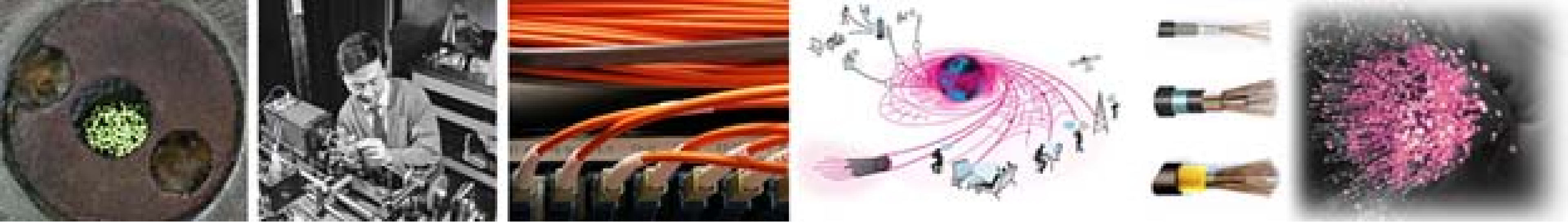

Data transmission Needs and Challenges for Frontier Particle Physics:

Radiation hardness and longevity

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Academia Sinica
Taipei, Taiwan

July 14 - 25, 2014
Paris Diderot Univesity

2nd International Summer School on:
INtelligent Signal Processing for FrontIEr Research and Industry

Outline

- Introduction
  - data transfer protocols, low loss fiber innovation
  - opto-electronics, industrial development
- Optical links in collider experiments
  - LHC devices
  - CDF tracker optical link, longevity
- Radiation hardness of optical links
  - predictions
  - tests to CDF transmitter
  - tests to VCSELs, PINs
- Radiation hardness of commercial devices
  - Light-coupling material
  - VCSEL, Control IC, BER

Introduction:

data transfer protocols
low loss fiber innovation
opto-electronics
industrial development

Introduction: data transfer protocols

- **Internet TCP (**Transmission Control Protocol) :

  Duplex data transfer, demanding reliability
  TCP forwards "packets" of Internet Protocol over networks between hosts
  Encapsulated, Telnet, FTP, SMTP, HTTP, … for applications

- **Computer peripherals,** e.g. **USB (**Universal Serial Bus) **:**

  Standardize connection of computer peripherals: keyboards, hard drives ..
  Host centric bus with layers of protocols

- **Detector data acquisition:**

  Detector measurements are analog signals,
  Front-end ADC, multiplexing … real-time data output, no handshape
  May require inputs for slow control for clock, setup,

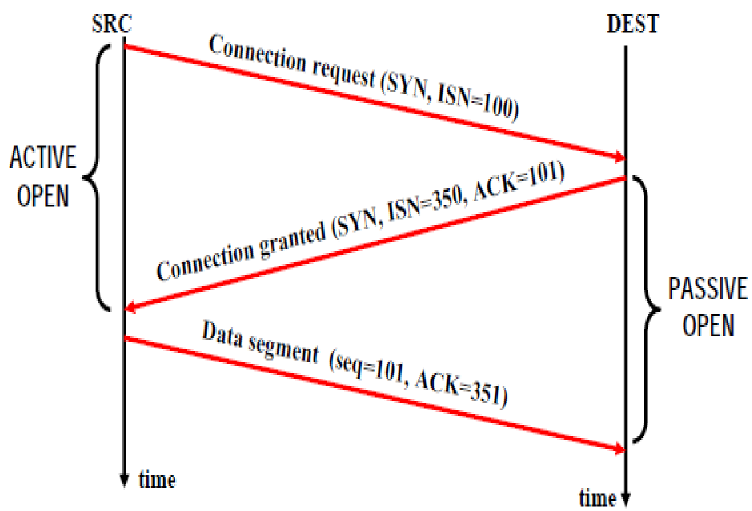
Internet TCP

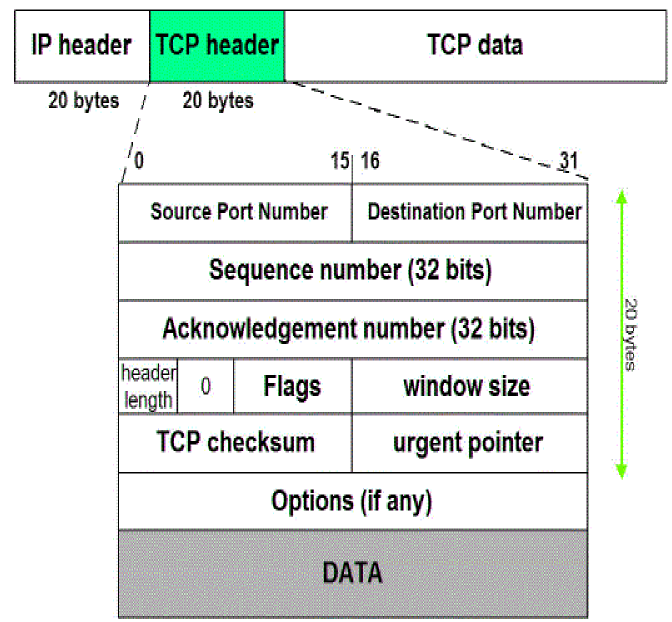
- **TCP** (Transmission Control Protocol)

  Internet communication with three way handshakes

  Reliable with data packets ACKnoleged in SEQuence

  - Acknowledgements indicate delivery of data
  - Checksums are used to detect corrupted data.
  - Sequence numbers detect missing, or mis-sequenced data.
  - Corrupted data is retransmitted after a timeout.

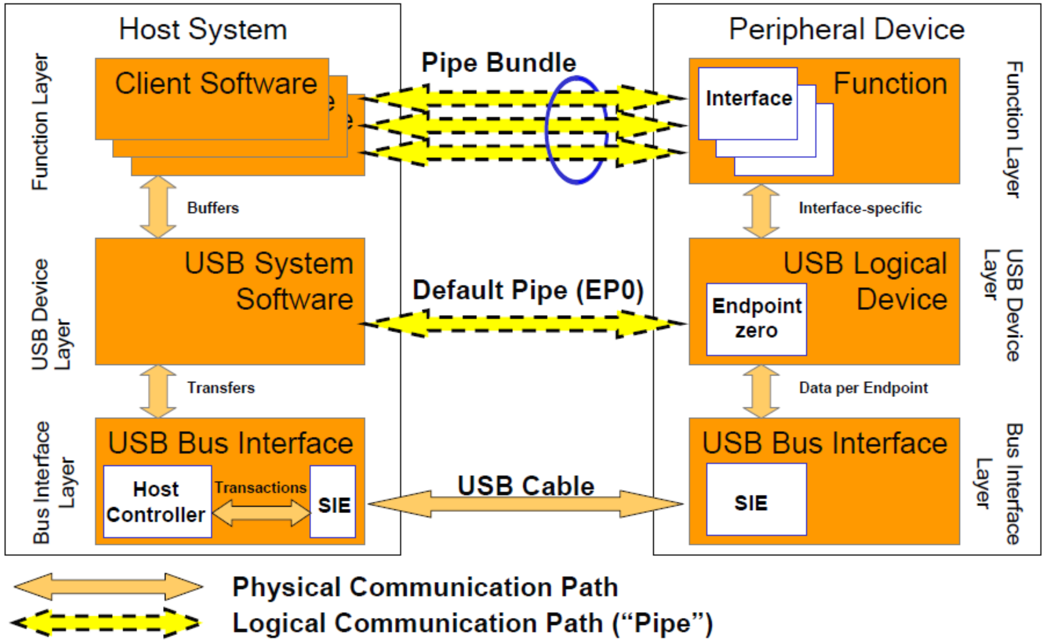


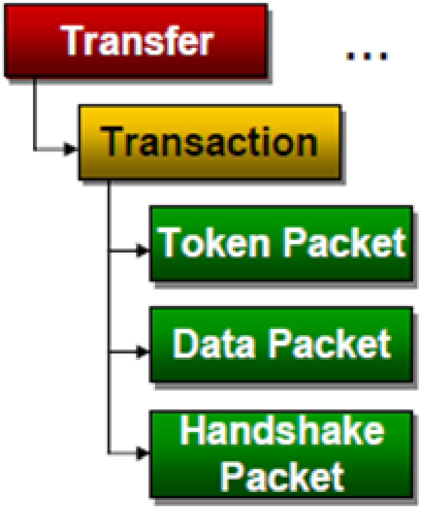


SYN (synchronize sequence numbers)
ISN (initial sequence number)

Computer network with USB

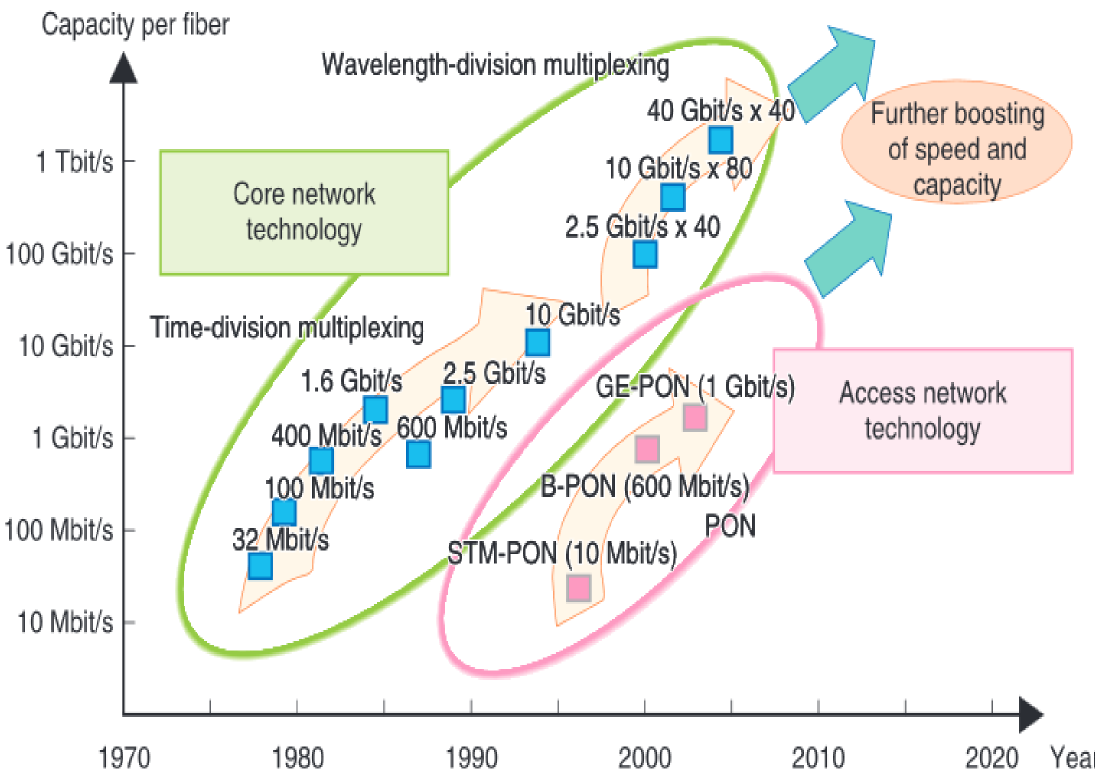
– **USB** (Universal Serial Bus) "Single Master + Multiple Slaves"
  One interface for many devices
  Hot pluggable, automatic configuration
  Hi-Speed – 4.8 Gbps (USB3)
– USB transaction ,
  strictly defined frame, error checking and handshaking
  - Token Packet, header defining what to follow
  - Optional Data Packet
  - Status Packet, to acknowledge transactions





Fiber capacity

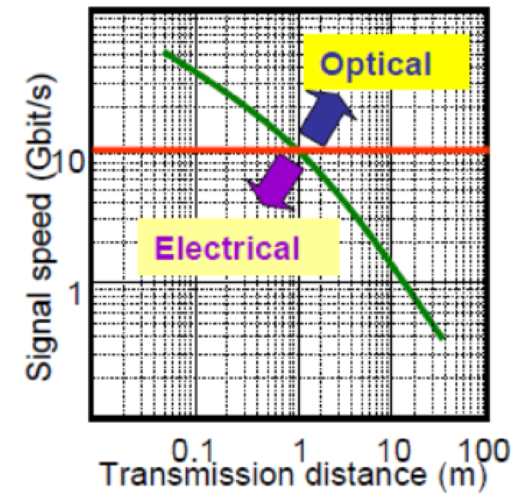
Speeds and capacities of optical core, access networks are being boosted



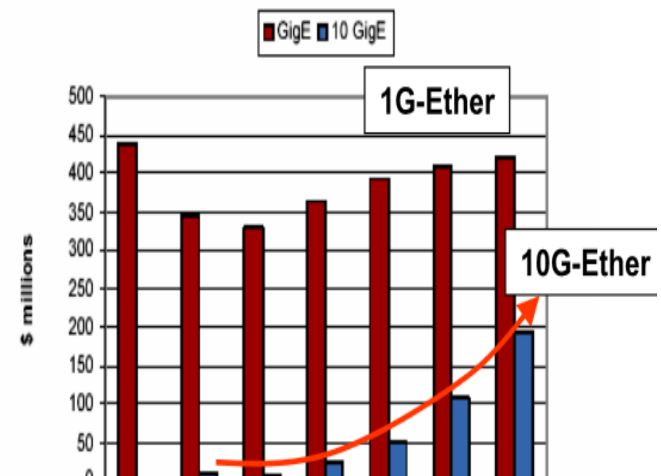
NTT Technical Review

STM-PON: synchronous transfer mode passive optical network
B-PON: broadband PON
GE-PON: Gigabit Ethernet PON

Optical vs. Electrical



10Gbit/s is turning point!



	2000	2001	2002	2003	2004	2005	2006
GigE	439	343	328	363	392	410	419
10 GigE	0	11	8	24	51	107	193

Source: RHK Inc.

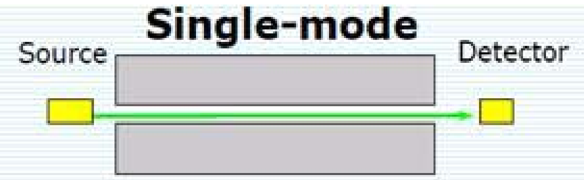
Fiber optical loss

Silica glass fiber:

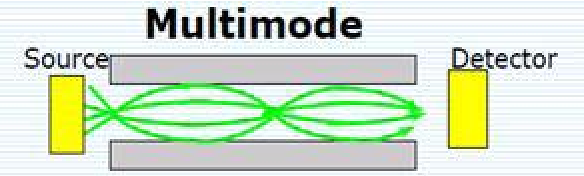
Low-mass, high bandwidth, little loss over long distance

− Absorption Scattering losses (Rayleigh, Raman…)

− Bending losses (micro bending)



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



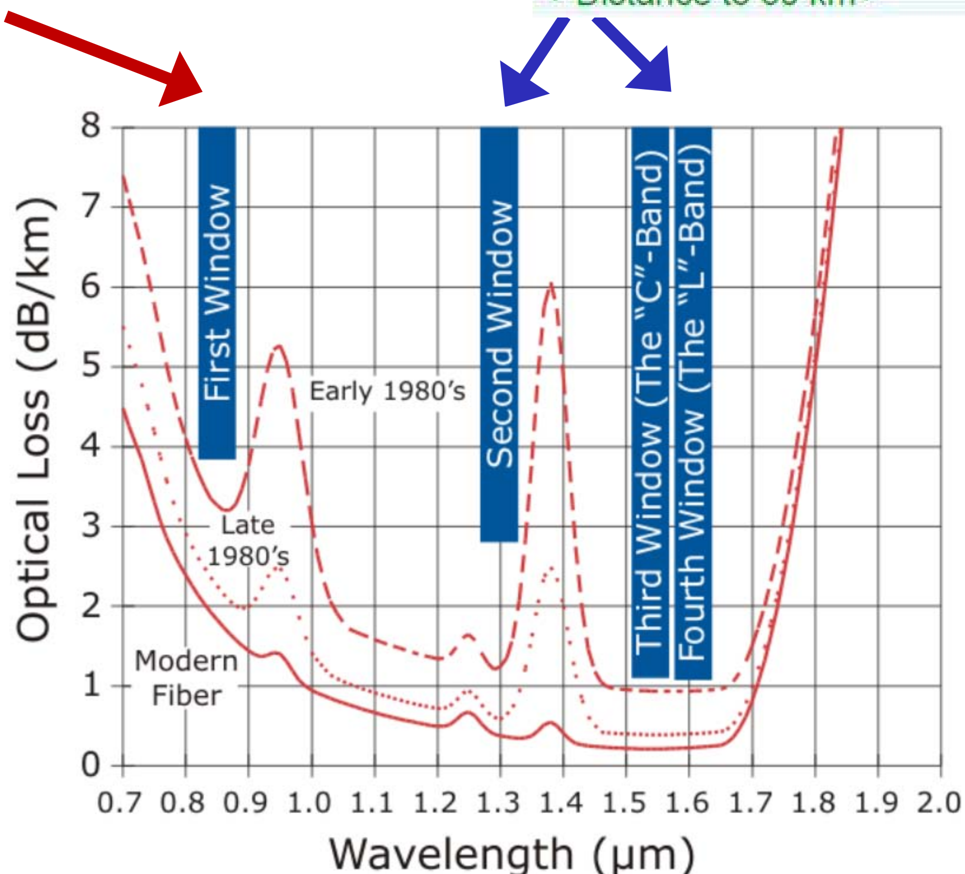
+ Low cost lasers and LEDs
+ Easy transmitter packaging
+ **Lower system cost**
- Higher loss, lower bandwidth
- Distance up to 2 km

1st generation, ~1975, 0.8 μm fiber-MM, Laser GaAs

2nd generation, ~1980, 1.3 μm, fiber MM SM, InGaAsP FP-laser

3rd generation, ~1985, 1.55 μm, fiber SM InGaAsP DFB-laser

4th generation, 1996, 1.55μm WDM



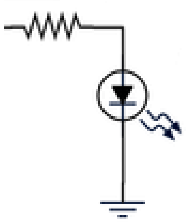
Opto-electronics

- **Transceivers:**
  Laser diodes as light source
  PIN diodes as photo detector
  Driver chip convert electrical signals to optical, and vice versa
  Control IC for the application protocols

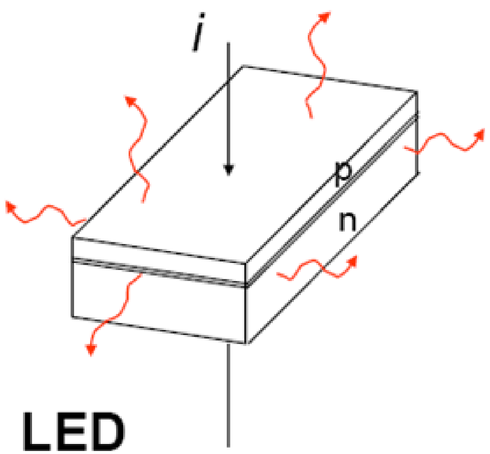
Laser type	Wavelength (nm)	Fiber type	Photo-diode type	Data rate (Gb/s)	Launching power	cost	Distance
VCSEL	850 1310	MM SM	GaAs InGaAs	10	Low	Low	< 300 m
FP	1300	MM SM	InGaAs	10	Med	Med	< 2 km
DFB	1310 1550	SM	InGaAs	>10	High	High	> 10km

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

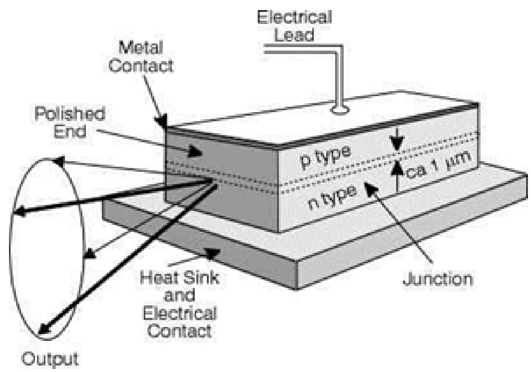
Light sources



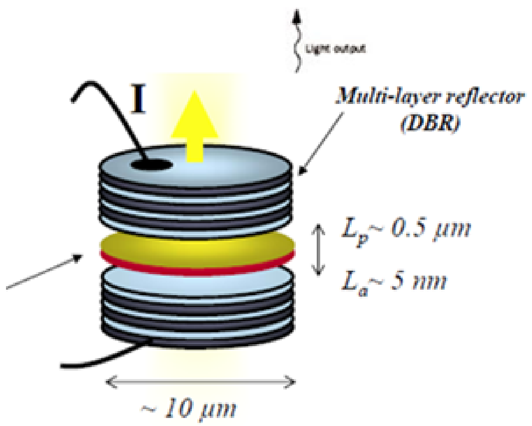
Spontaneous light emission
Laser Diodes (LD), Light Emitting Diodes (LED) LED
LD has an optical cavity for stimulated emission.
Light Amplification by Stimulated Emission of Radiation (LASER)



