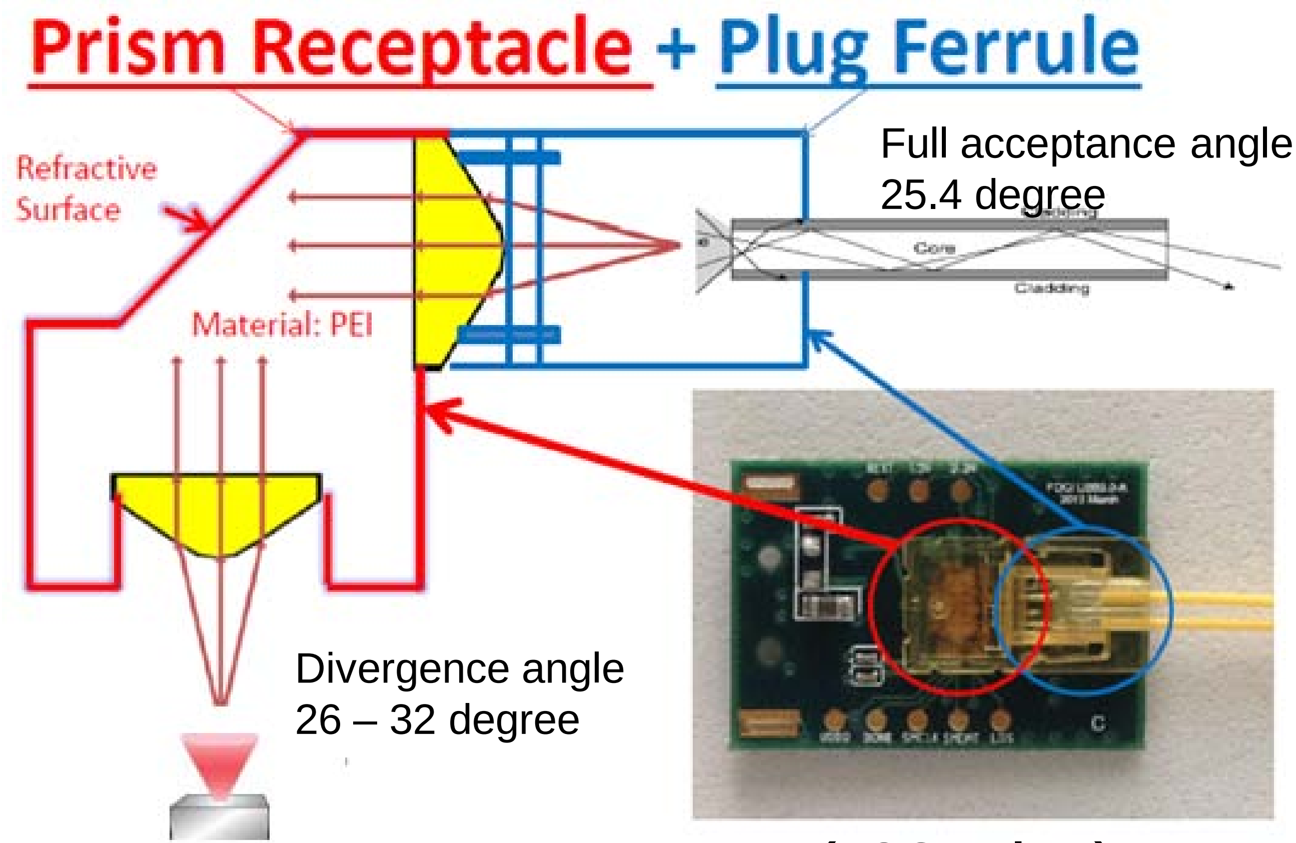
- QSFP, miniPOD, PPOD, ONET8501V, ONET1101L
  tested with X-ray or γ-ray, none meet the ATLAS LAr radiation requirement.
- Kintex 7, ONET8501
  tested with a neutrons in Los Alamos SEU rate of Kintex 7 is too high for LAr.

	Vendor	Part#	Gbps	# ch	Rad type	(krad/hr)	TID (krad)
QSFP	Avago	AFBR-79EIDZ	**10**	4	**^{60}Co γ**	10	75
miniPOD	Avago	AFBR-810FN1Z	**10**	1	**x-ray**	360	66
PPOD	Avago	AFBR-810EPZ	**10**	12	**x-ray**	360	150
VCSEL driver	TI	ONET8501V	**10**	1	**x-ray**	39	178
F-P laser driver	TI	ONET1101L	**10**	1	**x-ray**	9.6	464
					^{60}Co γ	10	< 900

	Vendor	Part#	# of ch	Flux (n/cm²/s)	Fluence (n/cm²)	# errors	σ (cm²)
Kintex-7	Xilinx	XC7K325TFF G900	16 (2 tested)	**4.6E5**	**2.1E11**	4/4 (2 shared)	1.6E-11
VCSEL driver	TI	ONET8501V	1	**4.6E5**	**2.1E11**	0	< 5E-12

Light coupling Technology

- **Light Peak example, Intel** technology delivers high bandwidth starting at 10 Gb/s to mainstream computing and consumer electronics
- **Lens/Prism :** precision PEI molding ..



Spherical-aberration free
Plano-Convex
Hyperbolic Lens

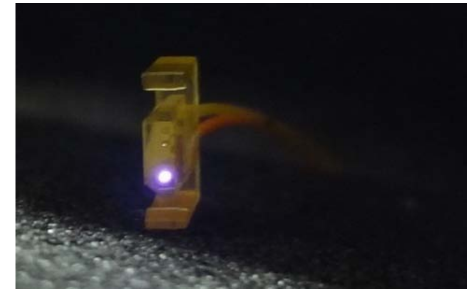
VCSELs aperture
from t Ø 5 to 20 µm

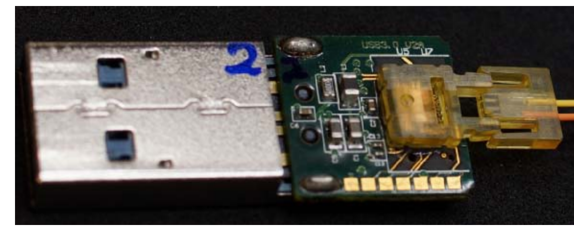
(FOCI prism)

Radiation damage to PEI coupling Lens

- **The light coupler cap**

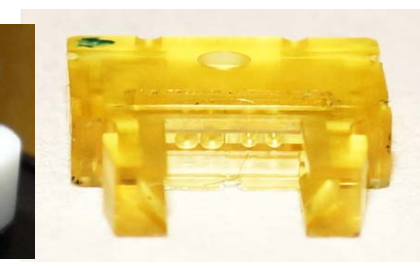
  Spherical-aberration free Plano-Convex Hyperbolic Lens
  Material: PEI (polyetherimide), as for the TOSA/ROSA tip
  optical quality surface

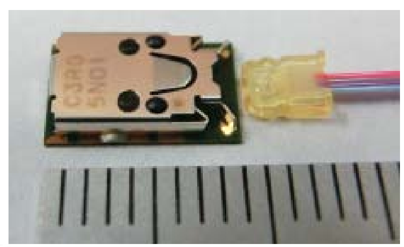


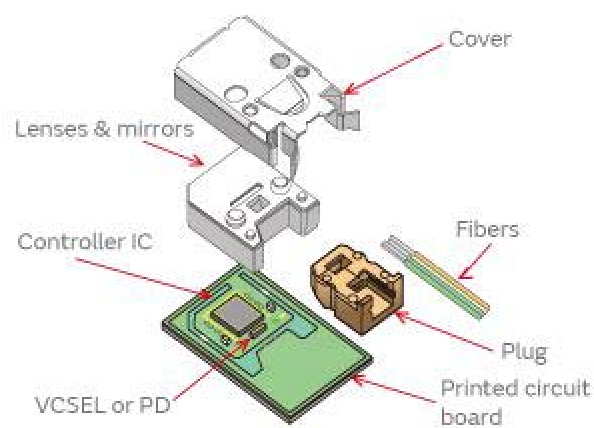


- **Deterioration by Total-Ionizing-Dose**

  Irradiated with Co^{60} Gamma ray
  at INER Taiwan
  flux: 3.5 kGy/hr, total: **117 kGy**
  ➔ NO LOSS !!
  for light transmission
  within the 2% systematic error





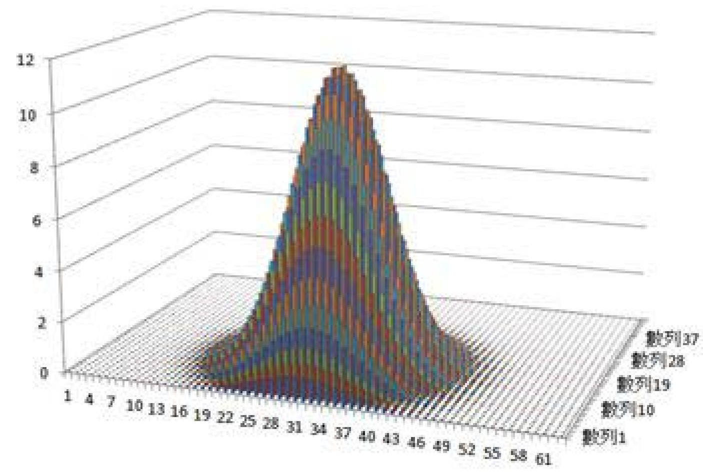


Internal structure of the FOT MMC3 series proc

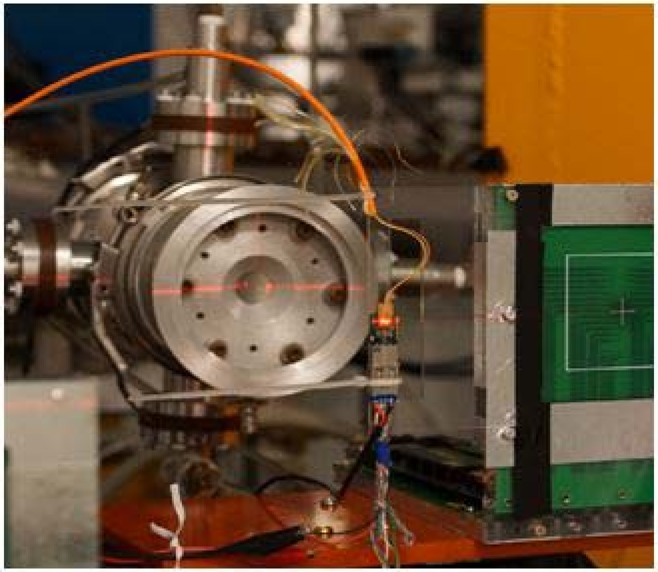
muRata epoxy lenses

Non-Ionizing Energy Loss to VCSEL, COTS IC

- **Proton Irradiation**
  INER 30 MeV proton beam
  flux of **2×10^{12}** p/cm^2s, to a total **1.2×10^{14}**
  equivalent to **4.8×10^{14}** $n(1MeV)/cm^2s$
- **Beam profile**
  Strip and pad chambers for beam profile
  strip pitch 1 mm



- **Irradiation measurement**
  FOCI module DC biased
  no signal input,
  VCSEL online monitored
  for mid-level DC light
  - **VCSEL light degradation**
  - **Optical IC function**



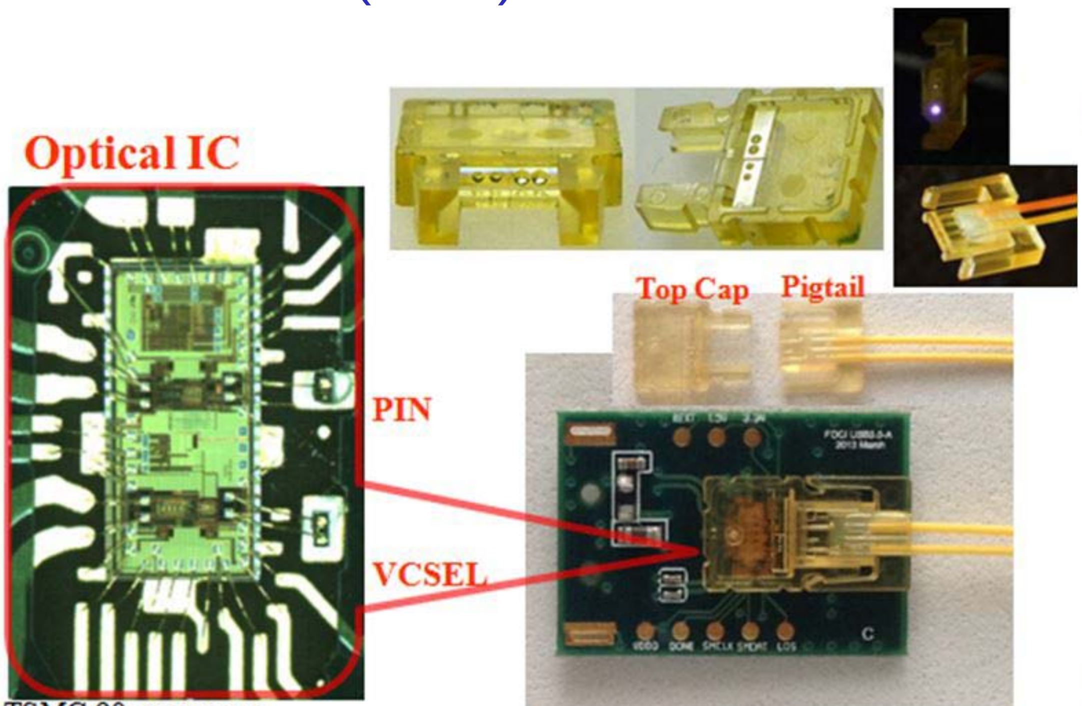
Optical driver, USB-3, 5 Gbps

VCSEL/PIN:

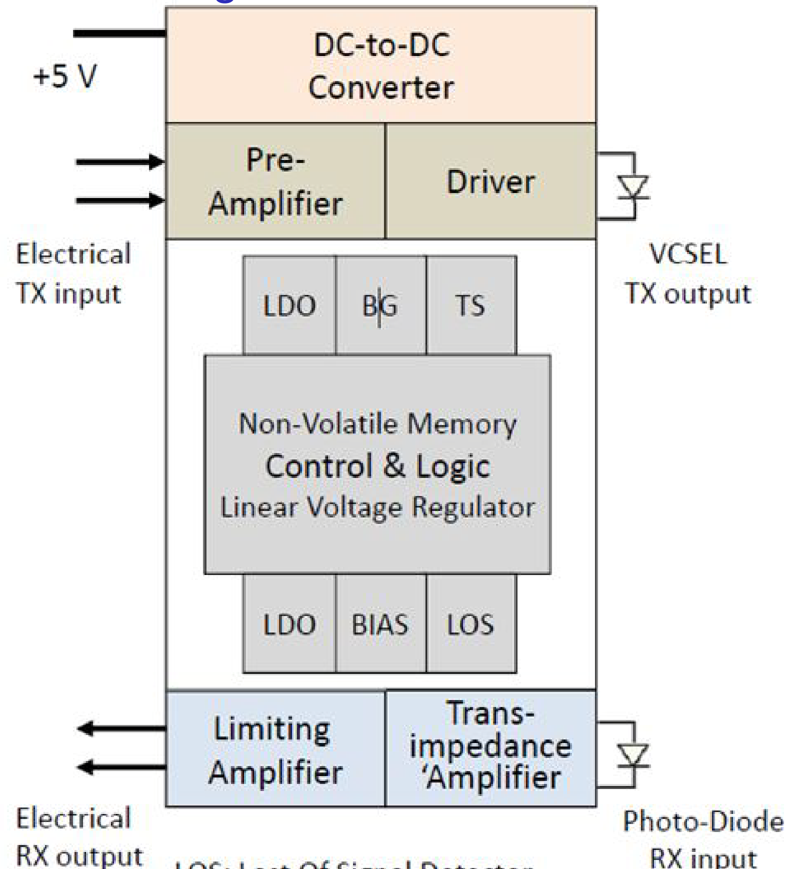
- 850 nm bare die,
- 4.8 Gb/s or 10 Gb/s
- >0 dBm (1mW)

Optical IC:

- **VIA Labs V0510**,
- TSMC 90nm technology
- USB-3 protocol, ~60 mW,
- 4.8 Gb/s TX/RX driver
  + regulator/controller

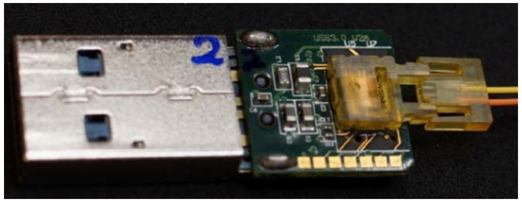


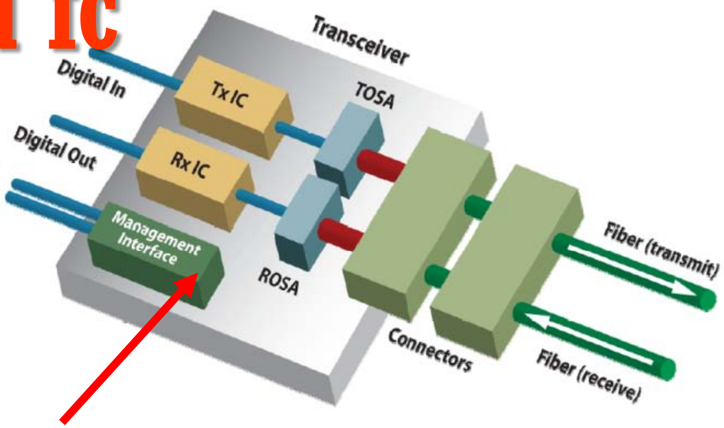
TSMC 90nm process
VIA Labs USB 3.0 V0510



LOS: Lost Of Signal Detector
TS: Temperature Sensor
BG: Band Gap Reference
LDO: Low Drop Out voltage regulator

NIEL damage to VCSEL, Optical IC

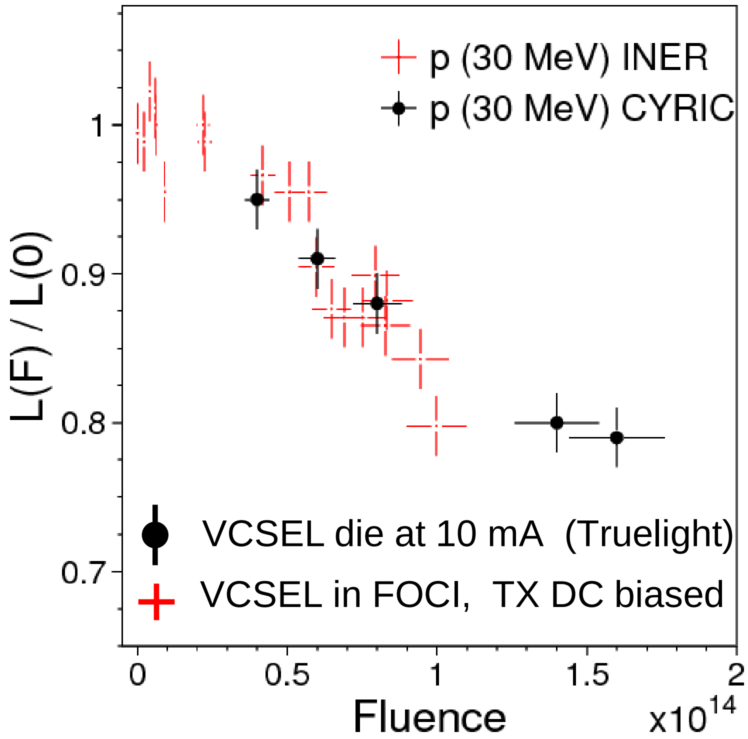




Configuration corrupted after irradiation

- **VCSEL degradation**
  - VO510 DC biased, (1.5 V to TX driver)
  - Annealing during irradiation
  - Linear loss to fluence