LED

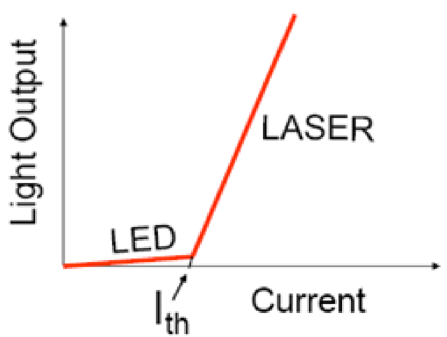


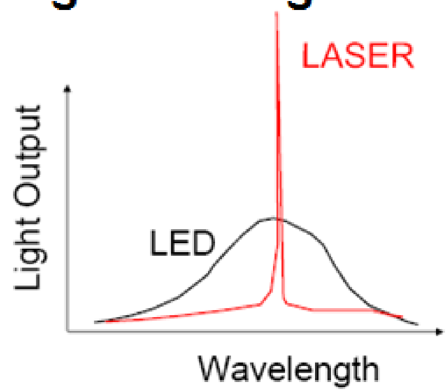
Edge-emitting FP laser



VCSEL

(Vertical Cavity Surface Emitting Lasers)





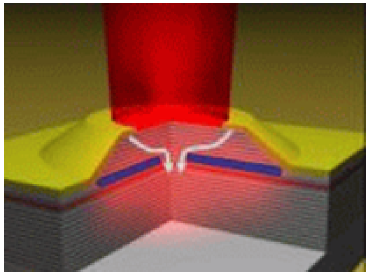
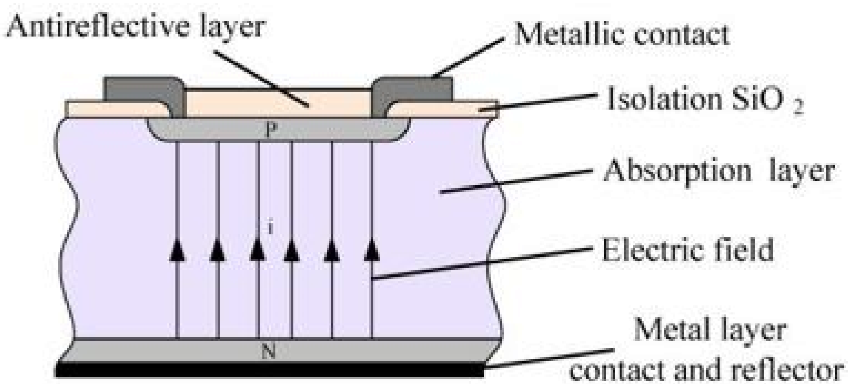
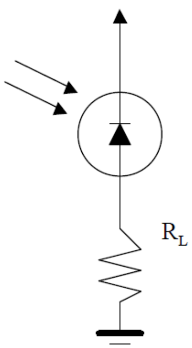


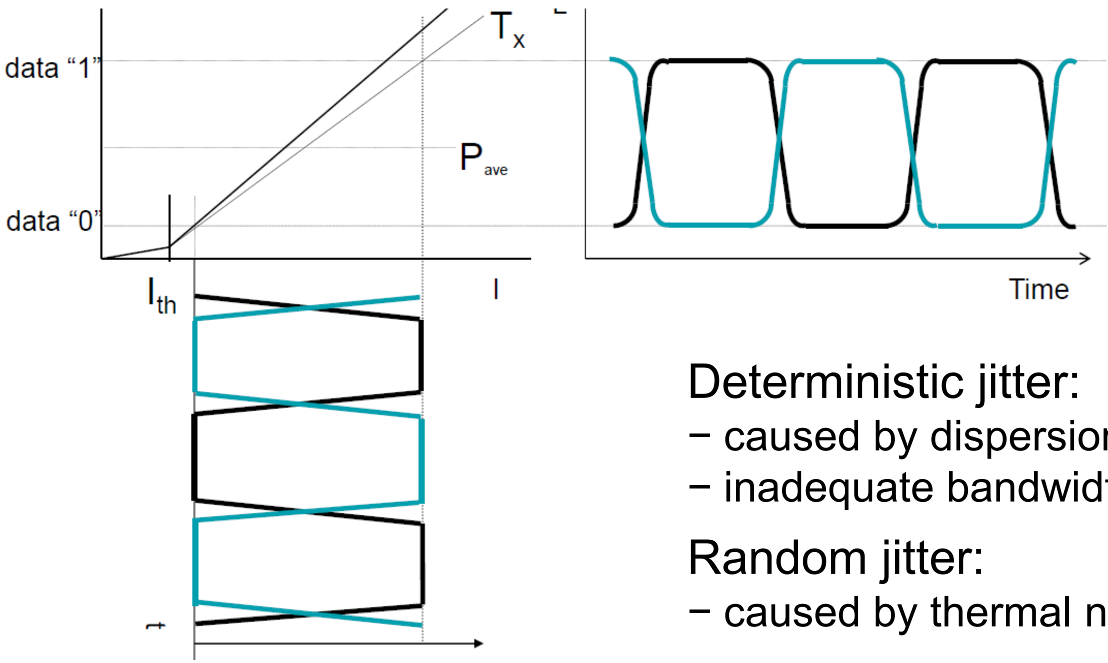
Photo-detectors

- **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





Building an eye pattern



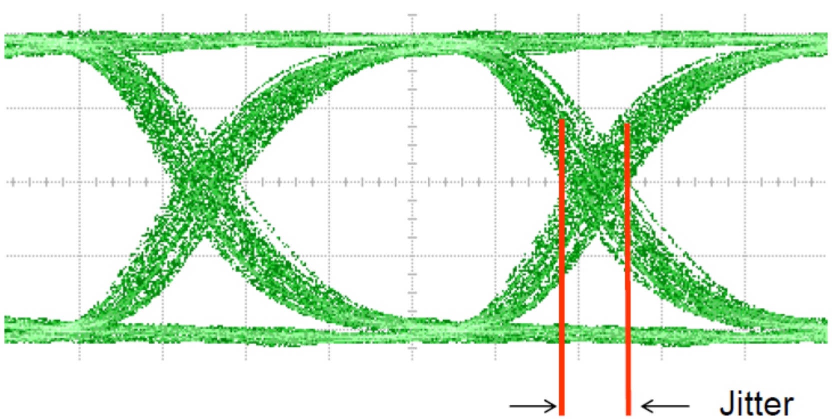
Eye Diagram on oscilloscope triggered by data clock.

Deterministic jitter:

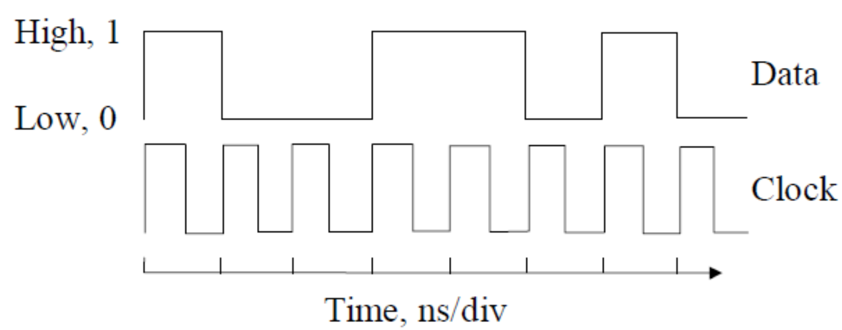
− caused by dispersion in fiber, and
− inadequate bandwidth of transceiver components

Random jitter:

− caused by thermal noise, shot noise in components



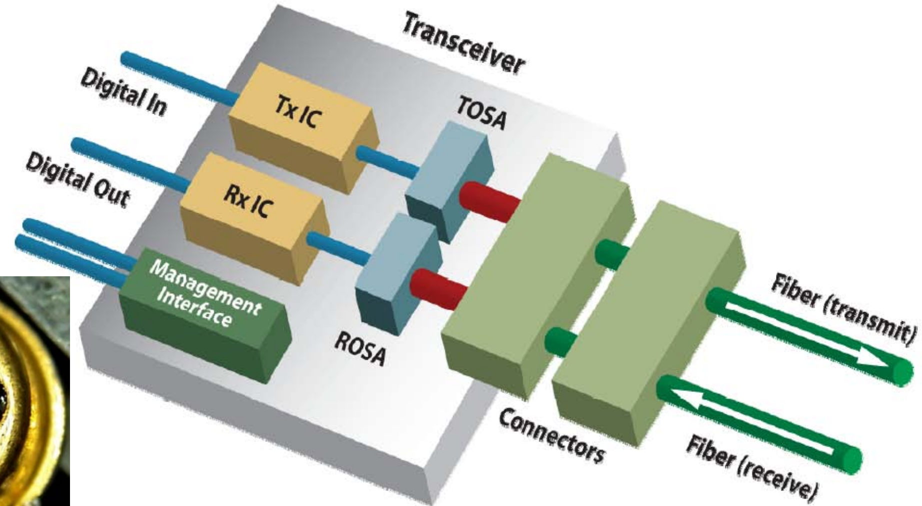
Non-Return to Zero (NRZ)



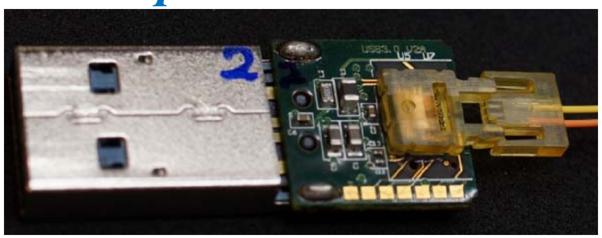
Commercial optical transceivers

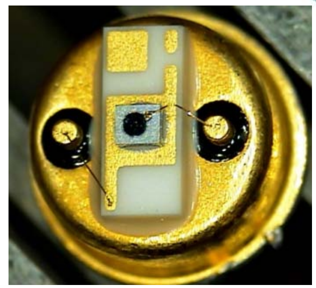
telecommunication and computing

- **10 Gb/s** SFP+ transceivers
- **4.8 Gb/s** USB3 Active Optical Cable

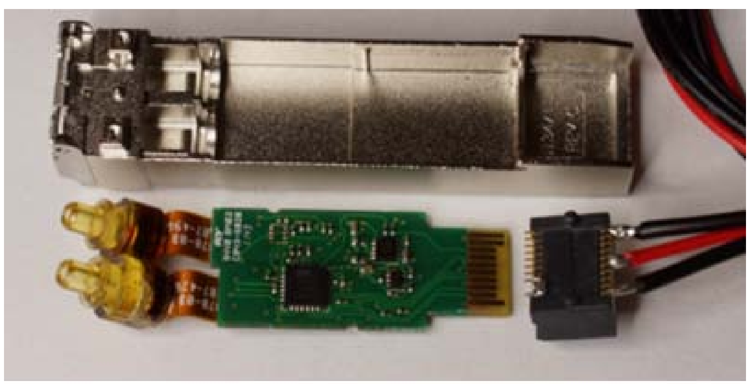


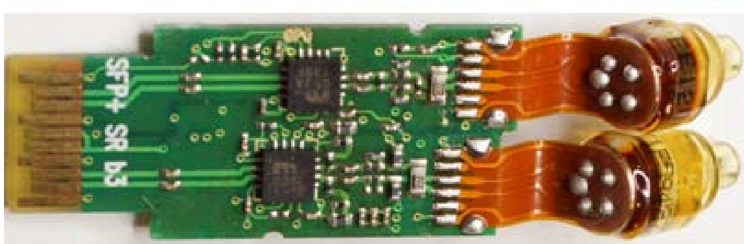
5 Gbps USB3

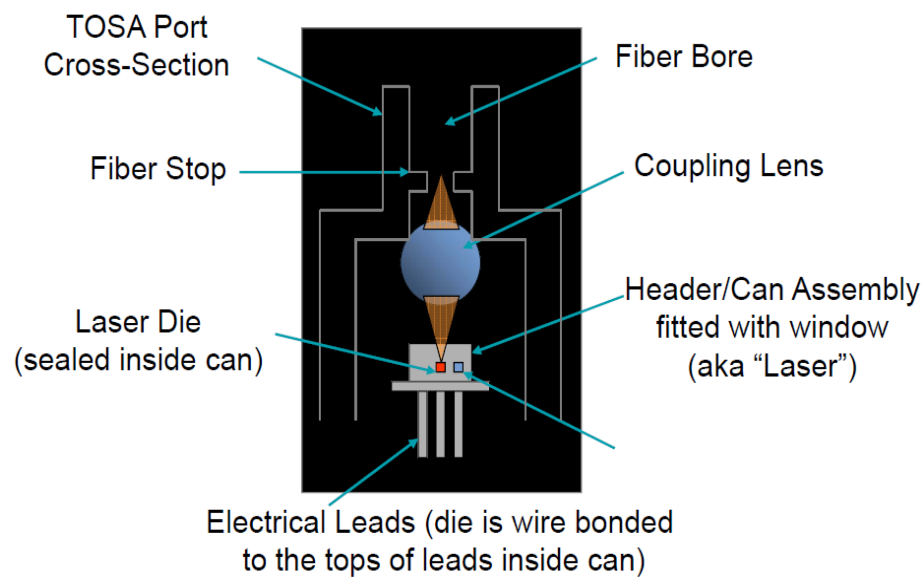




10 GB/s SFP+

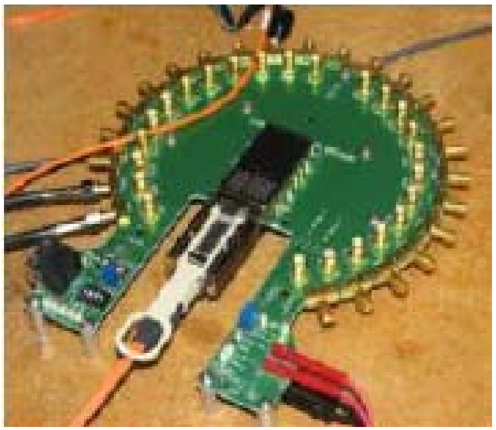




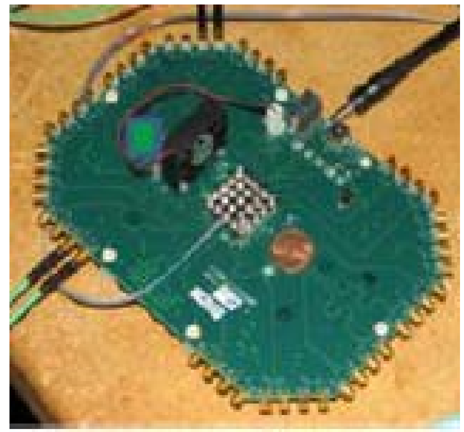


Dense parallel devices

- Commercial dense parallel devices
- 12 ch Transceivers

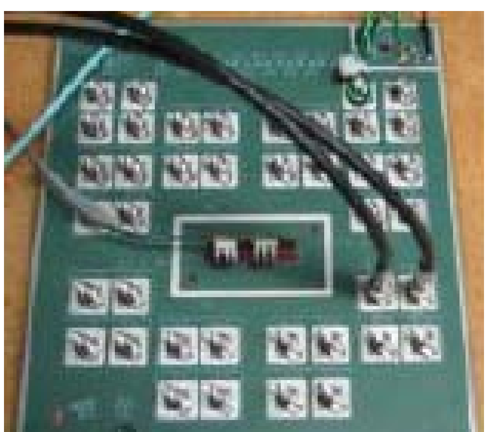


MTP/MPO connector

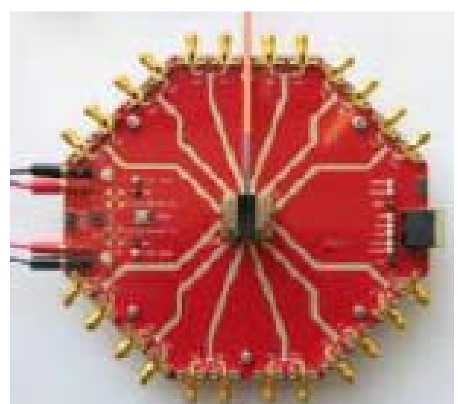


Pigtailed

- 4 ch Transceivers, 12 ch transmitter



Pigtailed



Chip-on-Board, QSFP of TrueLight

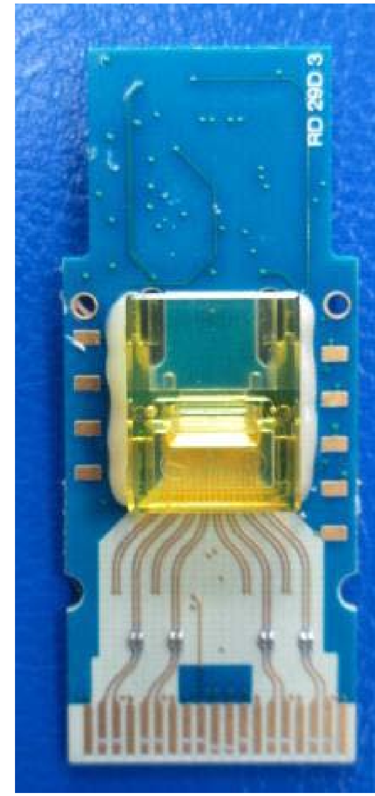
- **Assembly service to customer**
  VCSEL, PIN arrays of TrueLight
  Lens, driver, circuit provided by customer,
  MT ferrule, 4-in 4-out, 40 Gb QSFP optical engine

TX 10 Gb tests

mask margin: 42% mask margin: 36%

RX 10 Gb tests

Sensitivity: -14.2 dBm Sensitivity: -13.7 dBm



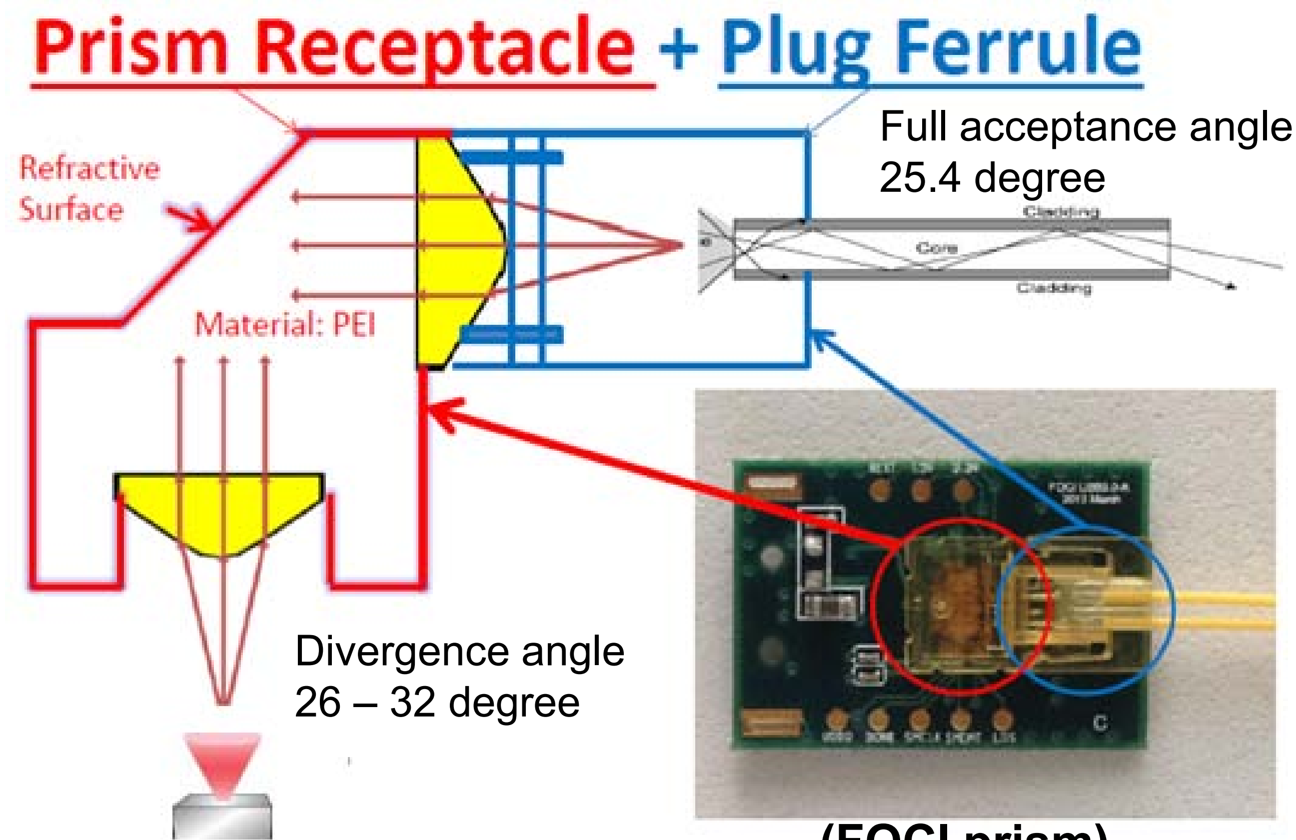
Non-hermetic VCSEL and GaAs PIN array

– TSA-8B04-xxx 1X4 VCSEL

– TPA-8D04-xxx 1X4 GaAs PIN

Light Peak Technology

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

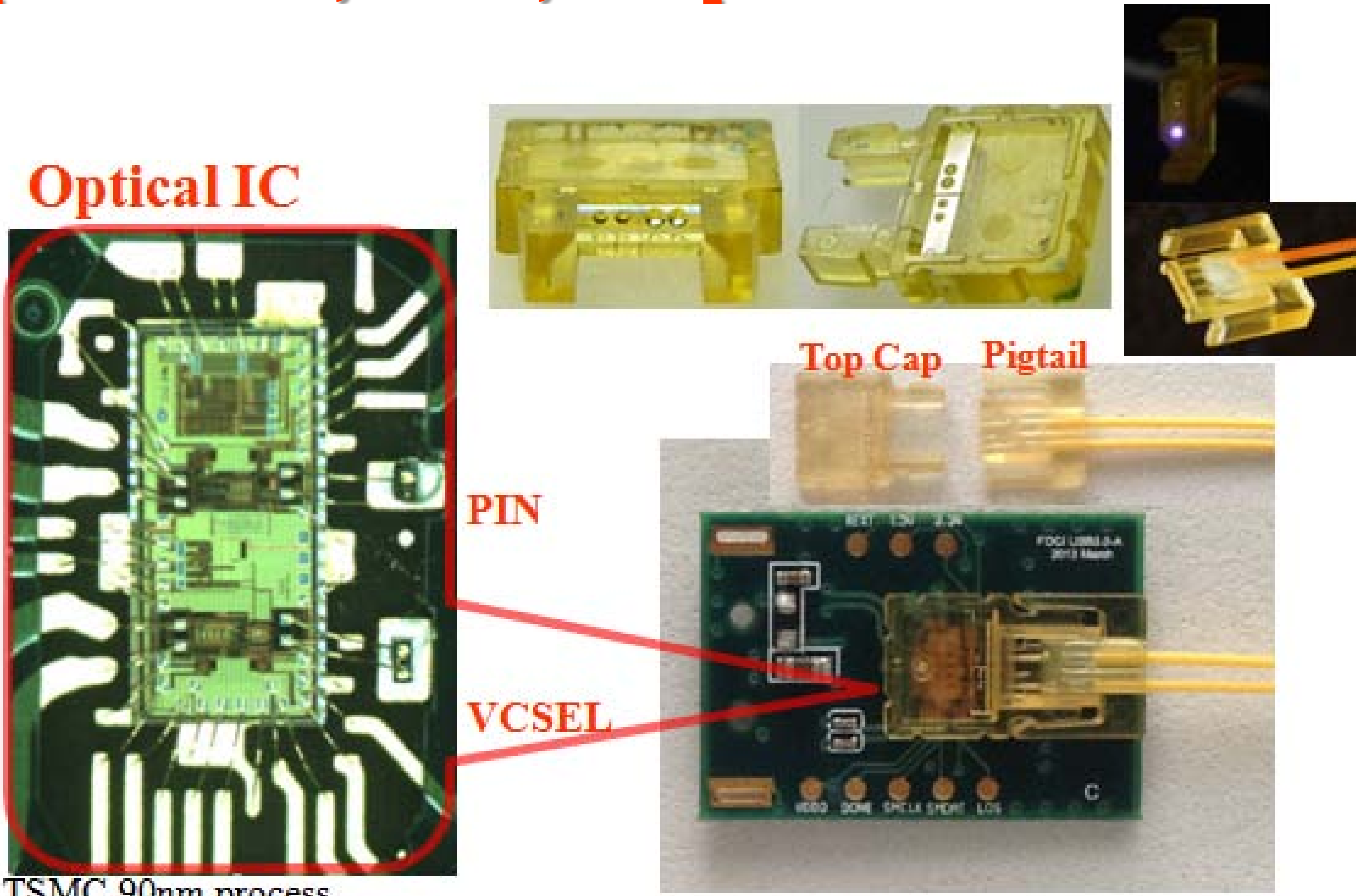


Spherical-aberration free
Plano-Convex
Hyperbolic Lens

VCSELs aperture
from t Ø 5 to 20 μm

(FOCI prism)