  ➔ VECEL degraded to **80%** of the original after **1x10^{14}** p(30 MeV)/cm^2 consistent with bare VCSEL tests



- **Single Event effect to Optical IC**
  - Single Event Effect = 3x10^{-3} Hz @Beam flux = 3.4x10^9 /cm^{2}s to controller circuits, observed by VCSEL DC light level hopping
  - Fatal damage to Optical IC after 1.2x10^{14} p(30 MeV)/cm^2

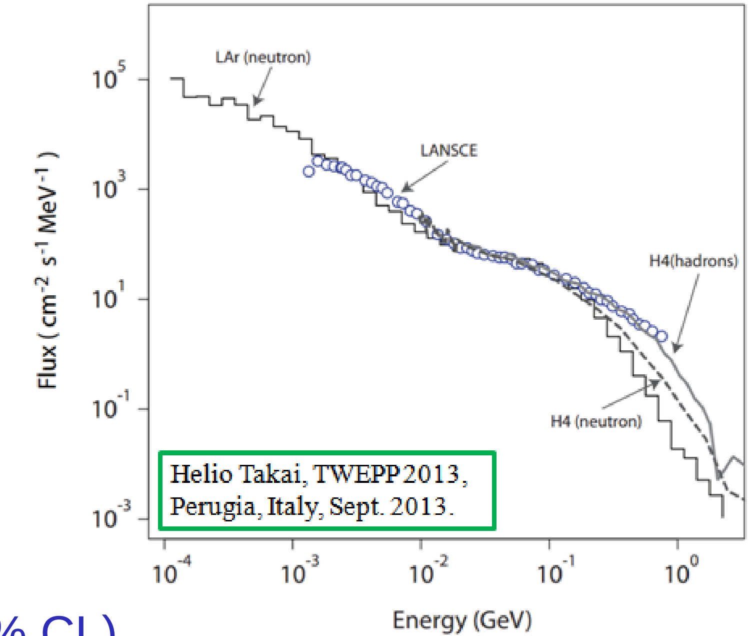
LANSCE neutron test

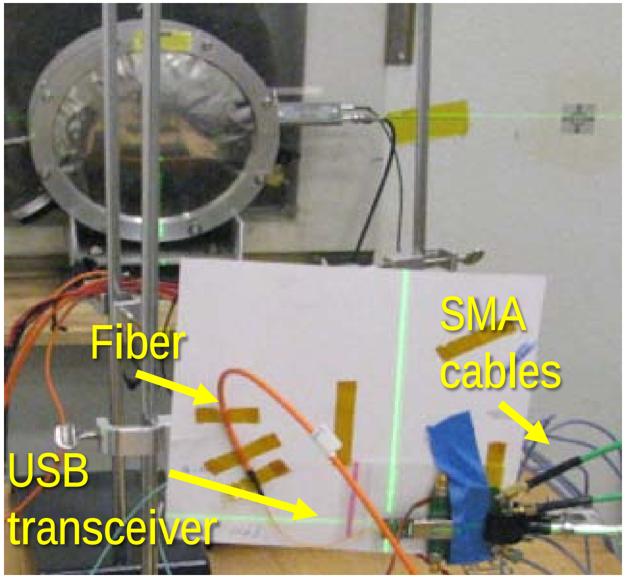
- Beam profile similar to ATLAS
- **USB transceiver in Bit-Err-Rate**
  Straitix II GX, PRBS 2^7-1 bit pattern
  TX path, RX path tested separately

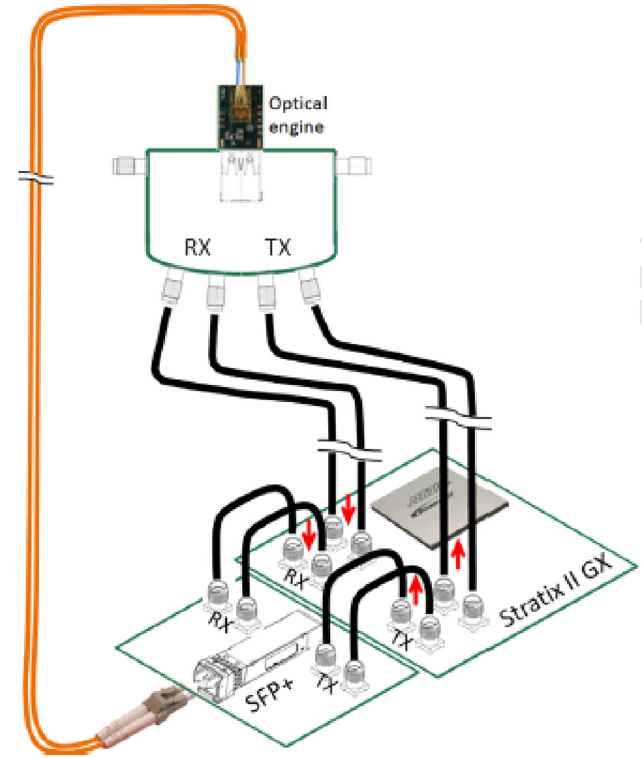
  neutron flux 2.9×10^5 n/cm^{2}s
  over 1.5 days to 3.8×10^{10} n/cm^2

  TX: 0 error, upper limit 1.0×10^{-10} cm^2/ch (95% CL)

  RX: 11 errors SEE cross section 2.9×10^{-10} cm^2/ch



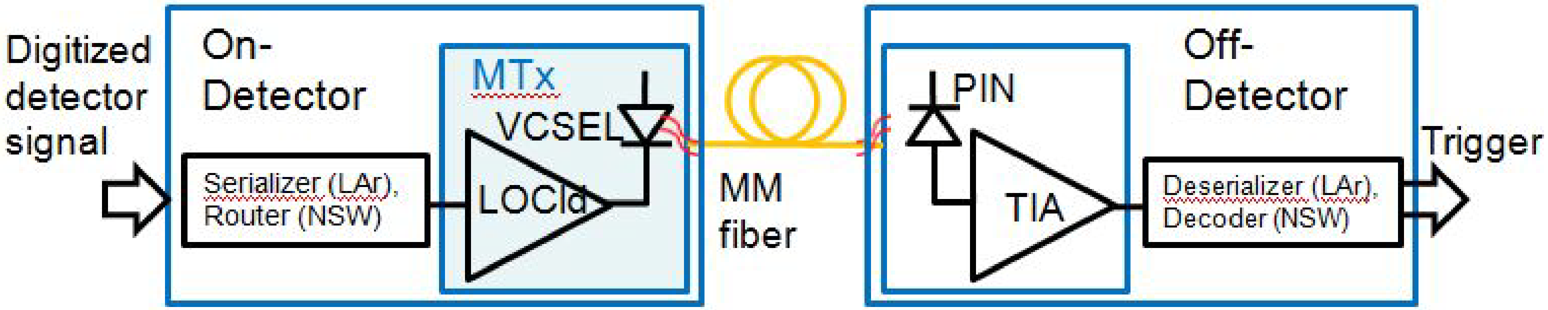




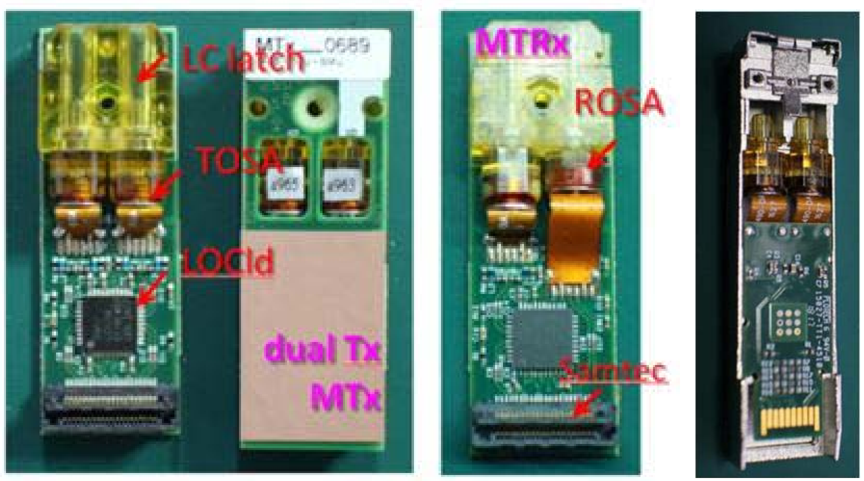
TW >10Gbps fiber-optics for collider experiments

- ATLAS P1 production, LAr, Muon NSW
- Prototyping upto 4TX-4RX 25Gbps

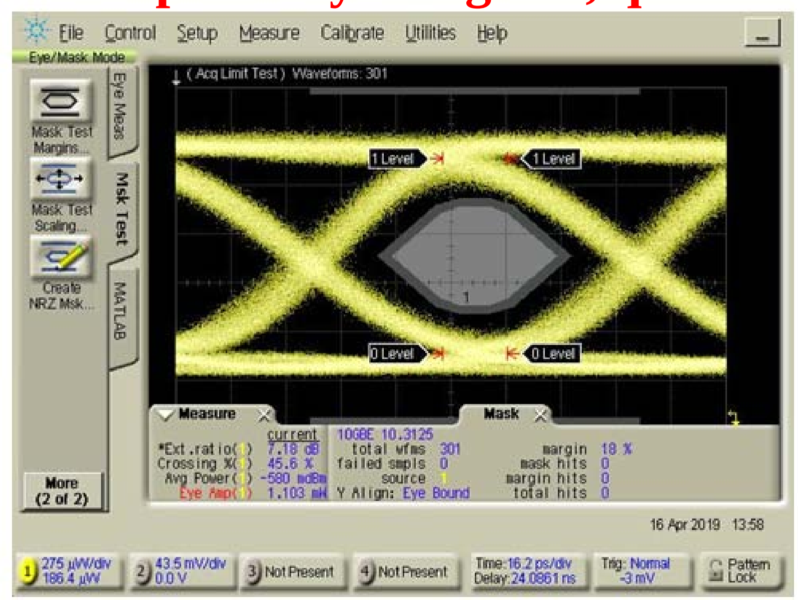
ATLAS LAr MTX, Phase-I upgrade



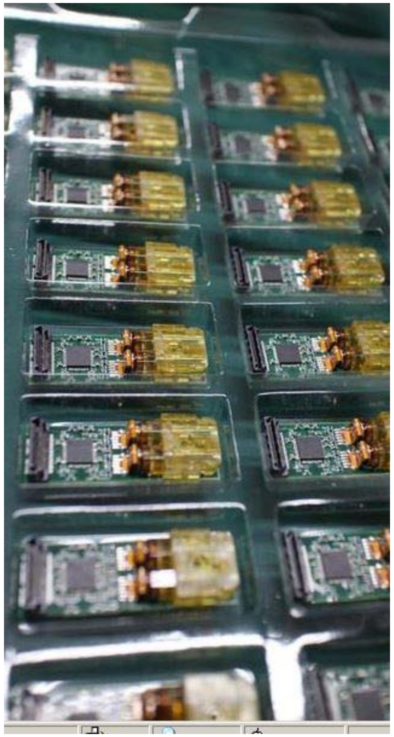
- 850 nm TOSA/ROSA, LC fiber coupling
- LOCld lazer driver of .25um SOS process, designed for 8 Gbps
- Customized latch to reduce thickness



10 Gbps TX eye diagram, qualified

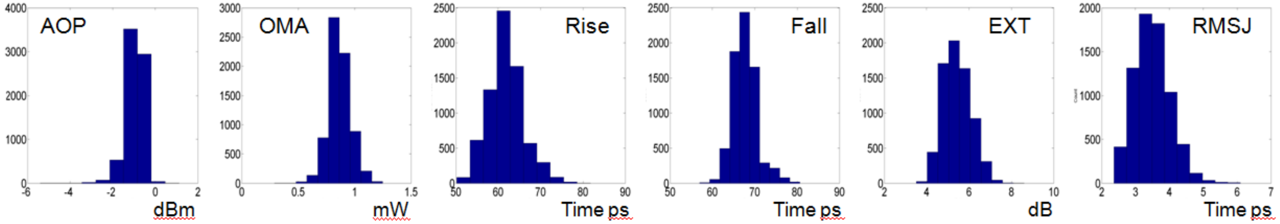


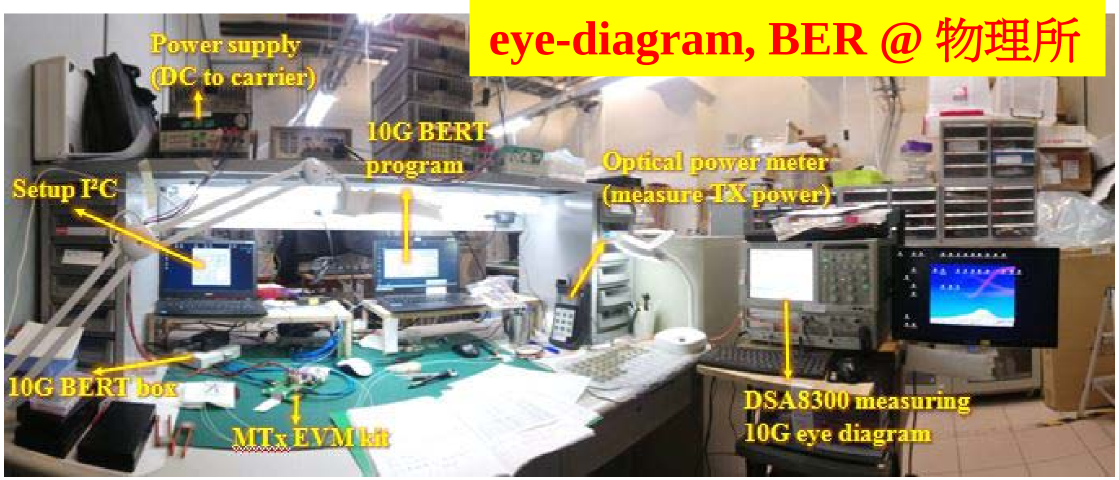
ATLAS LAr MTX, AS produciton, 2019 delivered