Optical driver, USB-3, 5 Gbps



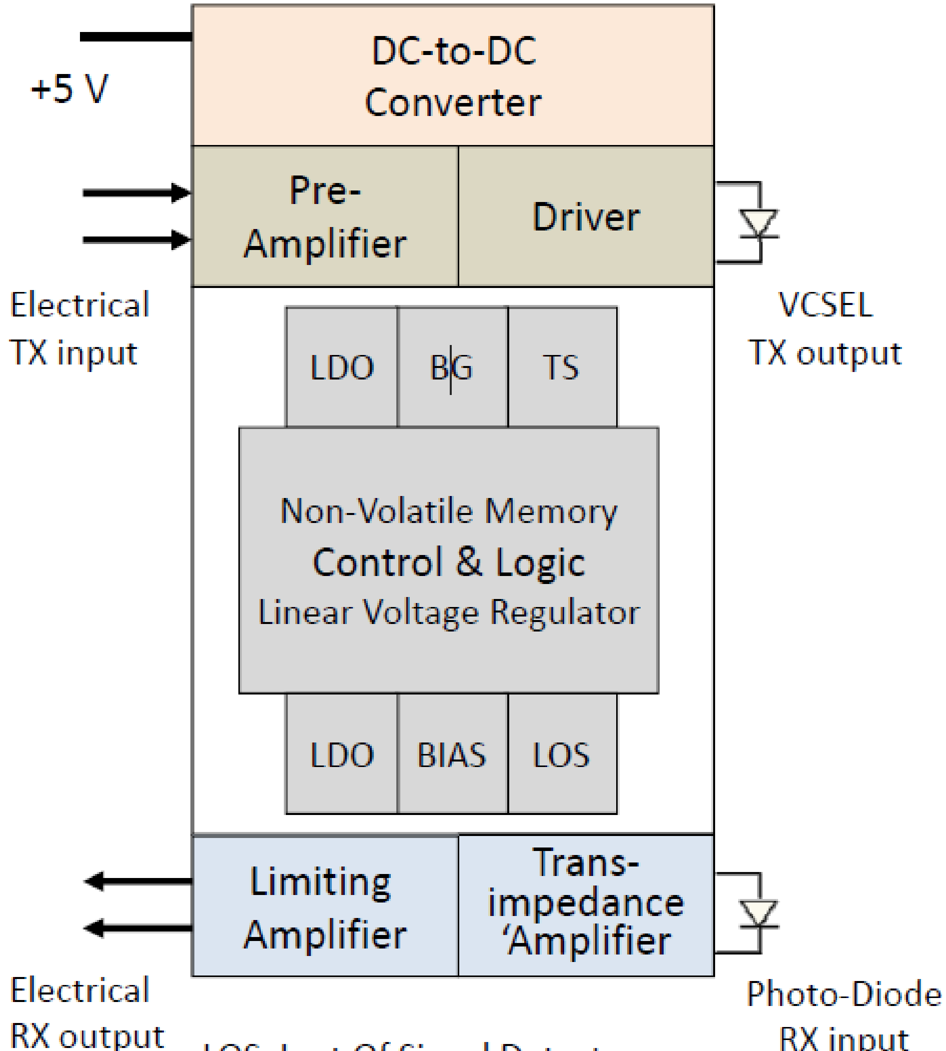
TSMC 90nm process

VIA Labs USB 3.0 *V0510*

FOCI optical engine functional diagram

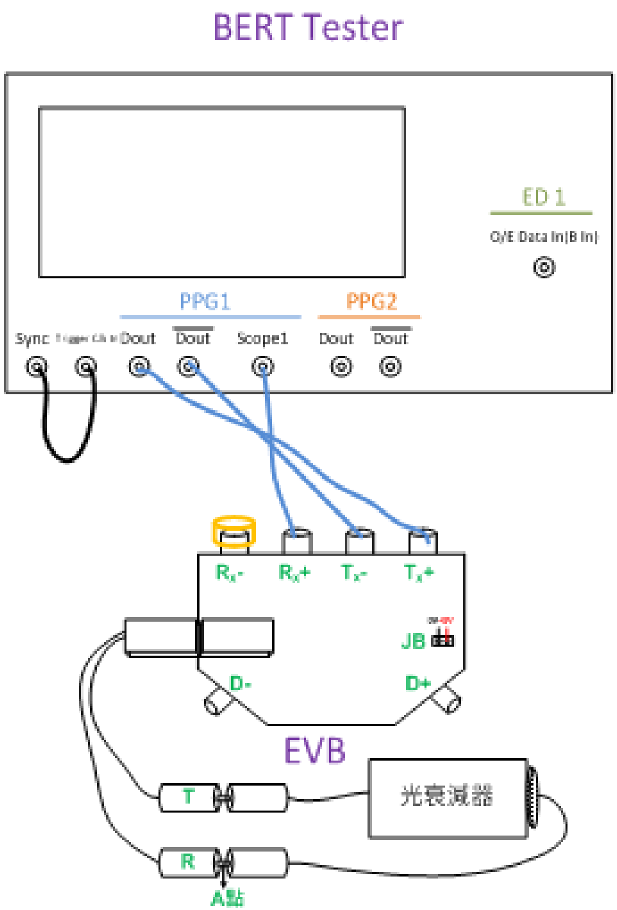
VCSEL/PIN:
- 850 nm bare die,
- 4.8 Gb/s or 10 Gb/s
- >0 dBm (1mW)

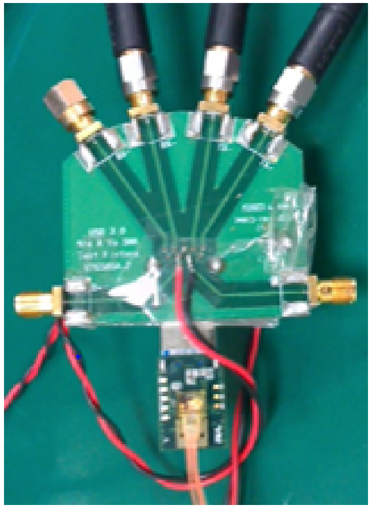
Optical IC:
- **VIA Labs V0510**,
- TSMC 90nm technology
- USB-3 protocol, ~60 mW,
- 4.8 Gb/s TX/RX driver
  + regulator/controller



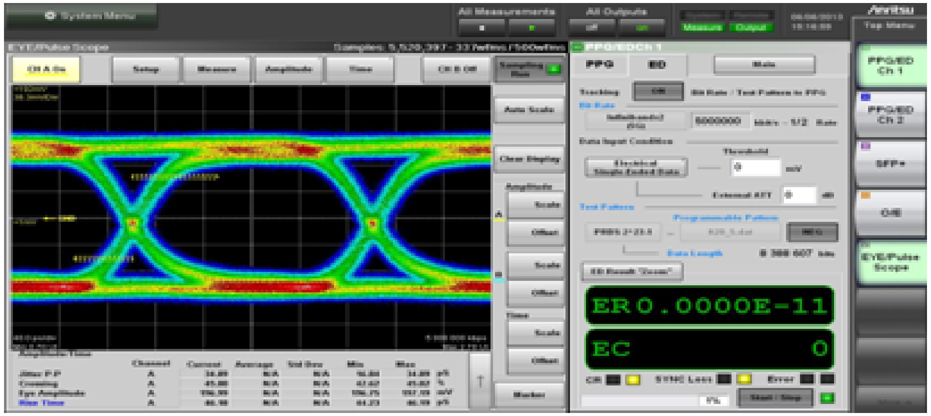
LOS: Lost Of Signal Detector
TS: Temperature Sensor
BG: Band Gap Reference
LDO: Low Drop Out voltage regulator

Bit Error Rate test

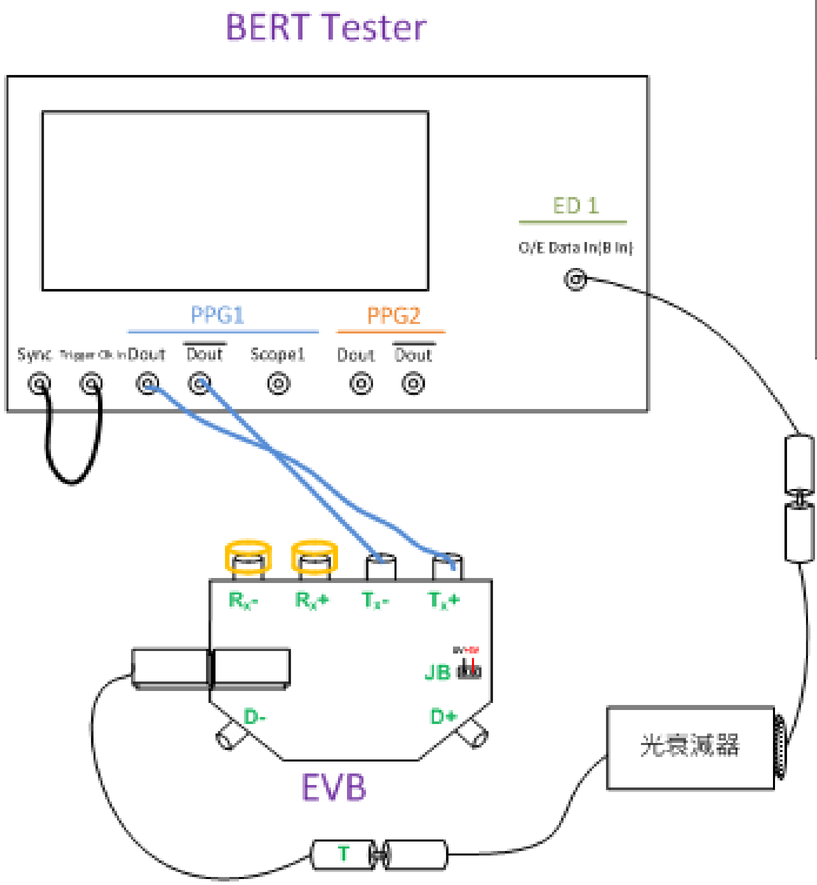


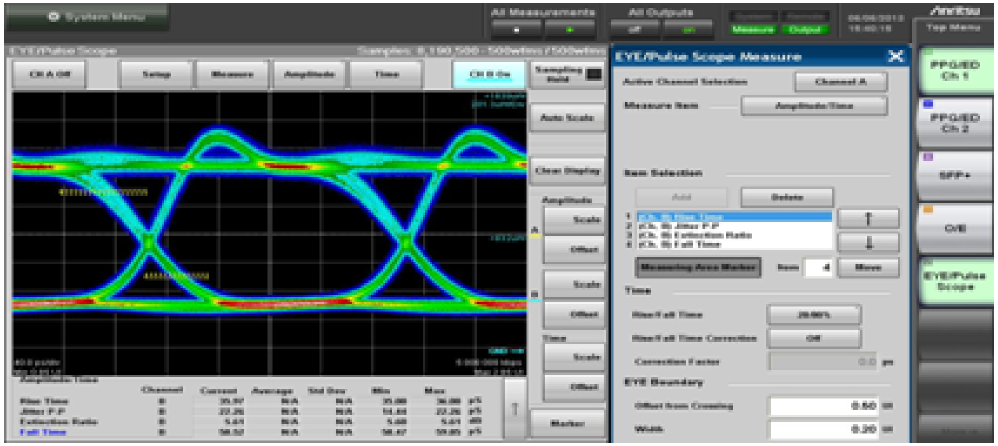


RX – Jitter P-P 34.89 ps, Crossing 45 %, Eye Amplitude 197 mV, Rise Time 46.18 ps



Bit Error Rate test



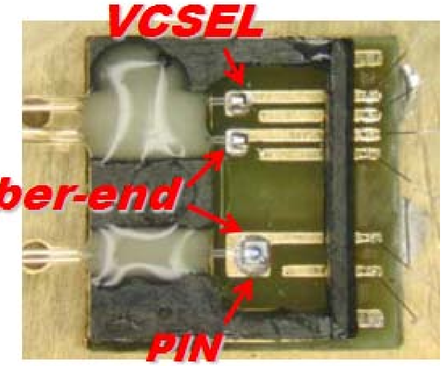


TX – Rise Time 35.97 ps, Jitter P-P 22.26 ps
Extinction Ration 5.61, Fall Time 58.52 ps

Optical links in collider experiments

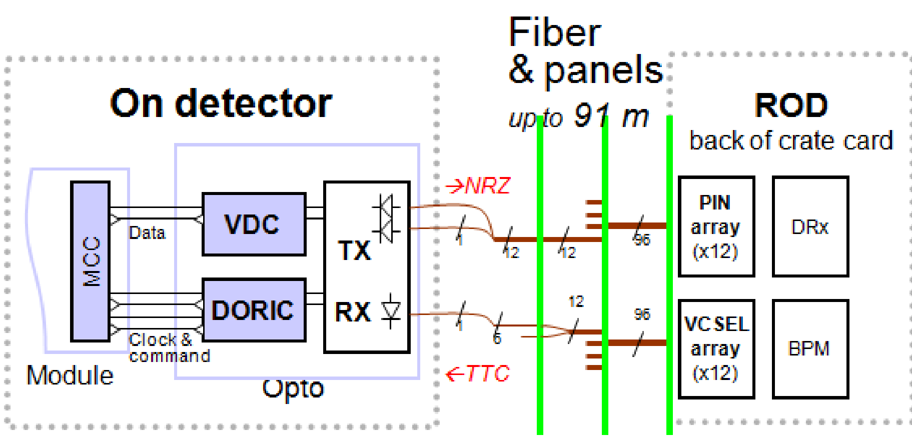
LHC devices
CDF tracker optical link, longevity

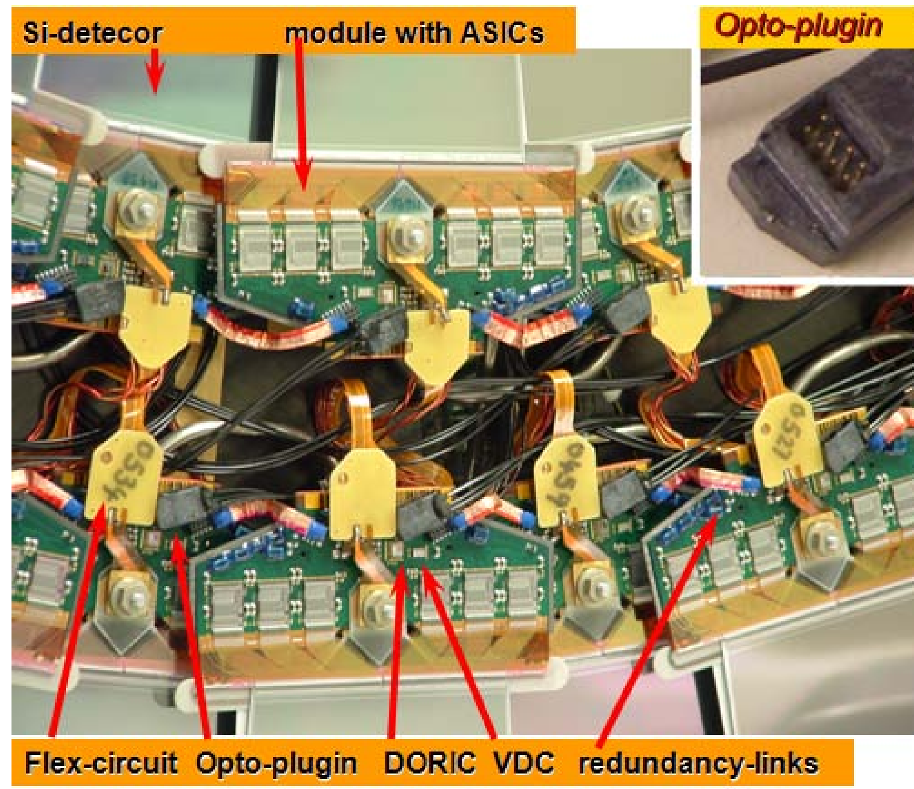
2. ATLAS SCT transceiver



– **Detector data acquisition:**
  Analog signals → digitization (front-end IC, ADC)
  → data transfer
  Front-end INPUT ← clock, IC configuration
  Front-end OUTPUT → continuous data transfer

1 RX PIN + DORIC for clock+command
2 TX VCSEL + VDC for data
45° fibre end, mirror to VCSEL, PIN face



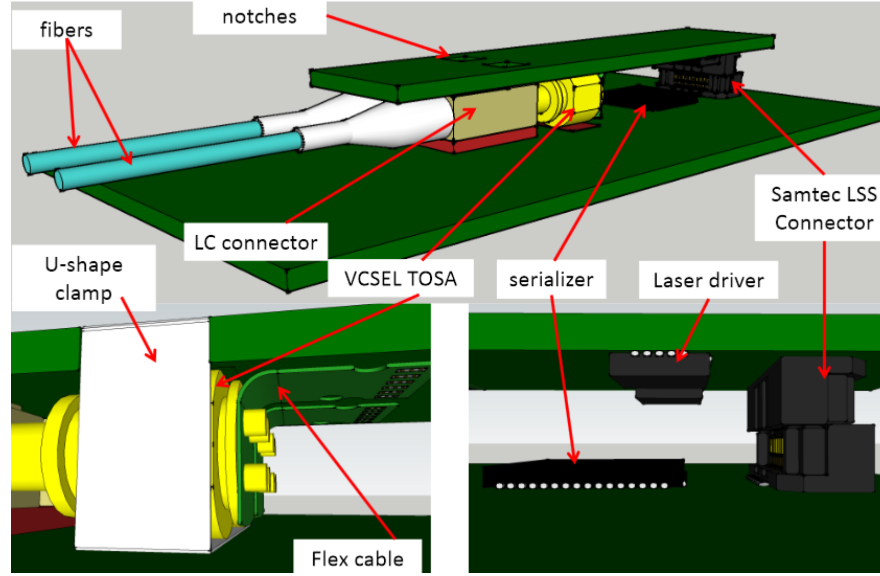


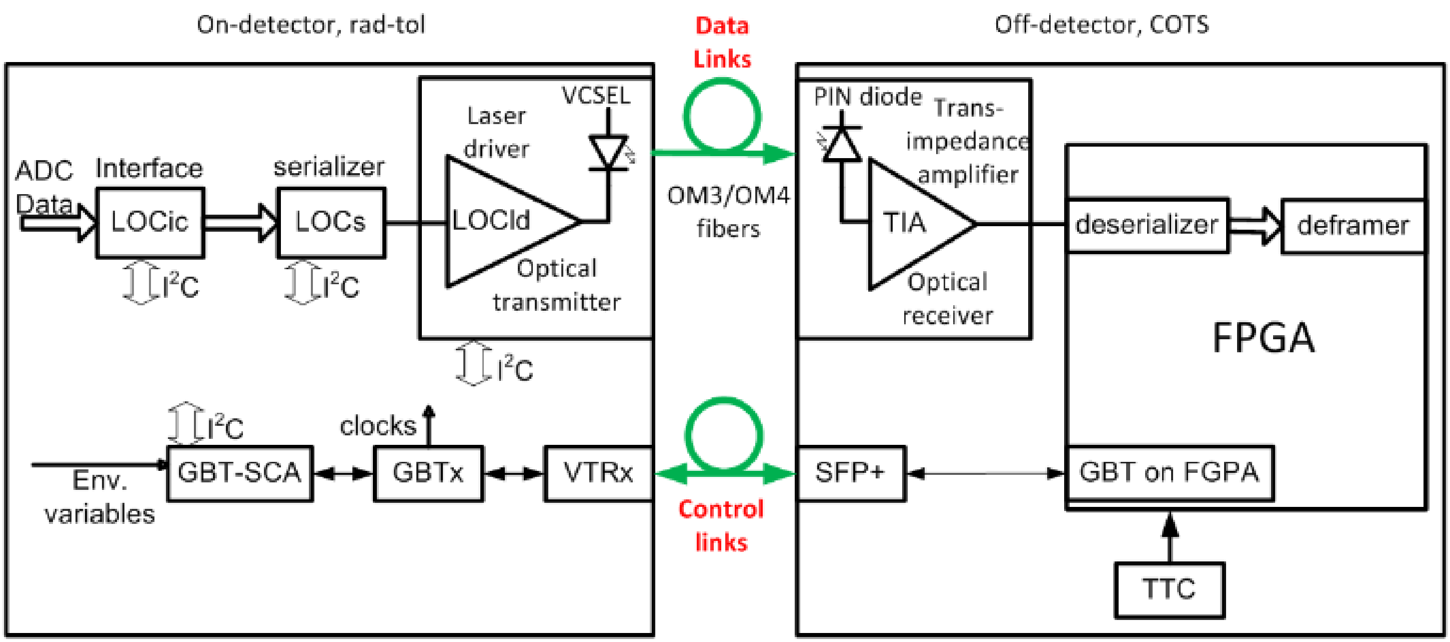
Opto-flex: Holds VDCs, DORICs, PINs, VCSELs
VDC: VCSEL Driver Circuit
DORIC: Digital Optical Receiver Integrated Circuit

ATLAS LAr MTX

Similar to CERN VL product,

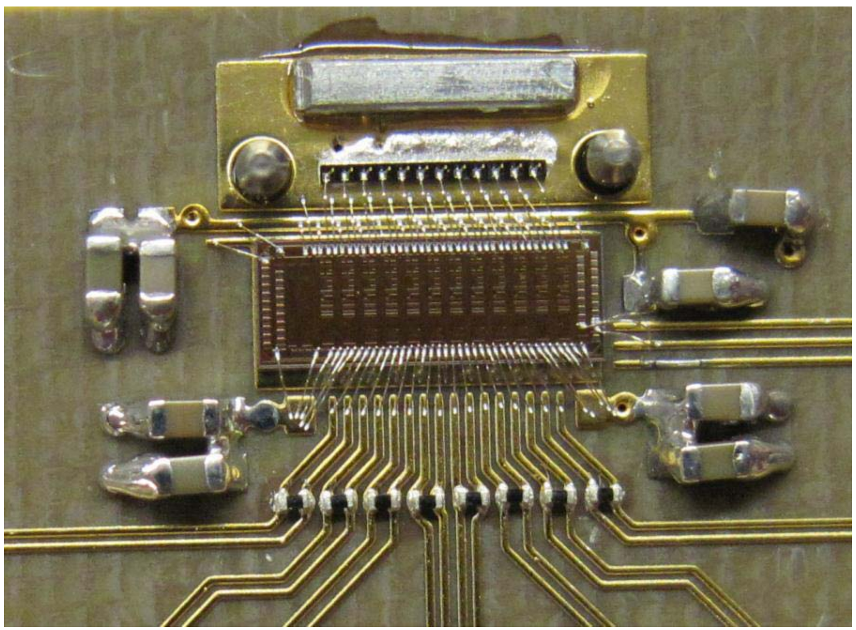
- TOSA + MM fiber, 850nm
- Use LOCld, driver of SOS process
  Speed 8 Gb/s
- Different geo/connector configuration
  constrain by LAr geometry

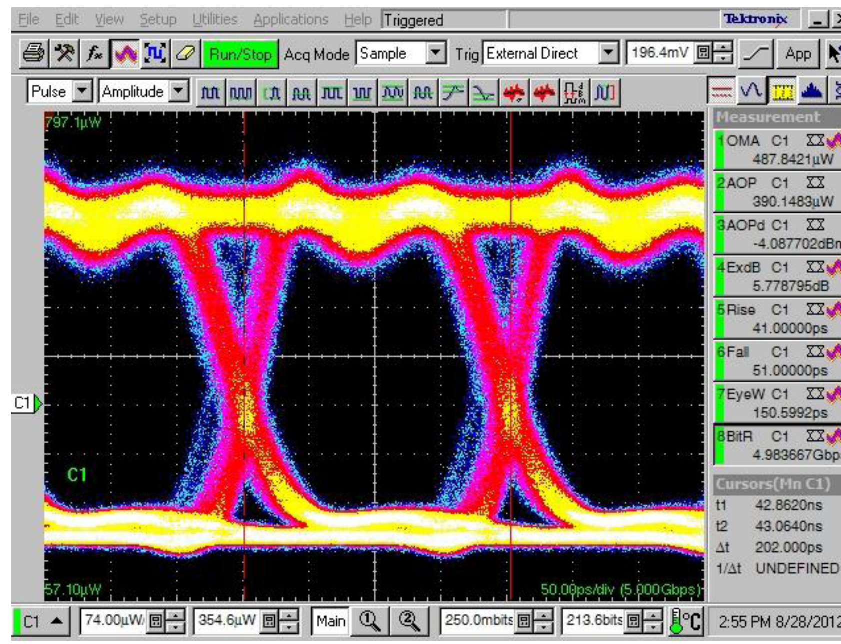




High throughput array

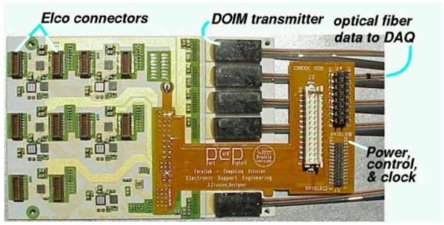
OSU prototype, ATLAS Pixel
VCSEL array, driver of 130 nm CMOS.
8 channel + 4 spare channels

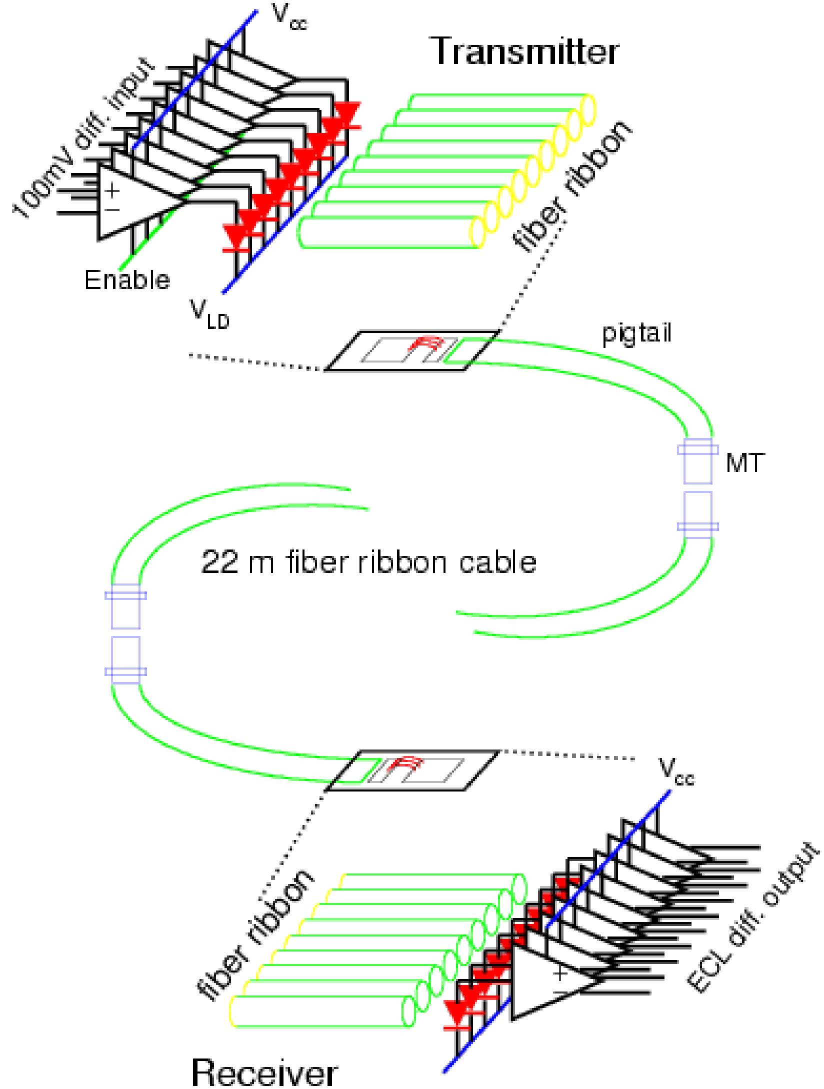




CDF optical link

The 1st optical link in Collider experiment inner tracker





- Dense Optical Interface Module
- Byte-wide parallel link
  - 8-bits + clock
  - 53 Mbyte/sec, BER$<10^{-12}$

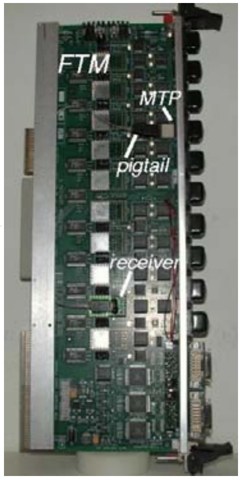
Transmitter on portcard :

- Laser-diode array
- ASIC driver chip

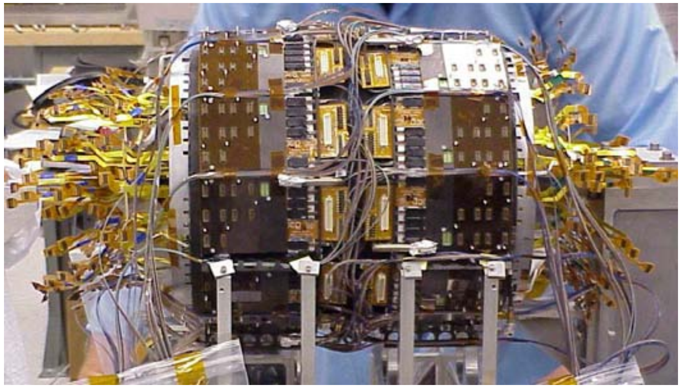
Receiver on FIB crate :

- PIN-diode array
- ASIC receiver chip

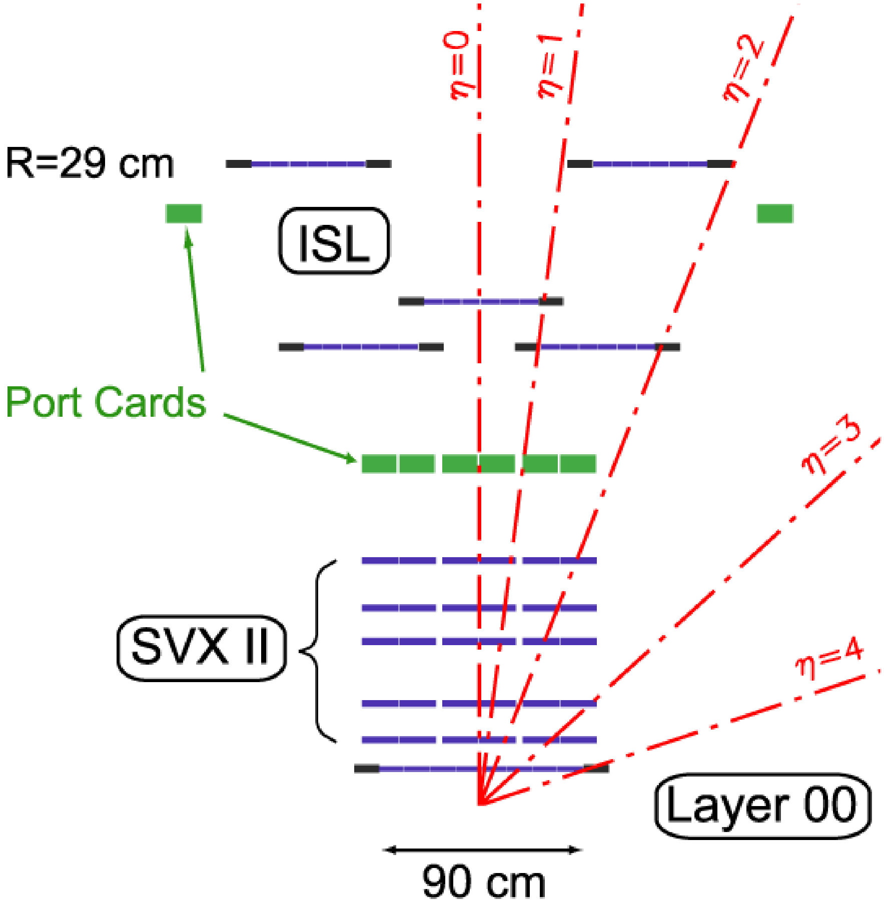
Multi-mode fiber ribbon



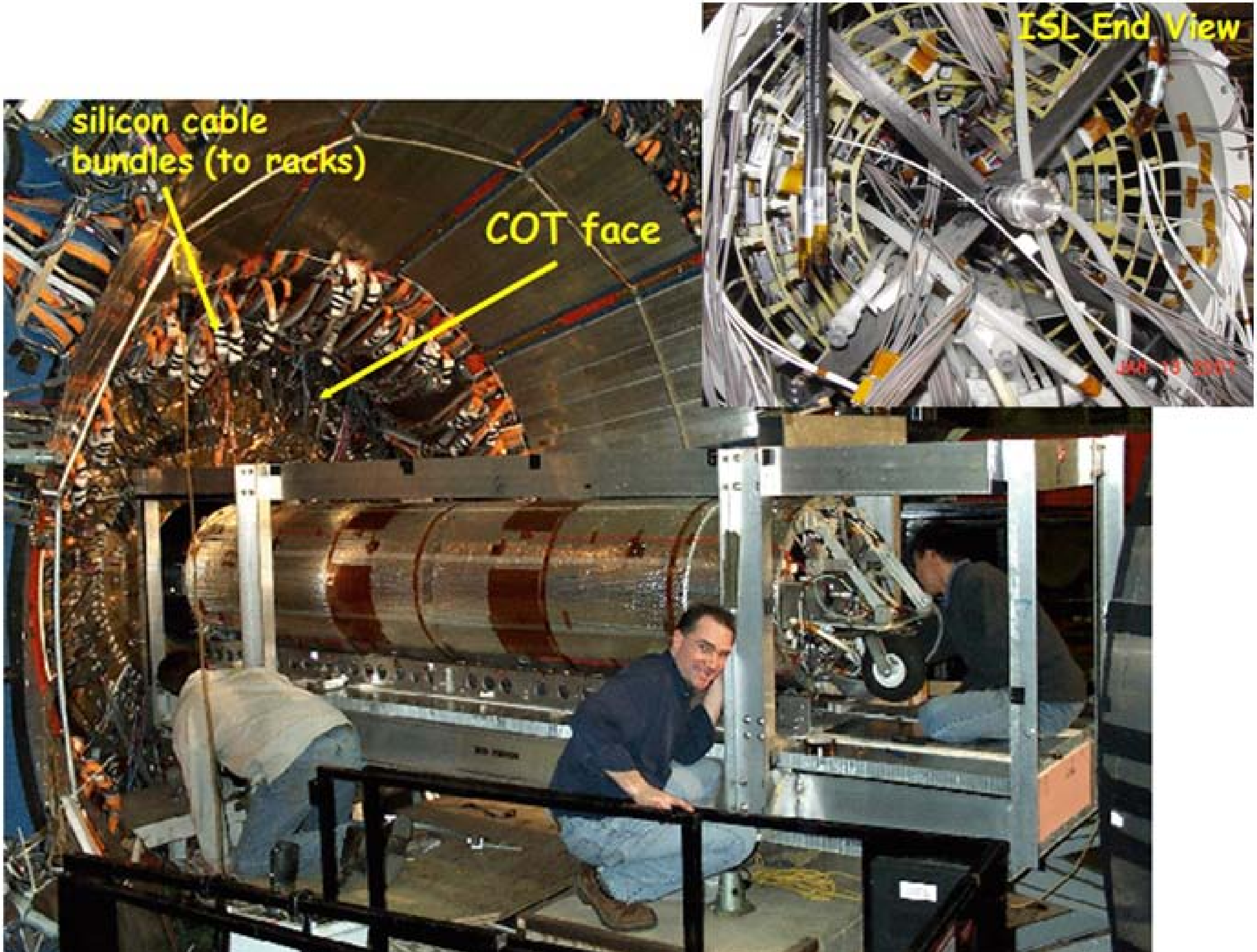
CDF tracker Port Card



- Total 128 portcards
  5 optical TX each portcard
  total 570 TX
- Transceiver : convert low-voltage differential signals from DAQ to Silicon detector
- Digital Data Receiver :
  Decode 5-bit commands into 10 SVX3D control and calibration
- Analog DDR: regulates AVDD for clean frontend operation
- Optical transmitter :
  8 data bit + 1 data valid signal to Laser Diode Array to 9-bit parallel optical link

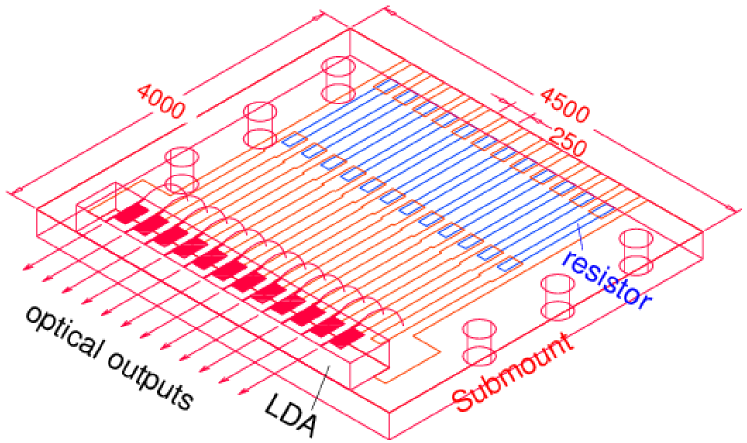


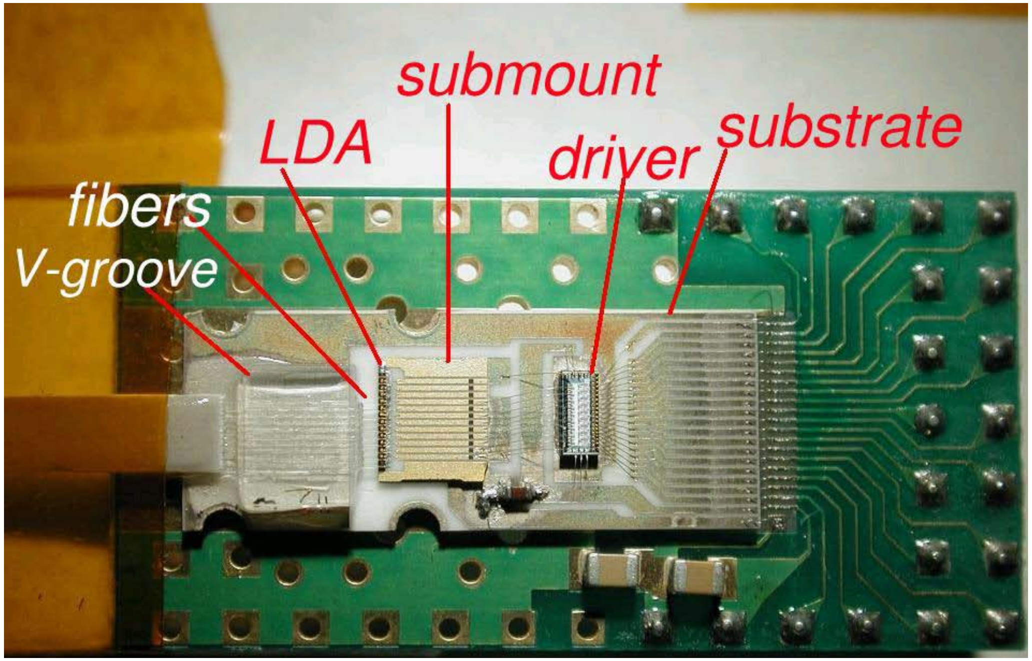
Silicon Detector Installation



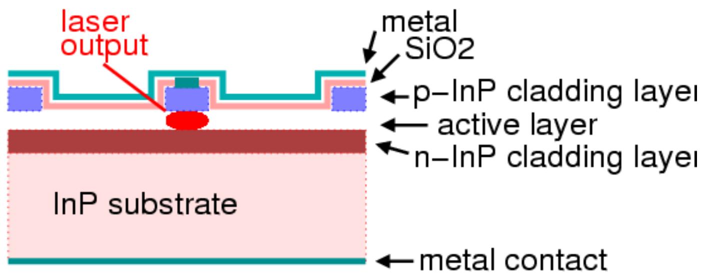
CDF optical link, transmitter assembly

- Die-bond / Wire bond
  - laser-diode array on BeO submount
  - driver chip on substrate
  - fibers on V-groove
- Alignment
  - fibers to laser emitting facets