- ~ 5k transceivers produced by AS
  TW opto-electronic companies: 光環，千才，修研，柏承
- Quality Assurance, Quality Contract at AS:
  every channel measured for
  Chip test, TOSA L-I, eye-diagram, Bit-Error-Rate, Burn-in
  eye-diagram parameters well within specification

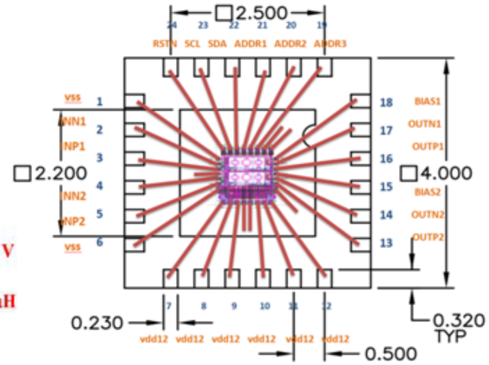
MTRx/MTx	AOP	OMA	Rise time	Fall time	EXT	RMJ
Criterion	> -3.5 dBm	>300 uW	<80 ps	<80 ps	>3dB	<4.5 ps

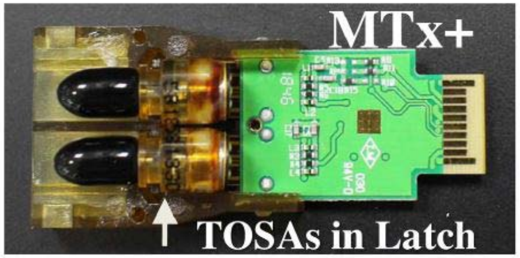


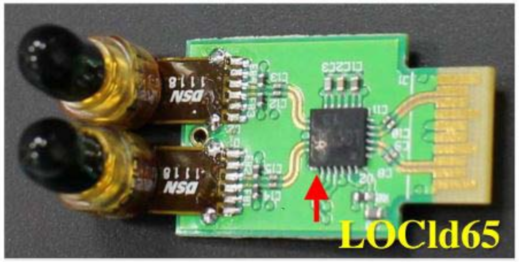


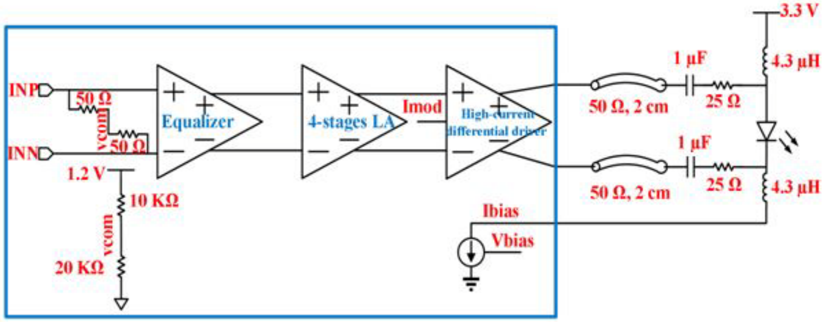
AS+SMU+前鼎 25 Gbps Transmitter

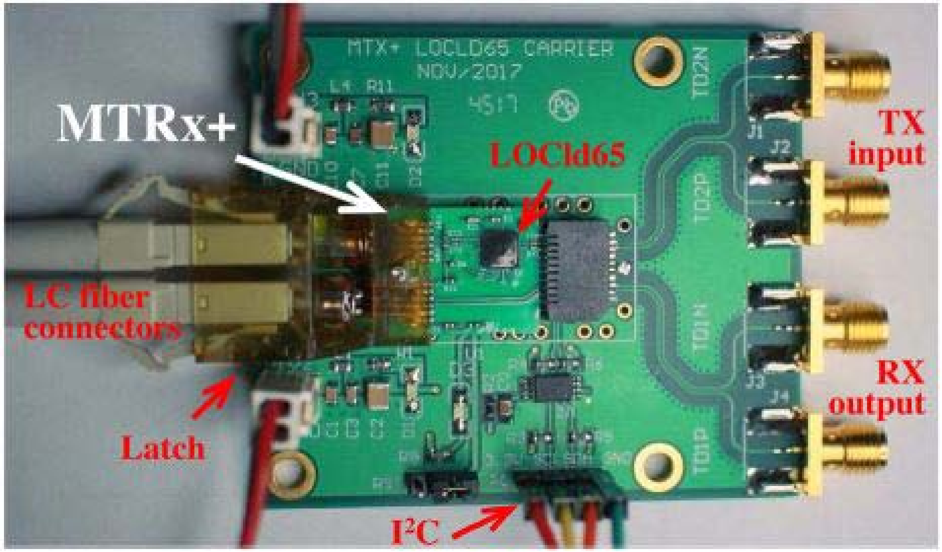
- 25 Gbps components, PCB, connectors
- Driver, LOCld65, TSMC 65nm