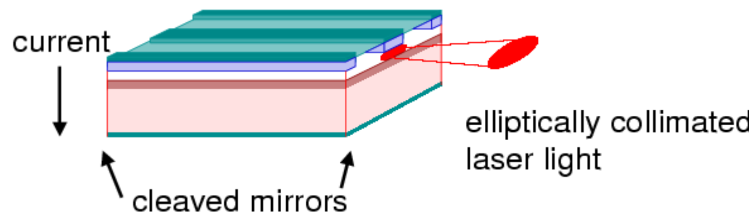


CDF optical link, transmitter electronics



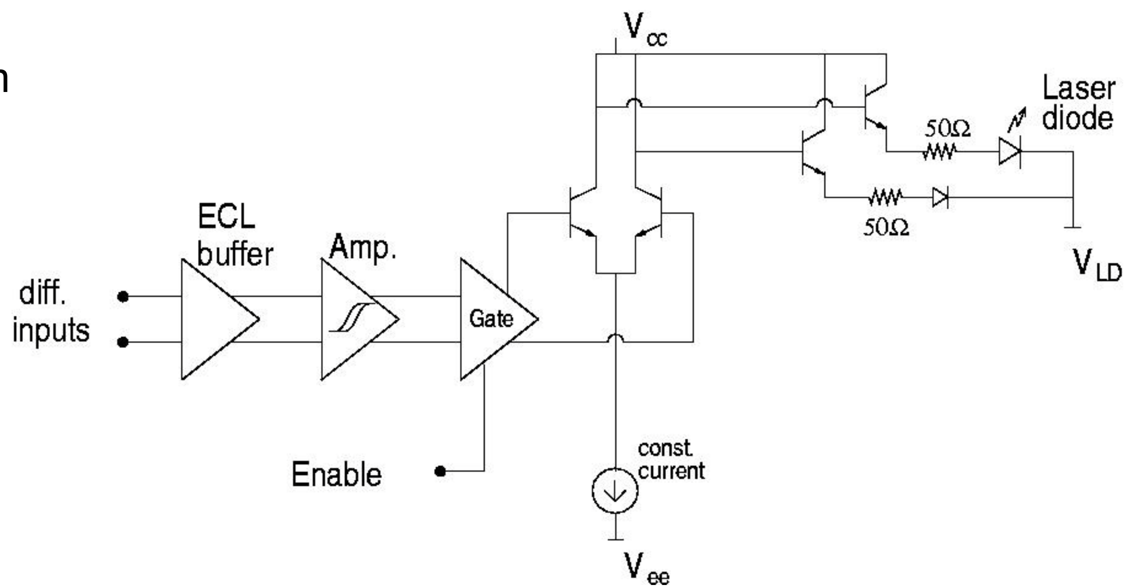
InGaAs/InP Edge-emitting laser diode array

1550 nm wavelength
12-ch diode array, 250 μm pitch
Bare die power, >1 mW/ch @20mA
Insertion to fiber: 200 ~ 800 μW/ch
Custom made by Chunghwa Telecom



biCMOS ASIC driver

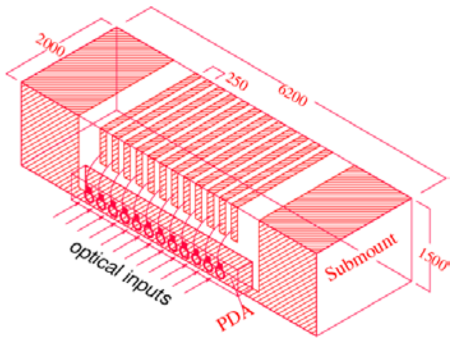
bipolar transistors, AMS 0.8 μm
9-channels
Inputs: Diff. ECL or LVDS
differential >100 mV
Enable by TTL low
Output light: adjustable by
~2mA/0.1V
At V_{cc}-V_{LD}=3V, 20mA/ch

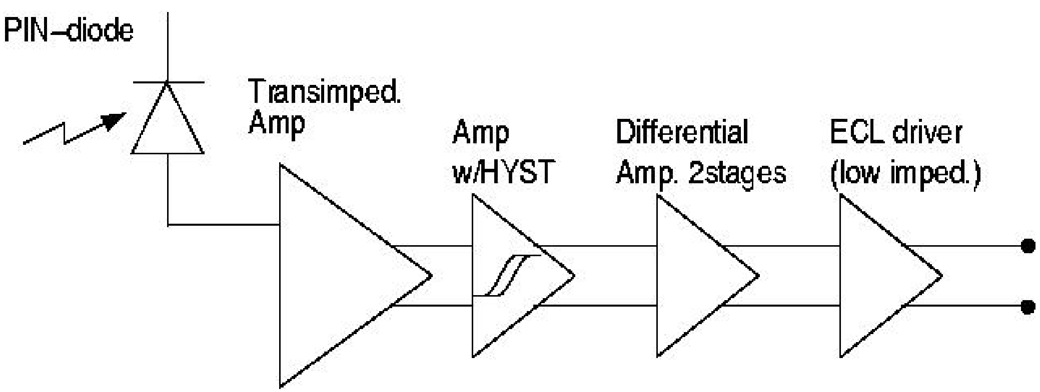


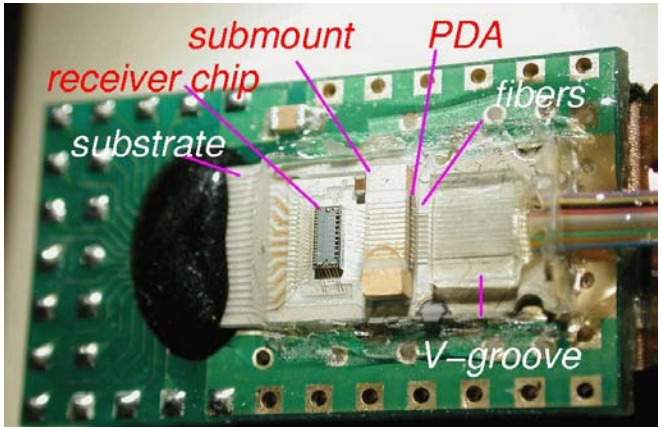
CDF optical link, receiver module

- InGaAs/InP PIN diode
  12-ch array, 1550 nm
  by TL, Chunghwa Telecom.
- Operation condition :
  light on: 50 ~ 800 μW
  light off: <10 μW
  <1.1 W/module
- Outputs :
  9 independent diff. ECL

- Die-bond / Wire bond
  PIN-diode array on Al_2O_3 submount
  driver chip on substrate
  fibers on V-groove to PIN diodes



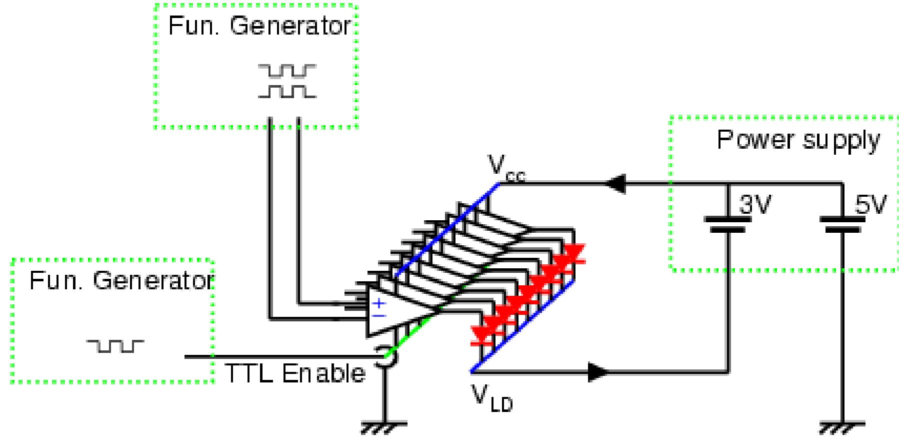


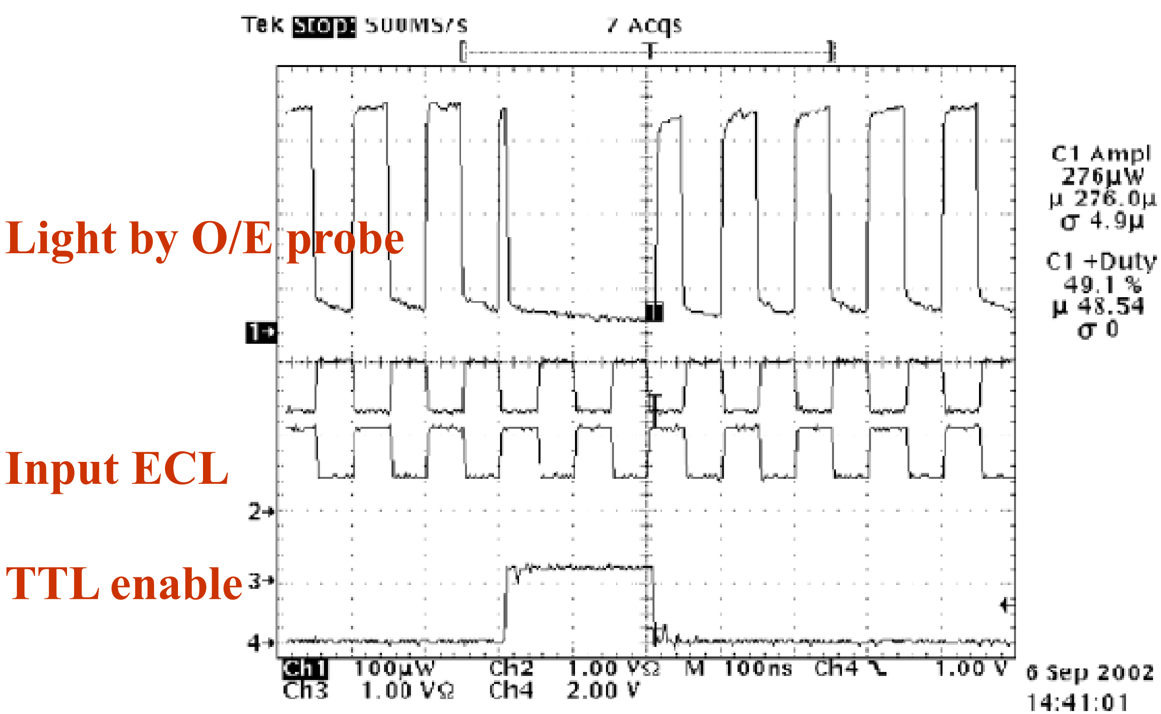


CDF optical transmitter test

Inputs:

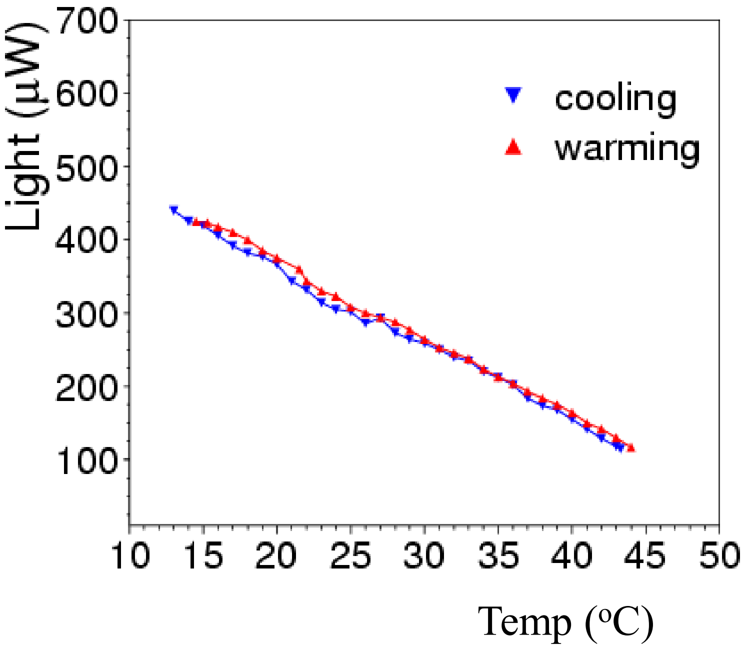
- ECL or LVDS signal
- TTL-enable

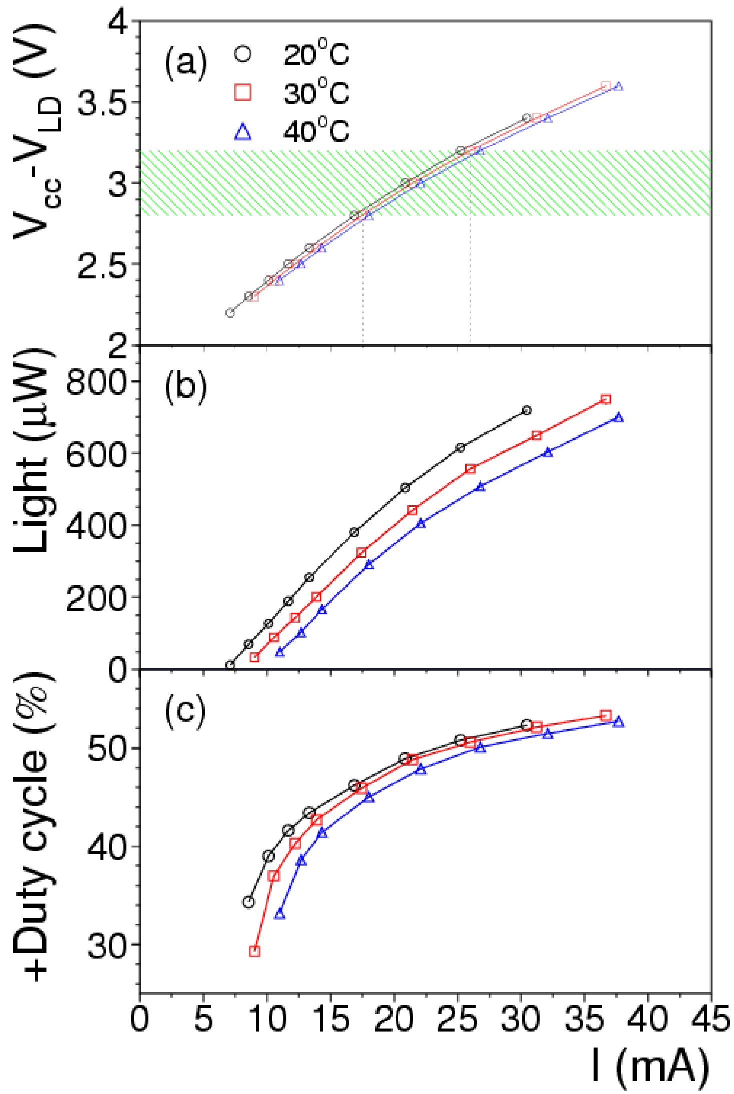




CDF edge-emitting laser, characteristics

- Laser light at I,V and Temperature
- I-V approximately linear
- Duty cycle
  stable output to input 50%
- Linear to temperature



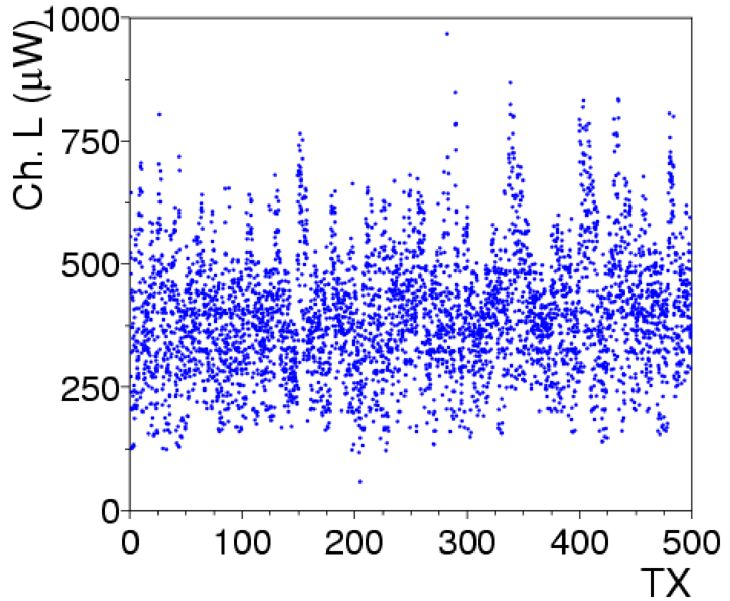


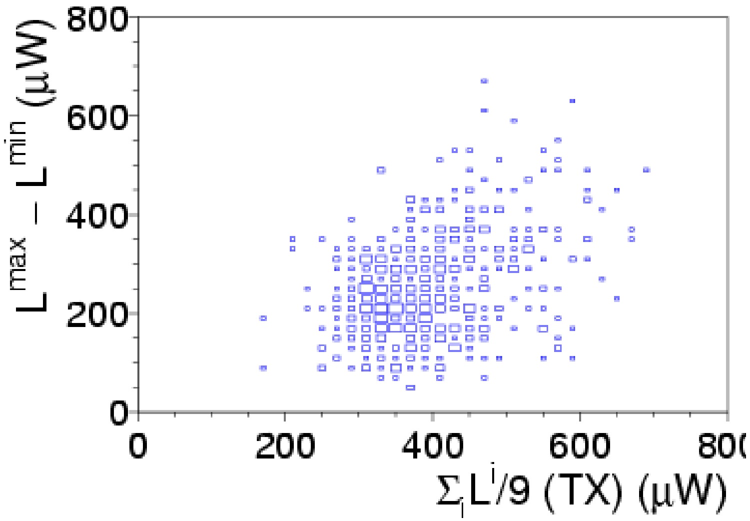
CDF optical transmitter production uniformity

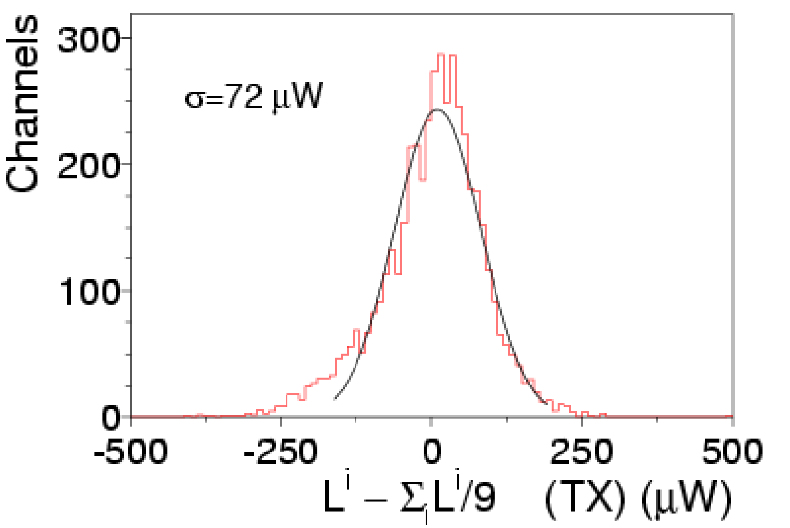
- Quality analysis

  light measured from pigtails at 30°C
  wide deviation channel-by-channel
  mainly due to insertion efficiency

  Span within ~400 μW
  σ ~72 μW to the mean/module







CDF optical receiver responses

- Receiver connected to a Transmitter

  Light power chosen for
  wide distribution

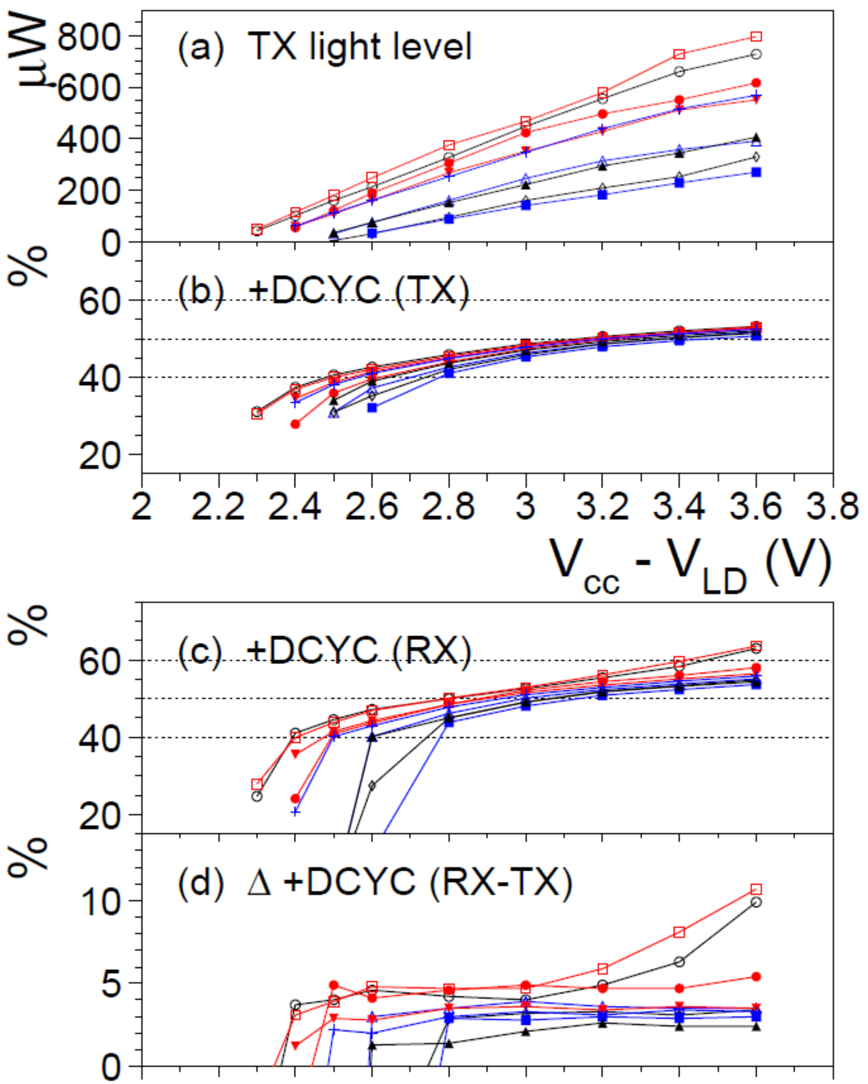
  Light pulse width are consistent

- Receiver ECL outputs

  by a Tektronix diff. probe

  Consistent duty cycles in favored operation range (2.8~3.2V)

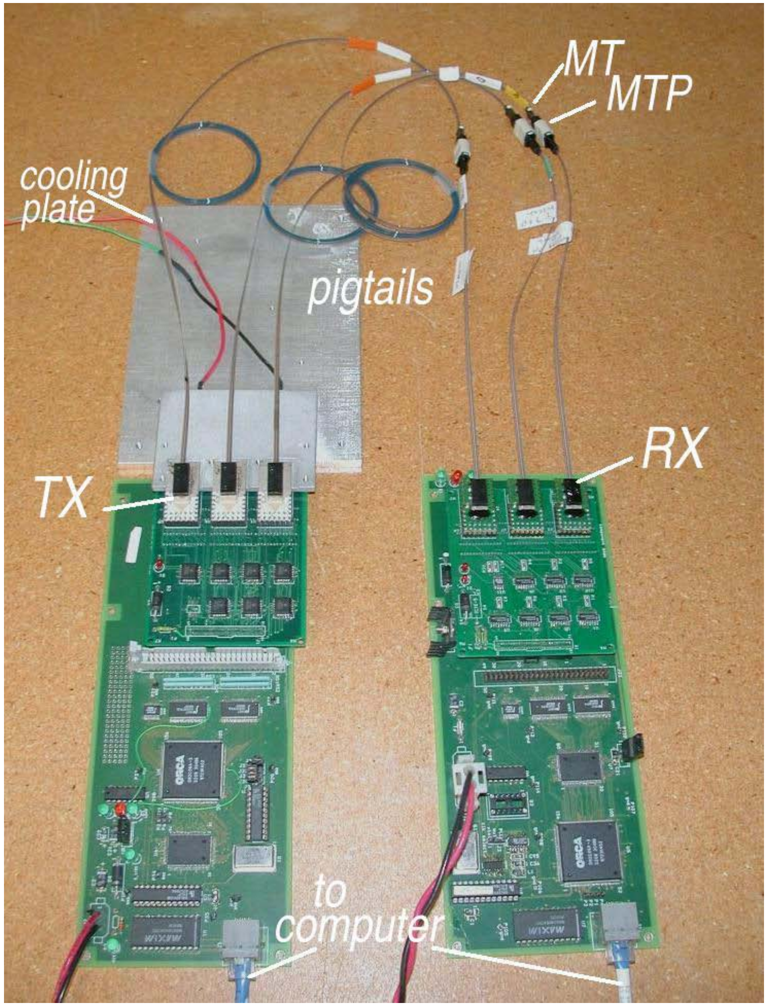
  Saturates for high light level



CDF optical link, Bit-Error-Rate test

- BERT by Fermilab
  PC ISA bus interface
  Tbert, Rbert - test boards
- At 63 MHz,
  minimum BER $<10^{-12}$
- Burn-in
  3-days on ASICs, diodes
  1-day BERT

$\Rightarrow$ reject devices infant mortality
bad components fail quickly



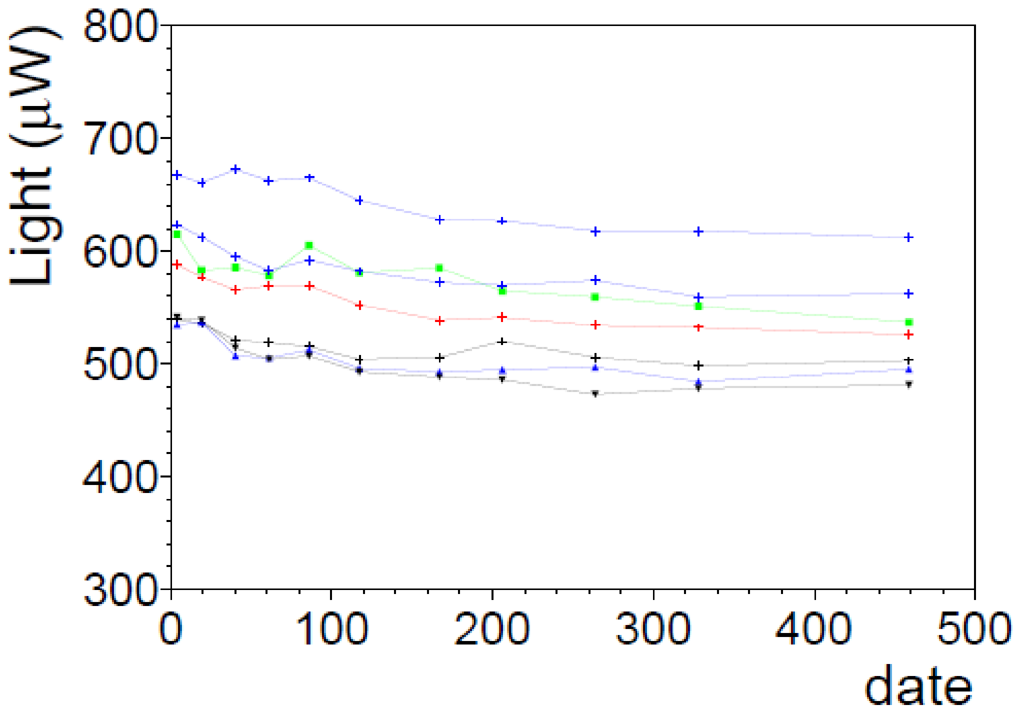
Optical transmitter, accelerated ageing

- Transmitters biased at **60°C** for 330 days
- Accelerating factor , Arrhenius eq.

$$F = \exp \frac{E_a}{k_b}\left(\frac{1}{T_1} - \frac{1}{T_2}\right),$$

E_a= 0.4 eV for GaAs
F=15 to T_1= +6°C

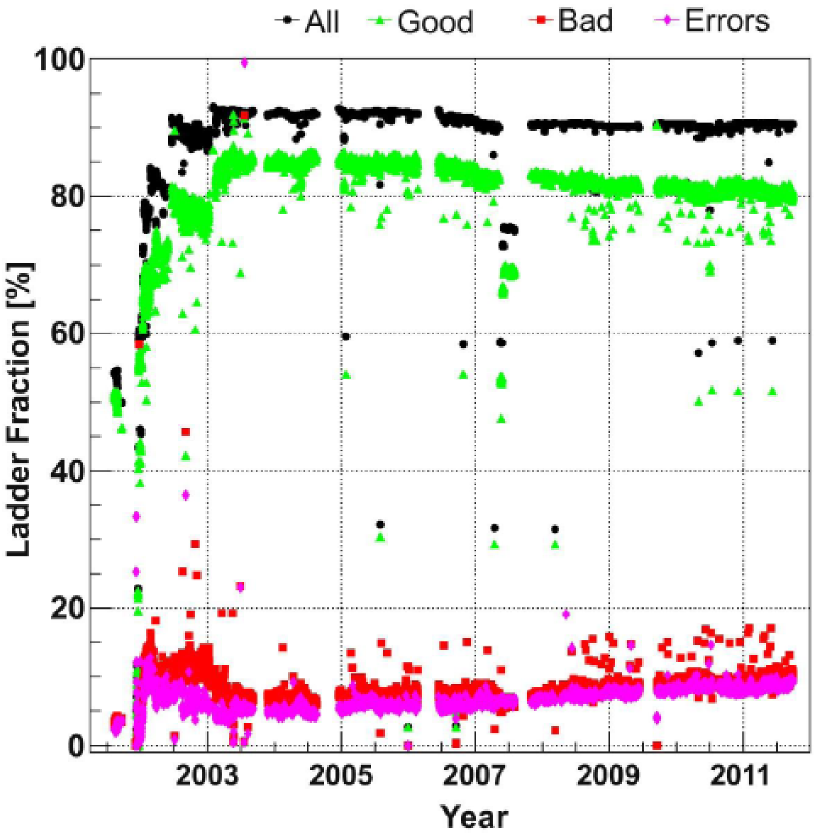
- Wear-out degradation
  ~10% at 60°C, no failure corresponding to CDF operation at +6°C for 15 years



CDF optical link longevity

- **Commissioning was problematic:**
  ~ a dozen bit-error channels
  - ➢ temperature from Room to 6^{o}C increased light power → wider width NRZ bit locku
  - ➢ loosened connectors → permanent loss
- **Optical link bit-error**
  after commissioning ~ 2%
- **10 years operation**
  ageing, radiation damage
  - → outer tracker (ISL) stay at ~2%
  - → inner most (SVX-II) increase to a total ~ 4%

Fraction of silicon ladders



Radiation hardness of optical links

Predictions
Tests to CDF transmitter
Tests to VCSELs, PINs

Radiation damage

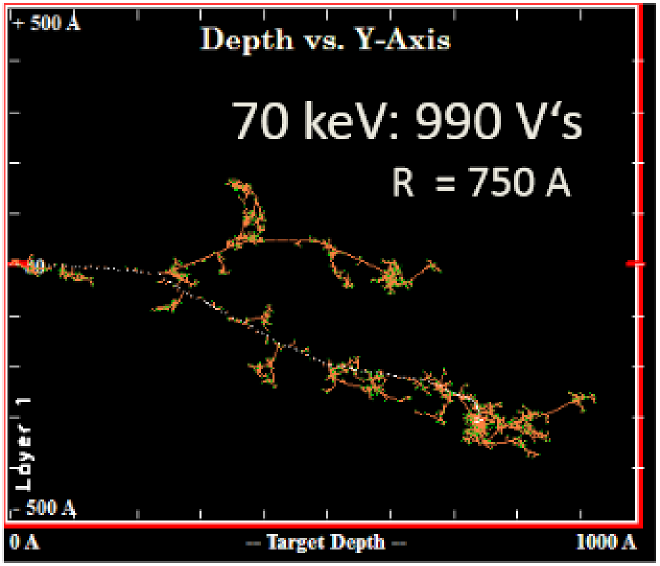
- **Interaction of radiation with material**
  Gamma → Total Ionizing Dose (TID), SEU
  Charge hadron, neutron → NIEL, degradation, SEU

- **Ionization:**
  charge trapped in oxide or at interface

- **Displacement:** (NIEL, non-ionizing energy loss)
  atoms can be removed from their initial crystal lattice positions
  → **defect in components**
  → **degradation, annealing**

- **Single event effect (SEE)**
  transient, corrupted bits,
  IC functional interrupt

TRIM →

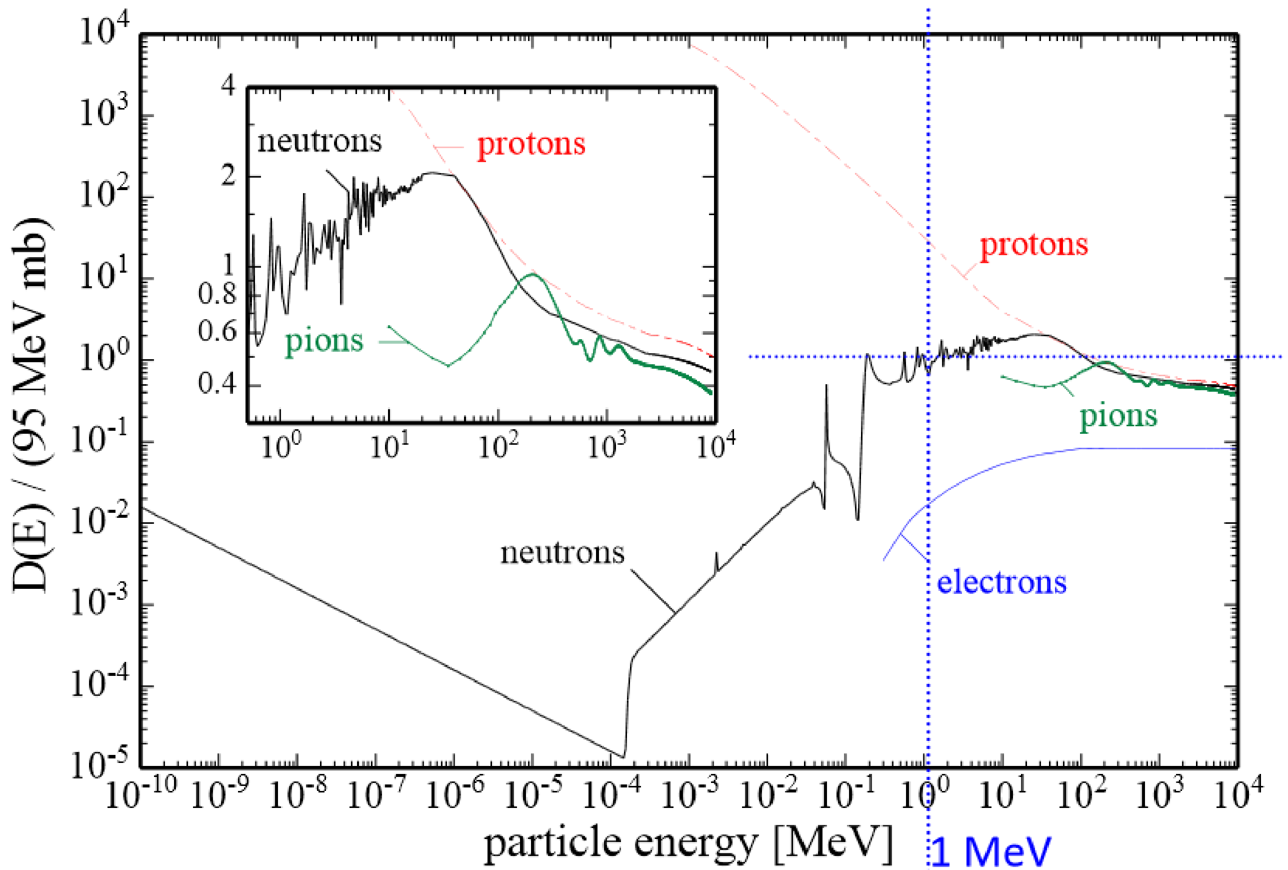


NEIL in Si damage function

- Hypothesis: Damage parameters scale with the NIEL
  1 MeV neutron equivalent damage

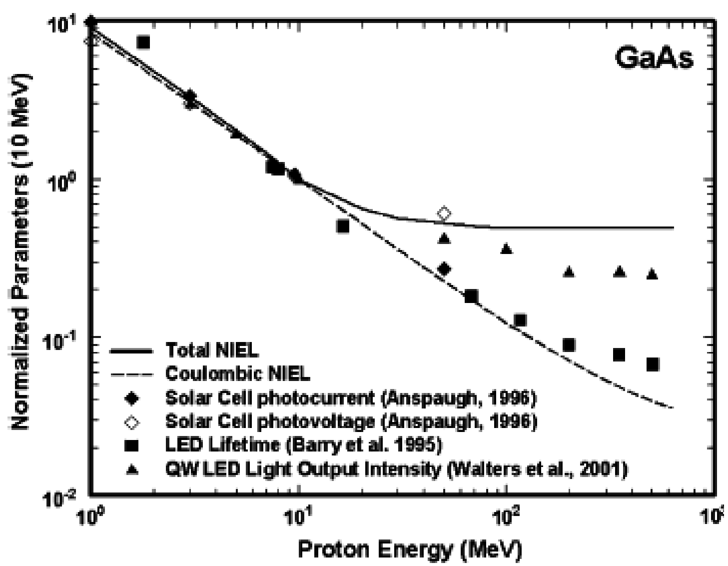
$$\Phi_{eq} = \kappa_x \, \Phi_x$$

κ_p =0.62 (24 GeV/c protons)
κ_p = 1.85 (26 MeV protons)
κ_π = 1.14 (300 MeV pions)
κ_n = 0.92 (reactor neutrons >100 keV)

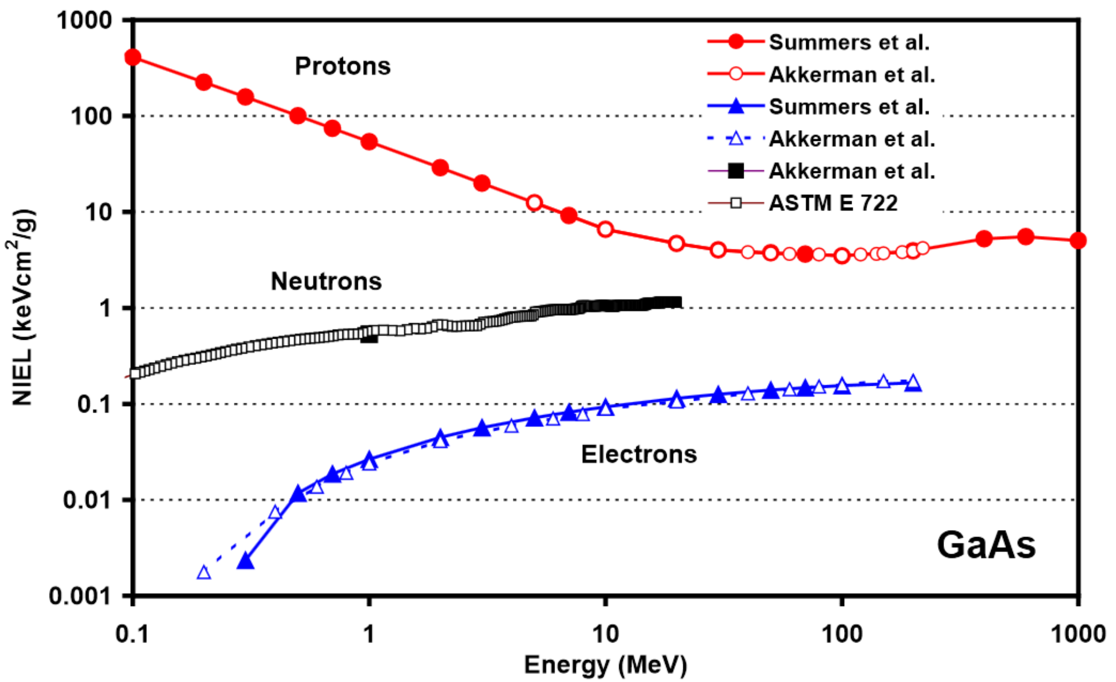


NIEL of Proton in GaAs

− Proton damage to GaAs LED, Solar Cell does not agree with beam tests



J.H. Warner et al.,
IEEE TNS 51, 2887 (2004)

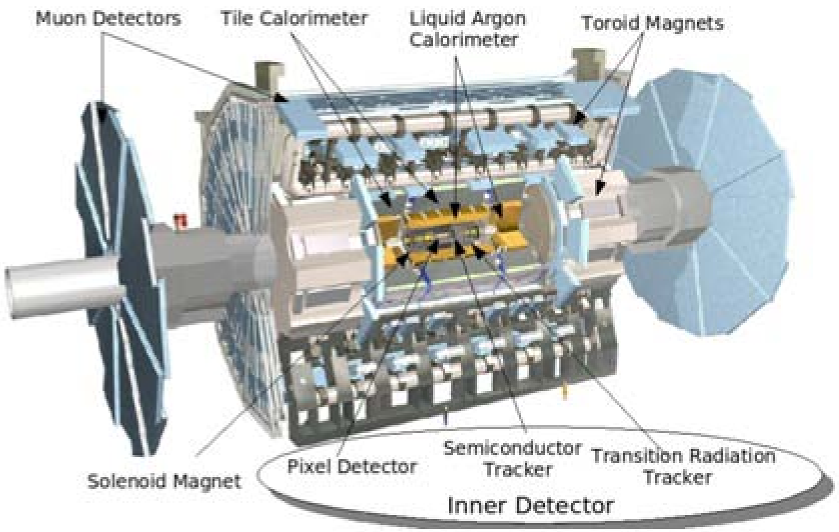


C. Poivey, EPFL Space Center 9th , Jun 2009

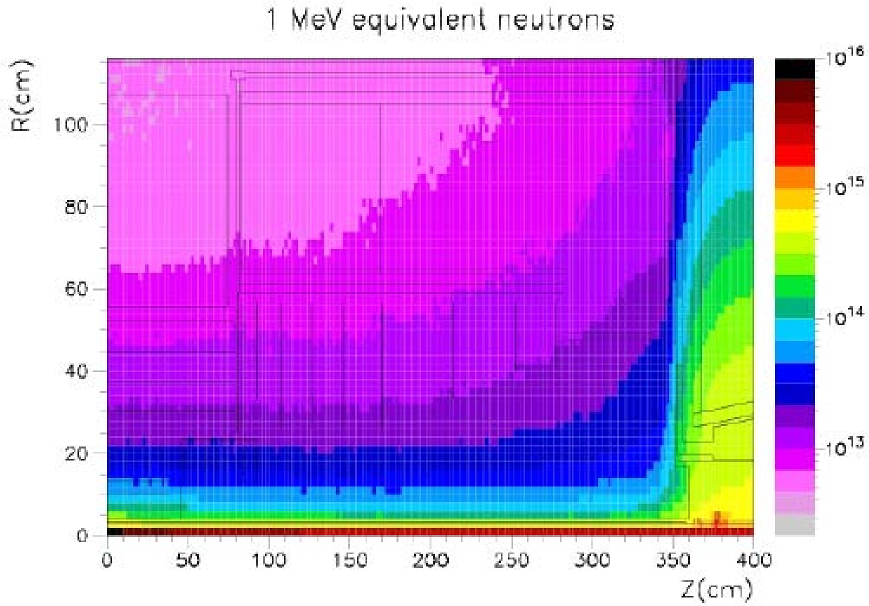
Radiation Field in ATLAS

- **Exposure to radiation from pp collisions**
  mainly pions
  neutrons (hadrons interact with material)