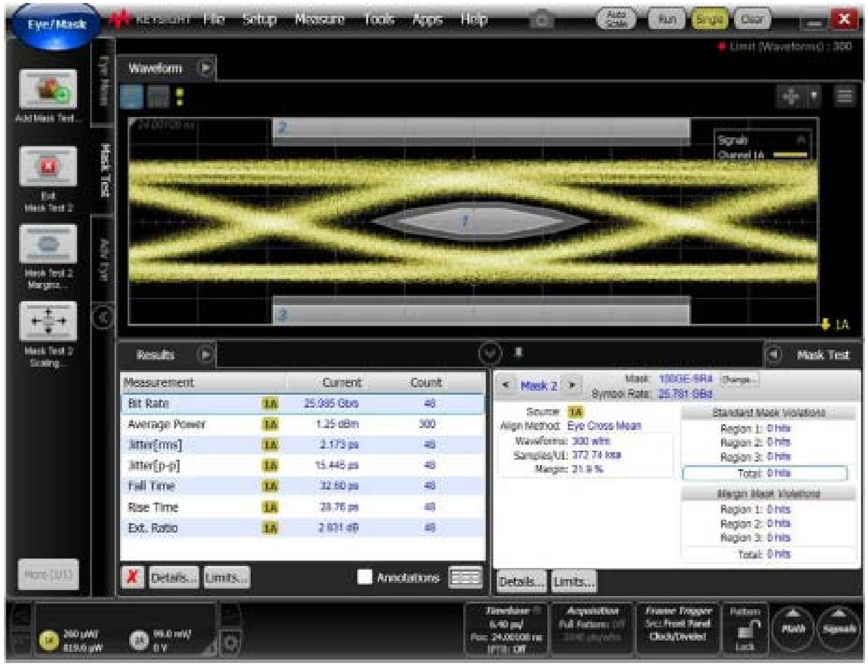






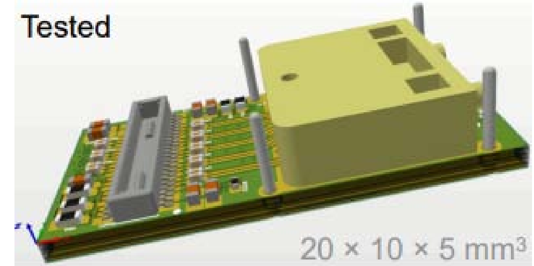






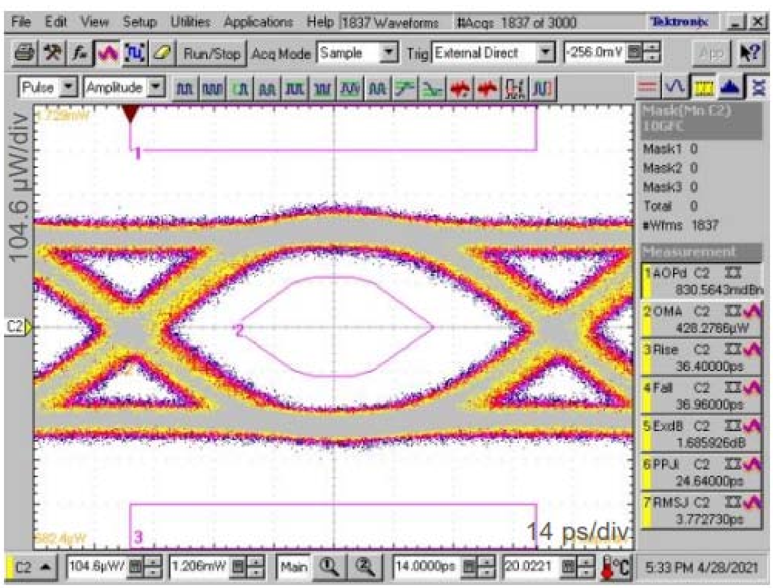
AS+SMU+前鼎 QTRx Transceiver

- 4TX+4RX, tested @10G, will do 25 Gbps
- VCSEL, PD, PCB all 25 Gbps qualified
- Driver, QLDD, QTIA, TSMC 65nm

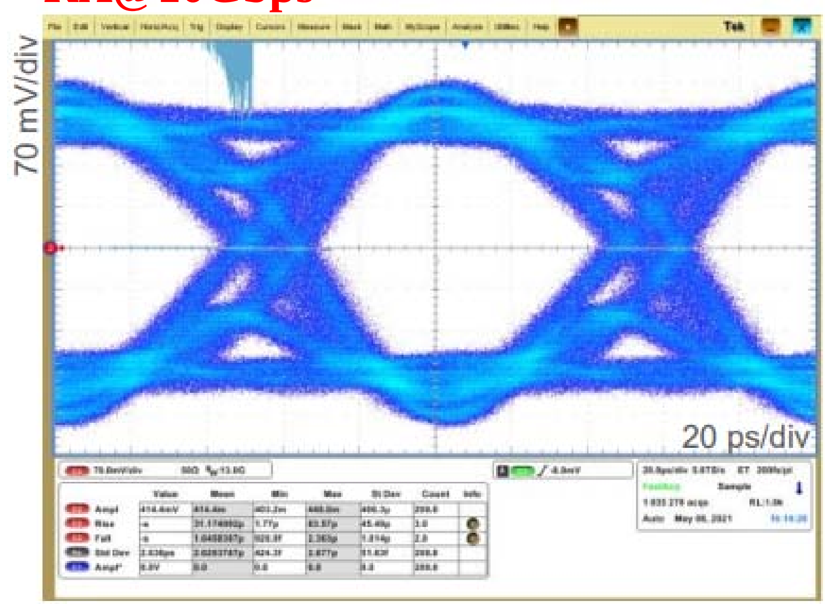


QTRx	QLDD	QTIA	
Data rate	10 Gbps	2.56 Gbps	10 Gbps
Power supply	1.2 V and 2.5 V		
Sensitivity (BER =1E-12)	80 mV	-17 dBm	-8 dBm
Rise /fall time	37 ps	40 ps	50 ps
Total jitter (BER =1E-12)	-	38.5 ps	52.4 ps
Power consumption /ch	124 mW	120 mW with CP	

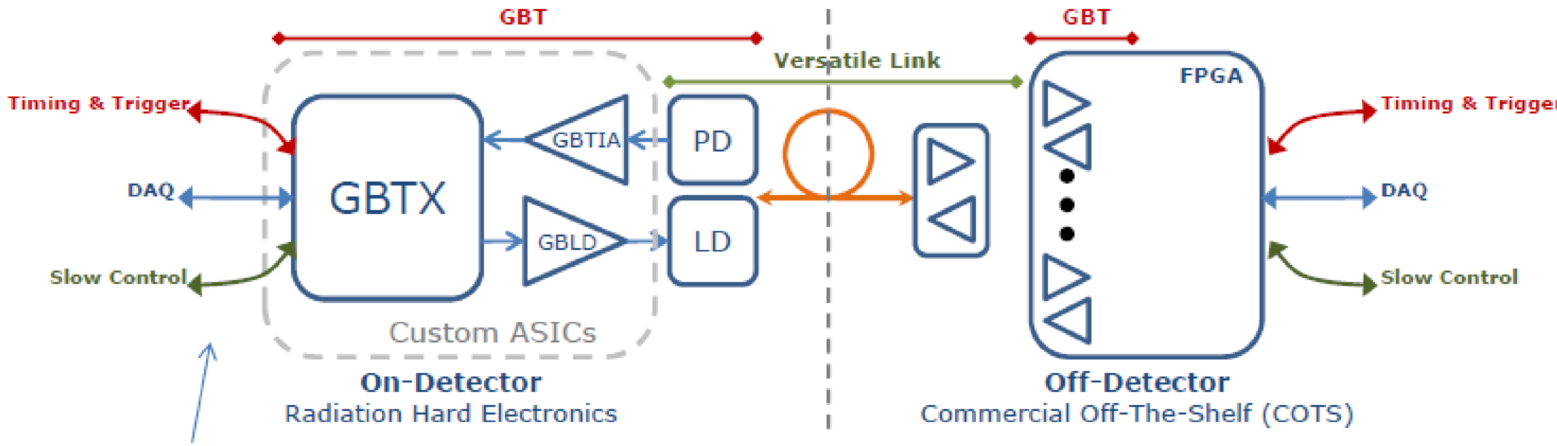
TX@10Gbps



RX@10Gbps



The CERN GBT chipsets



GBTIA:

- 4.8 Gb/s Transimpedance Amplifier
- Amplifies the weak photo-current detected by the PIN diode

GBLD:

- 4.8 Gb/s Laser Driver
- Modulates laser current to achieve electro-optical conversion

GBTX:

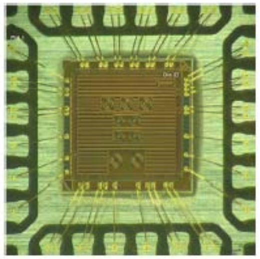
- 4.8 Gb/s Transceiver
- Manages the communications between the counting room and the frontend modules

GBT – SCA

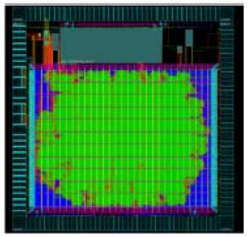
- Slow Control Adapter
- Experiment control and environment monitoring

GBTIA

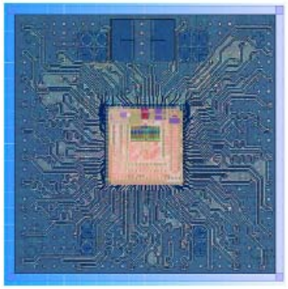
GBLD



GBT – SCA



GBTX

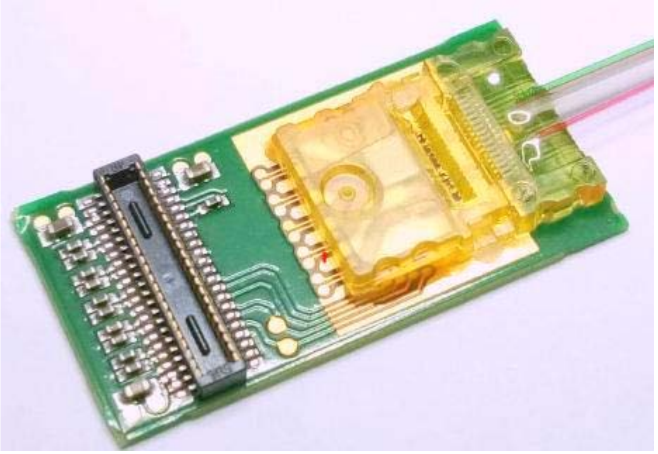


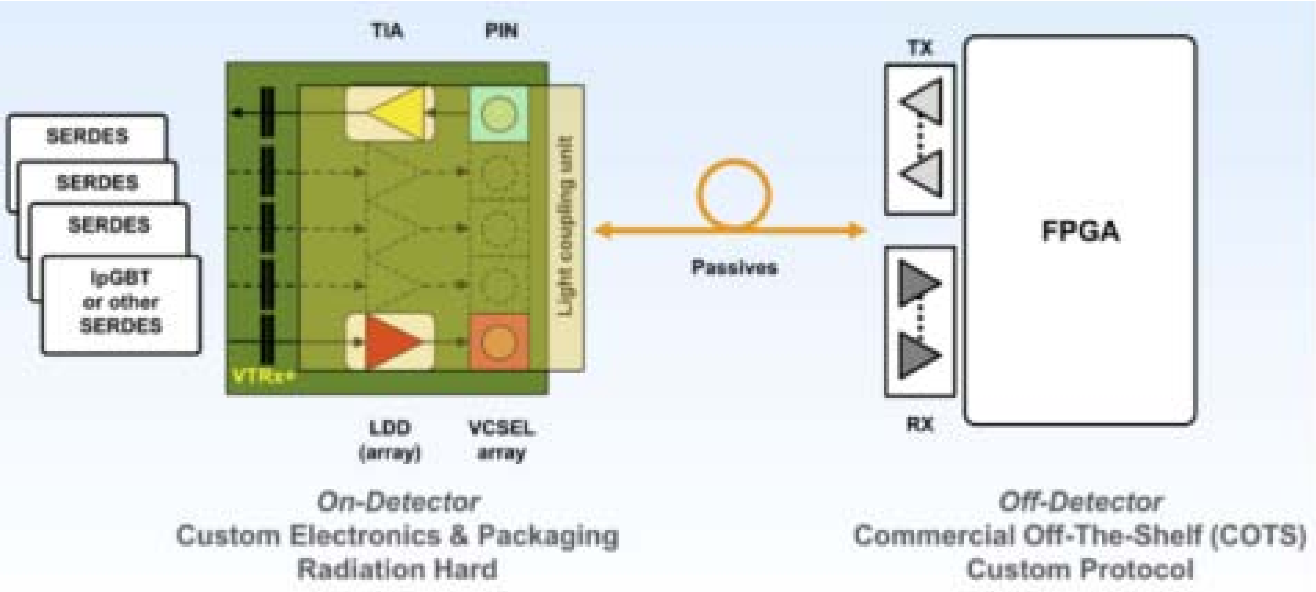
The CERN Phase-II VTRx+

- CERN Versatile Link+ group ➔ one module for all

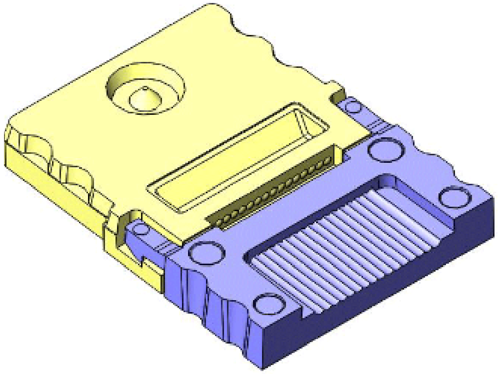
- 10x20 mm^2 height 2.5mm, 4.5mm
- 4TX+1RX, 10Gbps TX, 2.56 Gbps RX
- VCSEL array laser driver LQD, TSMC 65nm
- Optical Receiver GBTIA TSMC 65nm
- production 65K pcs

- Lens is the TW Orange-tek





Orange-tek
OT-12, OT-13



Action items

- **NSC proposal**, fiber-optics for EIC, submit this winter
- **Join EIC,** DAQ and sub-det group on opto-electronics
- **INER** revise 30 MeV proton NIEL facility beam target, beam profie calibration
- *upon TW EIC approval, collaborate with US groups on **opto-ASICs** and data-link protocal*