- **10 years operation**
  TID > 100 kGy
  NIEL $\varphi_{eq} > 10^{15}$ 1 MeV n/cm^{-2}



Non Ionising Energy Loss in the ATLAS Inner Detector



FLUKA simulation by Ian Dawson

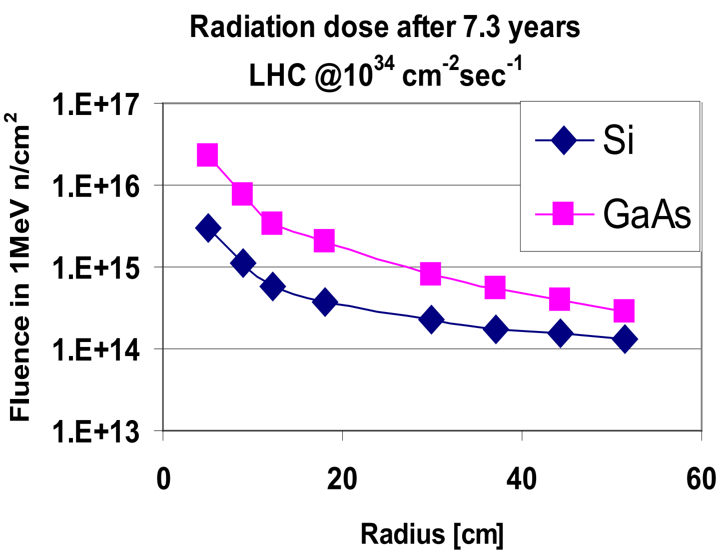
Radiation fields @LHC, SLHC

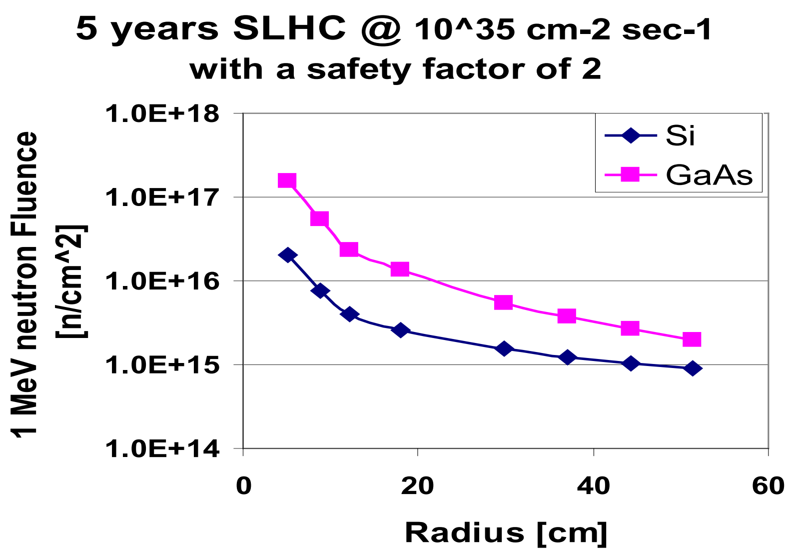
- Fluence expressed for 1 MeV neutron equivalent of the NIEL (Non-Ionizing Energy Loss) calculations

NIEL factors for Neutrons [MeV]	1	20			
GaAs [keV cm^2/g]	0.55	2.3			
Si [keV cm^2/g]	1.8				
NIEL factors for Protons [MeV]			**30**	**70**	**200**
GaAs [keV cm^2/g]			4.03	3.64	3.93
Si [keV cm^2/g]			4.78	3.16	1.94

[Summers, IEEE NS. 40 1372 (1993)]

- Radiation level @LHC/SLHC



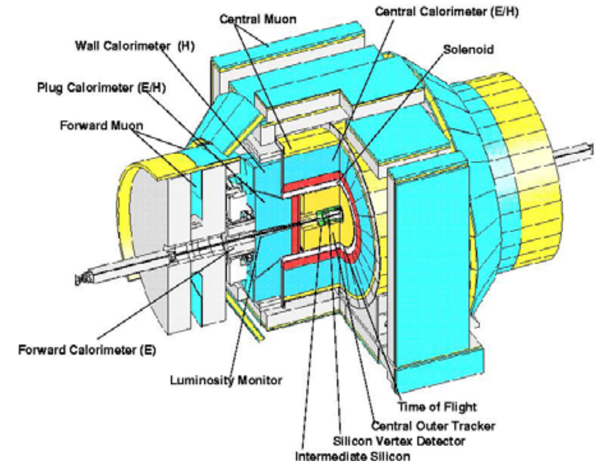


CDF Radiation Measurement

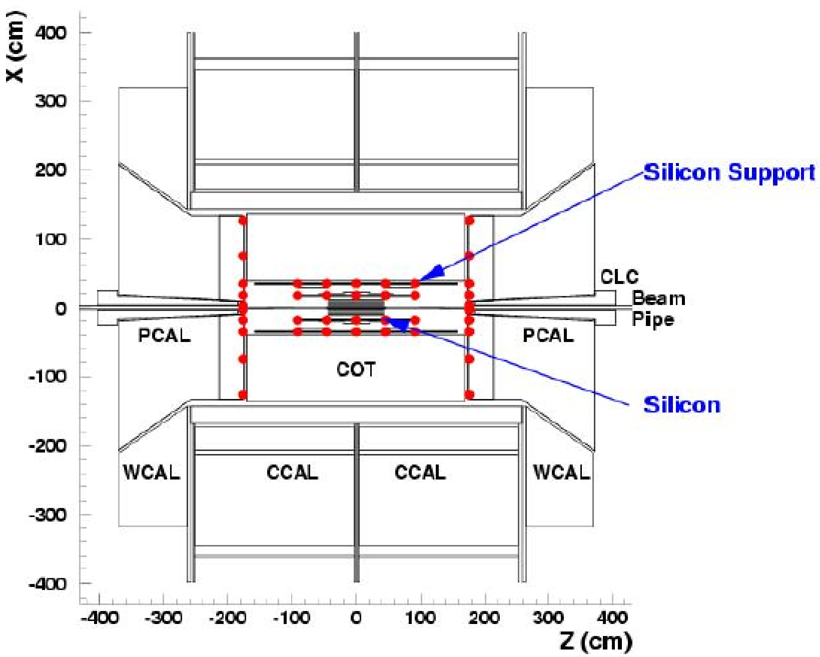
Radiation from p$\bar{p}$ Collisions
TLD measurements + model

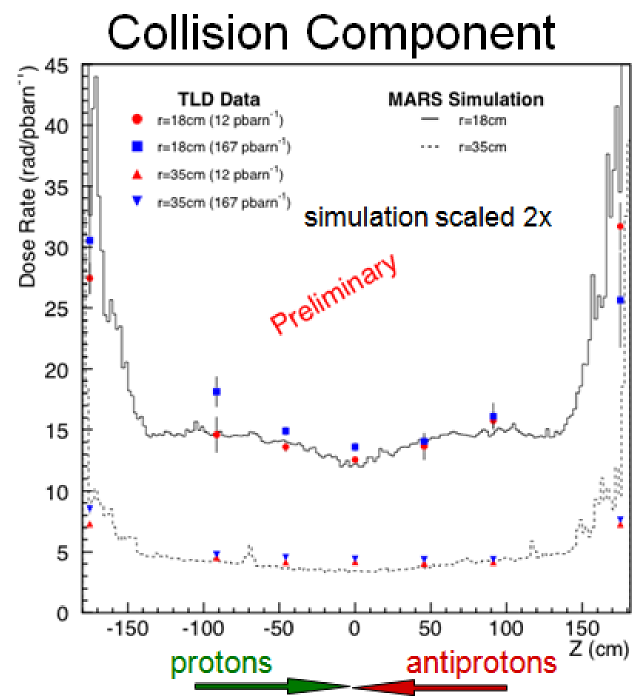
$$dose = \frac{A}{r^{\alpha}}$$

r = radius to the beam
$\alpha \sim 1.5$ in barrel region



Locations of TLDs
(Thermal Luminescent Dosimeters)



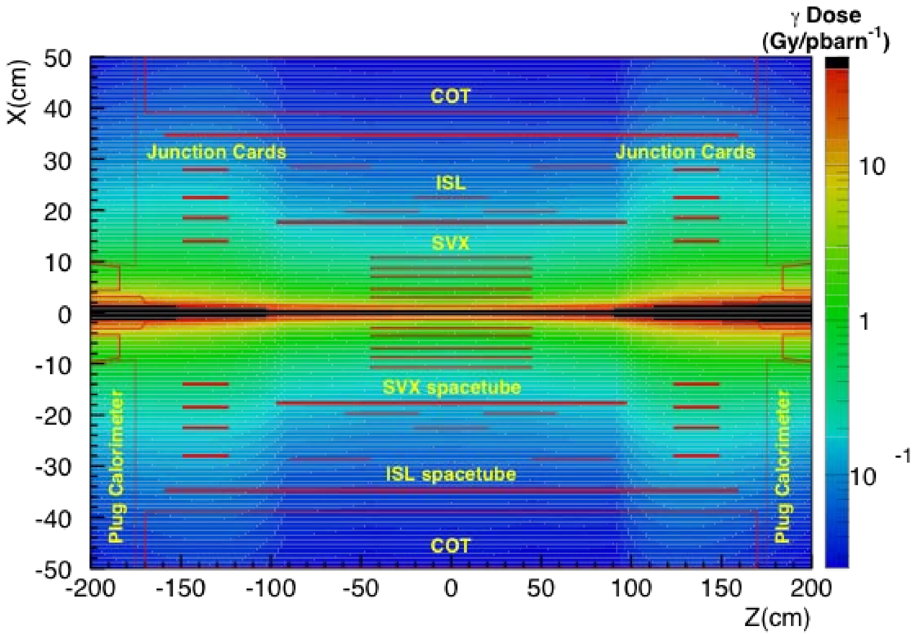


CDF Radiation estimation

By MC for distributions of particles in $p\bar{p}$ Collisions

Dose to fluence conversion:
1 Gy = 100 Rad = 3.8×10^9 MIPs/cm^2

(Silicon tracker is specified for 2 MRad)



Radiation tolerance:

Optical Transmitter required for
200 kRad ➔ 7.6×10^{12} MIPs/cm^2

Dose rate at the optical Transmitter
r=15 cm, dose rate = 17 Rad/pb^{-1}

200 kRad ➔ 11.8 fb^{-1} in the beam

Team tests with fixed energy hadrons

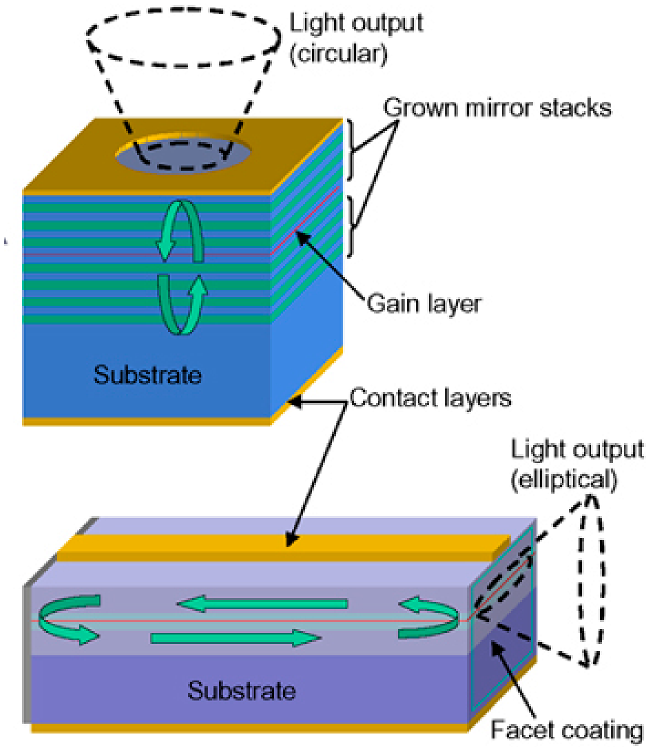
dose scaled by dE/dx

1 Gy = 2.1×10^9 p(200MeV)/cm^2
= 5.4×10^8 p(30MeV)/cm^2

Radiation tolerance of laser diodes

- **Displacement, NEIL →**
  Light degradation, partial recovery by annealing
  Increasing threshold current

- **Edge-emitting Fabry-Peror laser**
  Active optical cavity, typically
  ~500x50x10 μm^3
- **VCSEL**
  very small active volume
  ~ø20x10 μm^3
  very high Rad-hardness

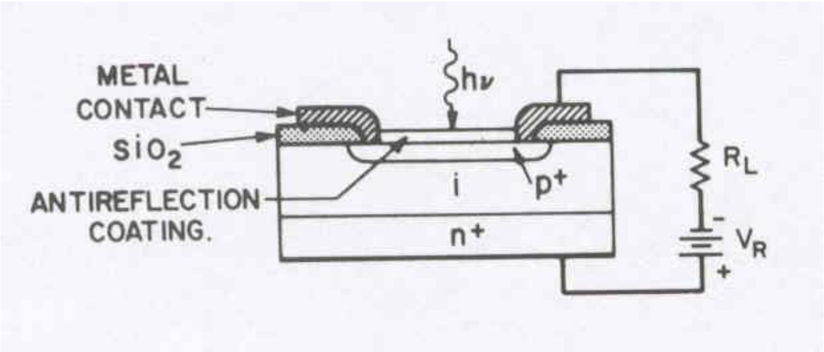


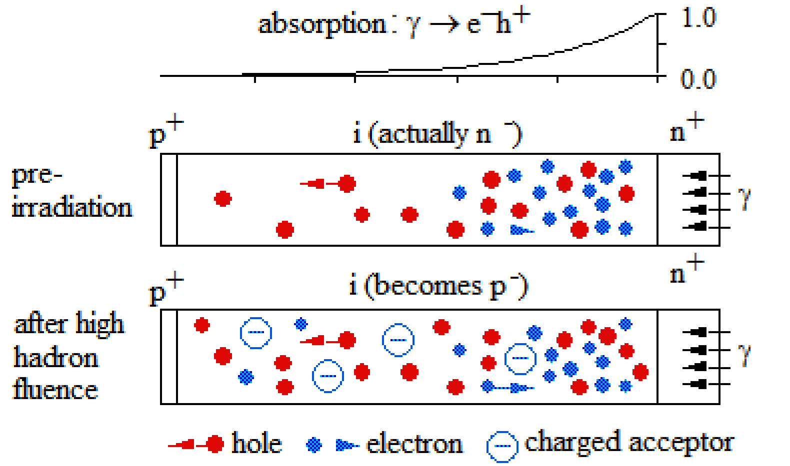
Radiation damage to PIN photo-detectors

- **Displacement, NEIL ➔**
  Increase in leakage I_{leak}
  decrease in responsivity I_{photo}

- **Damage pattern varies**
  Si Epitaxial PIN
  GaAs PIN

- **Faster PIN**
  ➔ smaller device,
  Higher rad-hardness

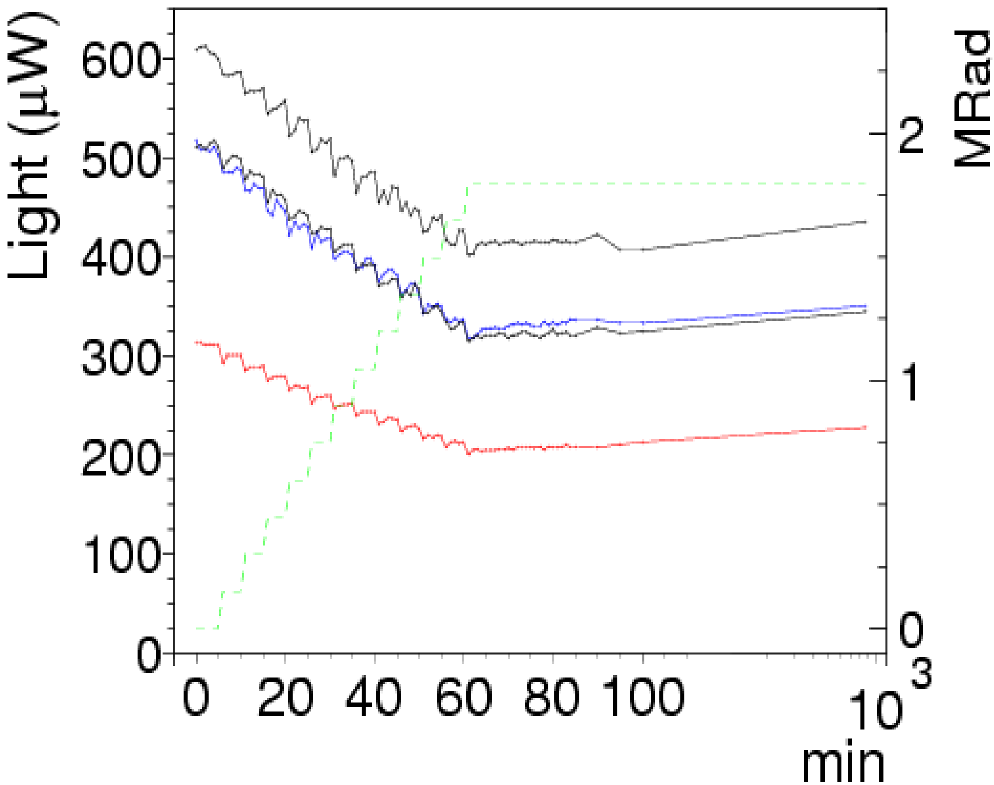


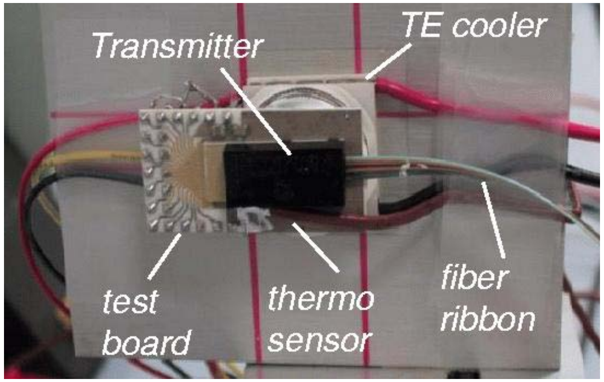


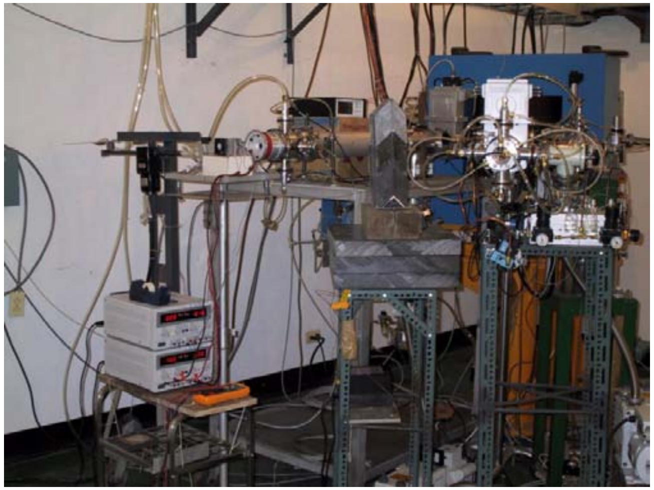
Defects: acceptor type
(good hole traps)

Proton beam tests on CDF transmitter

- Cyclotron 30 MeV protons at INER
- Measuring L, temperature at DC mode
- fiber connection out of beam area







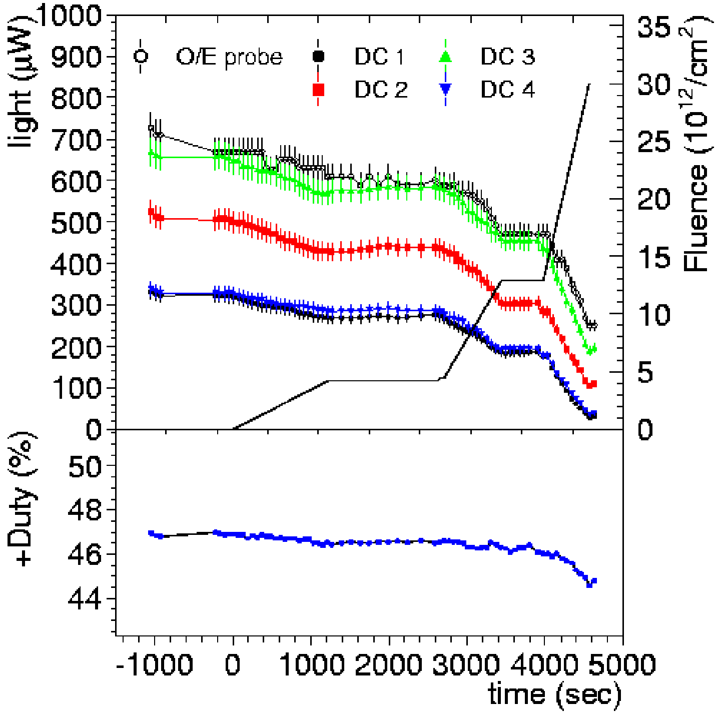
Proton irradiation to CDF transmitter

CDF edge-emitting type laser

Flux rate dependence not obvious

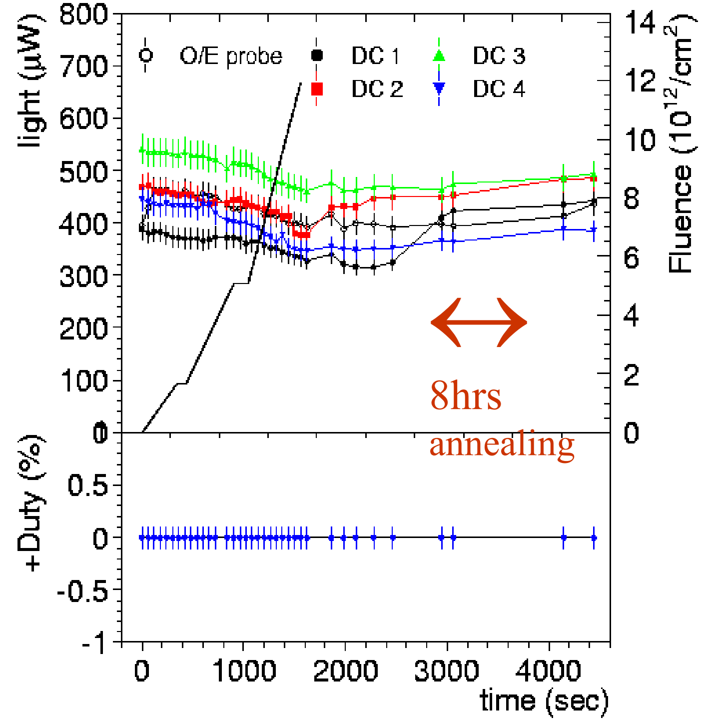
- IUCF 200 MeV protons at 3 flux rate
- Pulsed by 50% duty cycle signals

flux- = 3.4 E9, 11.5 E9, 29.2 E9/cm^2sec
fluence = 4.3 E12, 12.8 E12, 30.0 E12/cm^2



Slow annealing after

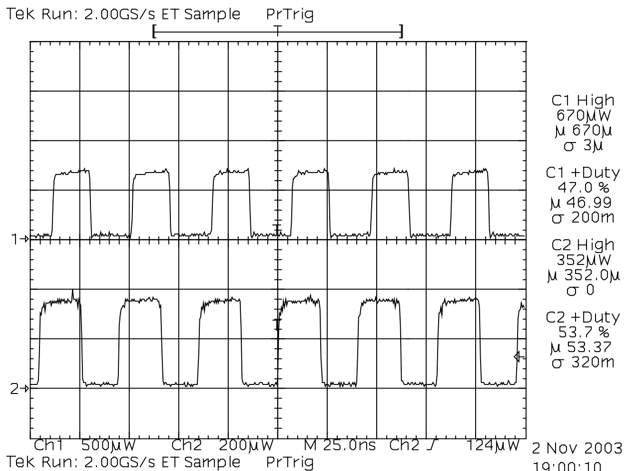
- IUCF 200 MeV protons
- Transmitter at DC mode
- Total fluence 1.2E13 /cm^2
- 8 hours annealing



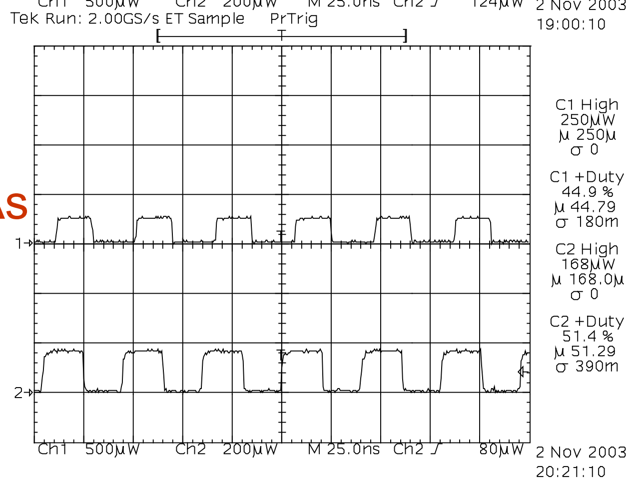
Proton beam tests to CDF transmitter

- IUCF 200 MeV proton
- ECL 25MHz inputs
- O/E probing for biCMOS driver wave form

Before irradiation



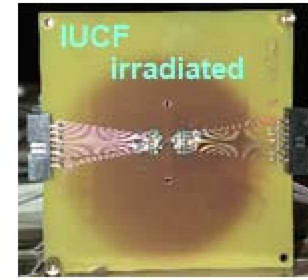
@ 3.0×10^{13} (1.4 Mrad GaAs 1.8 Mrad Si)

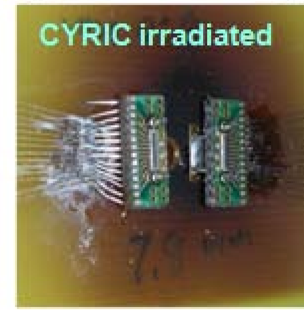


Rad-hardness of VCSELs and PINs

VCSEL and **PINs** tested for LHC

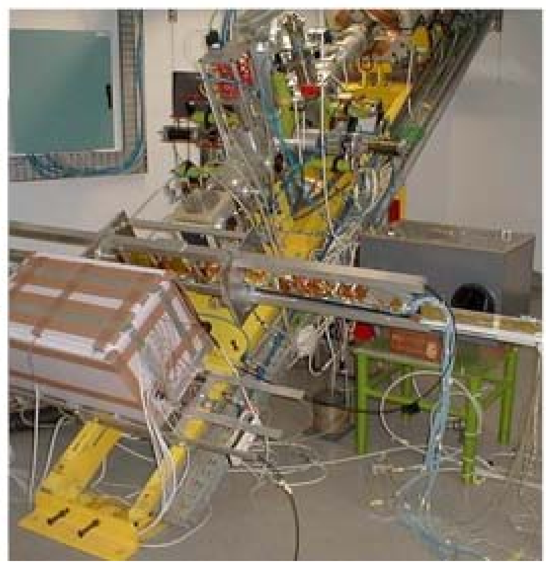
- Louvain-la-Neuve CRC:
  neutron 20 MeV (av) of deutron on Be target
- Tohoku CYRIC: **proton 30, 70 MeV**
- Indianna IUCF: **proton 200 MeV**
- INER: **proton 30 MeV**
- Los Alamos: **neutron**



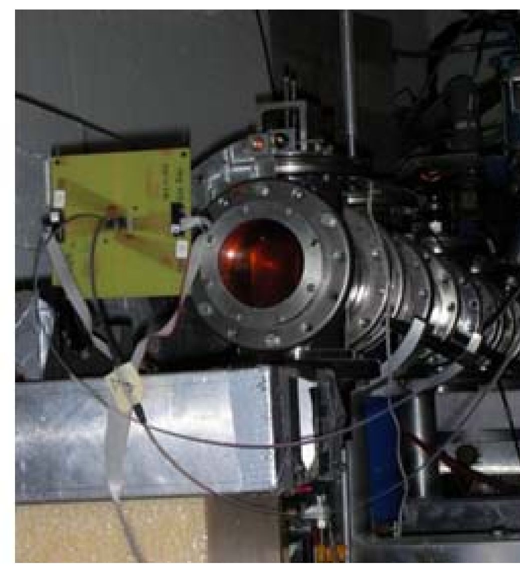


CYRIC control room

CRC beam area



IUCF beam area



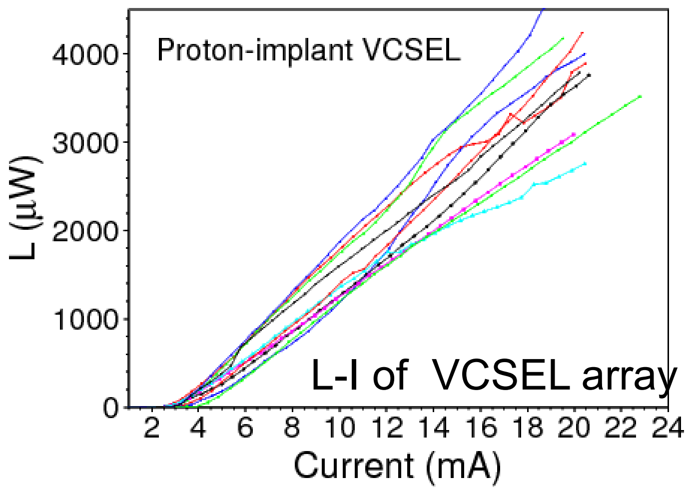
VCSEL characteristics

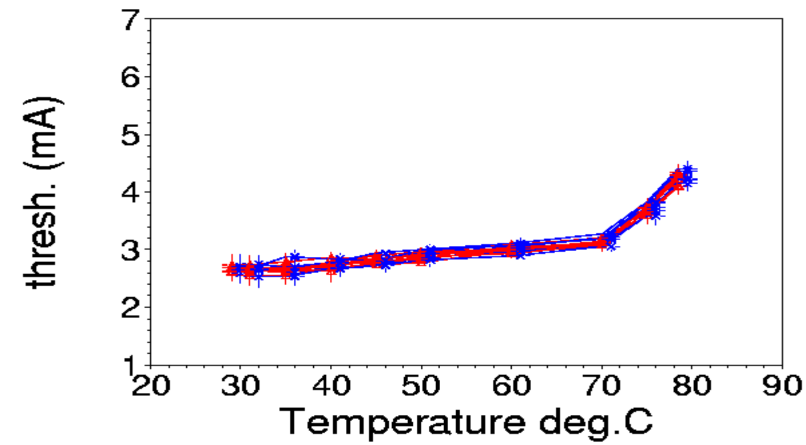
Two types of GaAs VCSEL (850 nm)

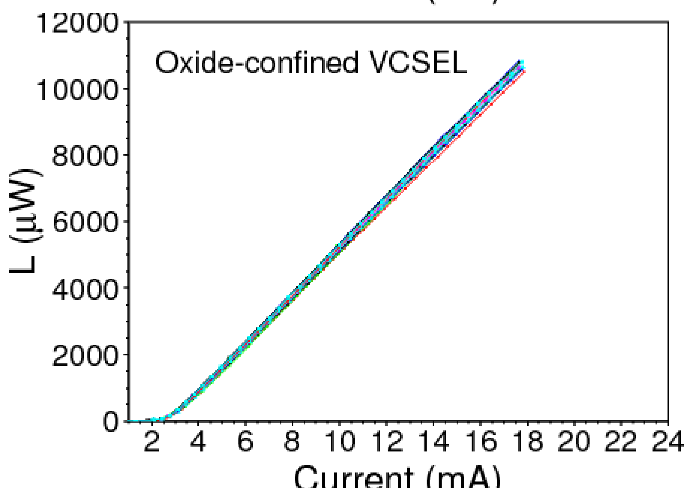
- **Proton implant** VCSEL (ATLAS on detector)
- **Oxide confined** VCSEL (off-detector on ROD)

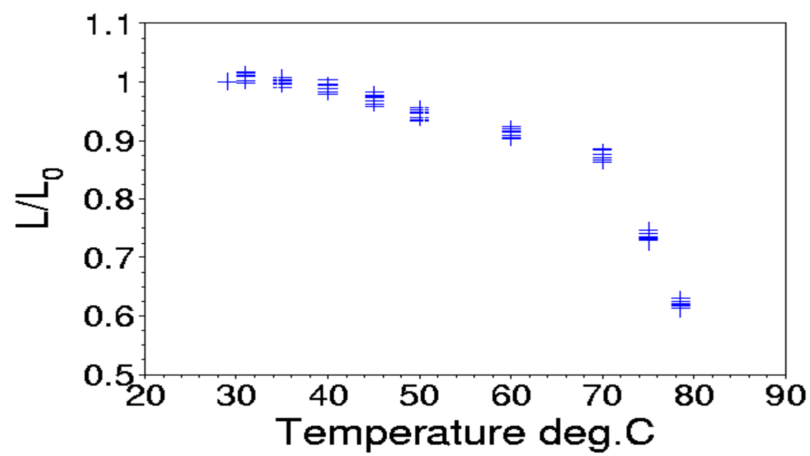
Thin active layer 10 μm, **very rad-hard**

Little temperature dependence





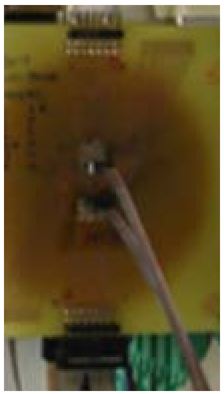




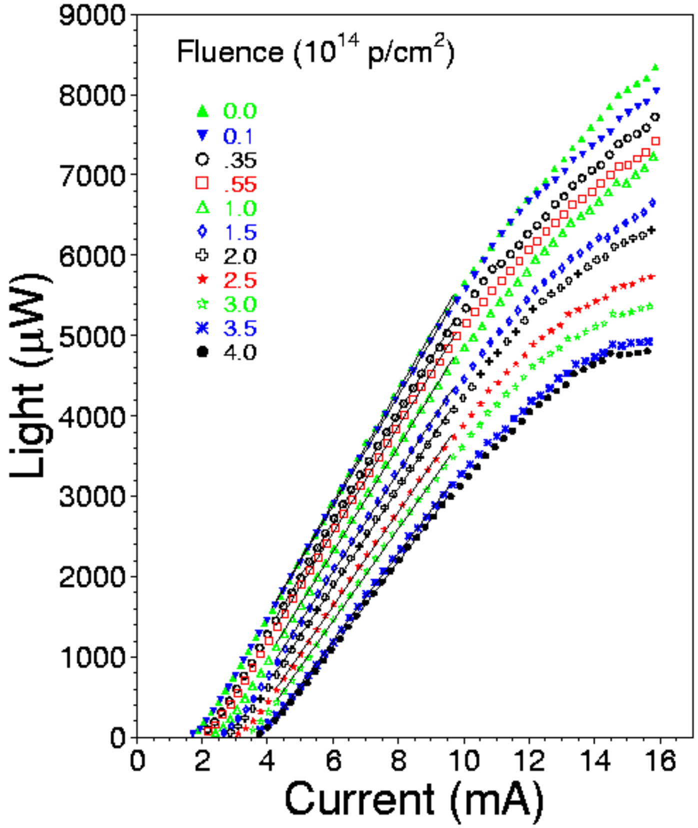
VCSEL degradation, annealing

VCSEL light degradation ➔ linear to fluence
rad-hard fiber connected to readout, independent of flux rate

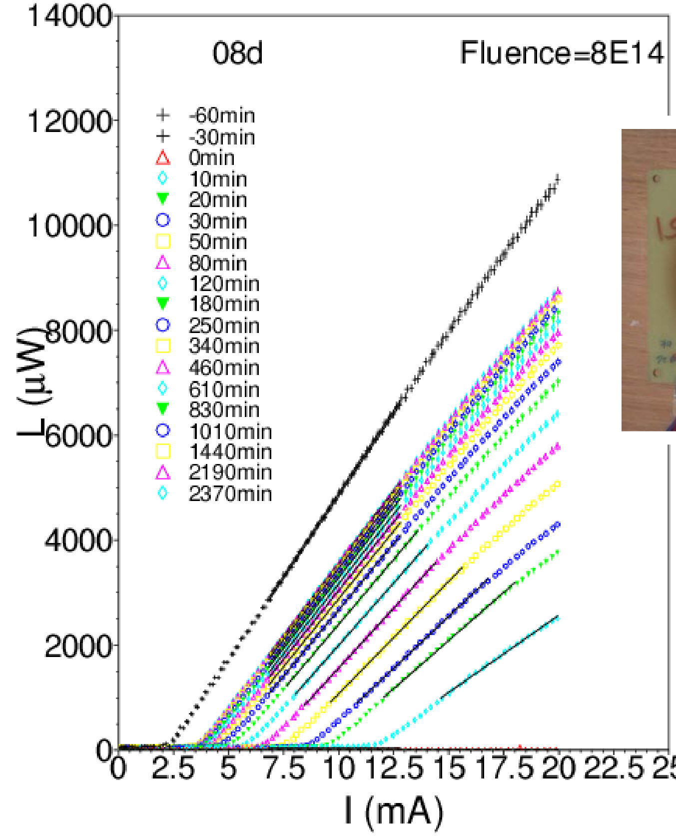
Fast annealing by charge injection
at operation current (10 nA) applied

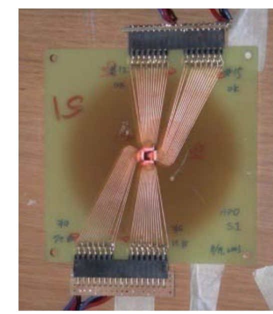


L-I of VCSEL (oxide)
vs. **online** Fluence



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



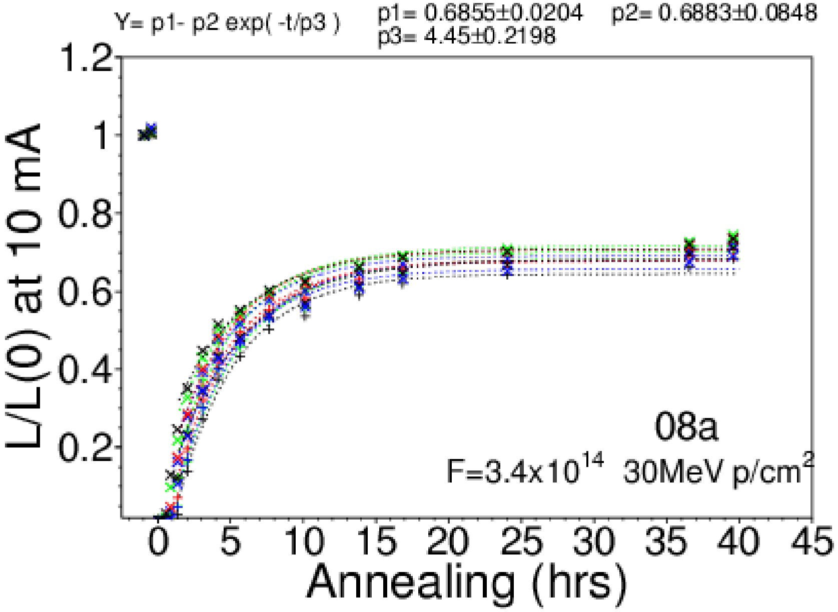


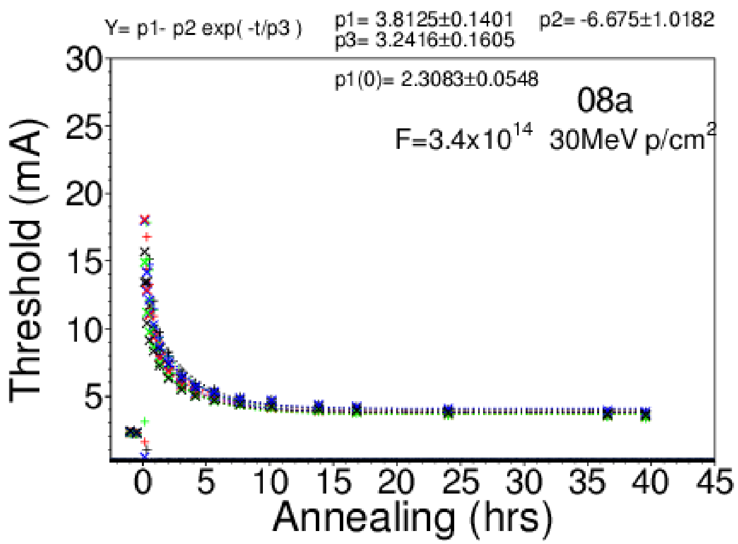
VCSEL annealing in time

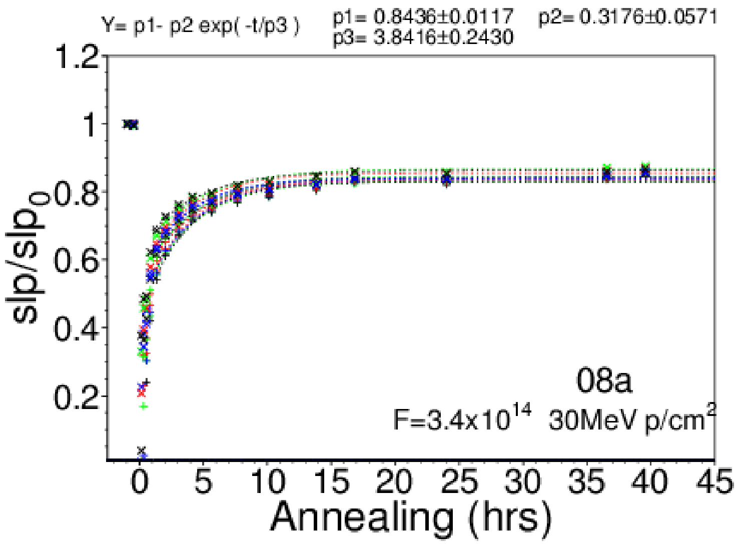
- Charge injection at at the operation 10 nA

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

➔ recovery time $\tau \sim 5$ hours

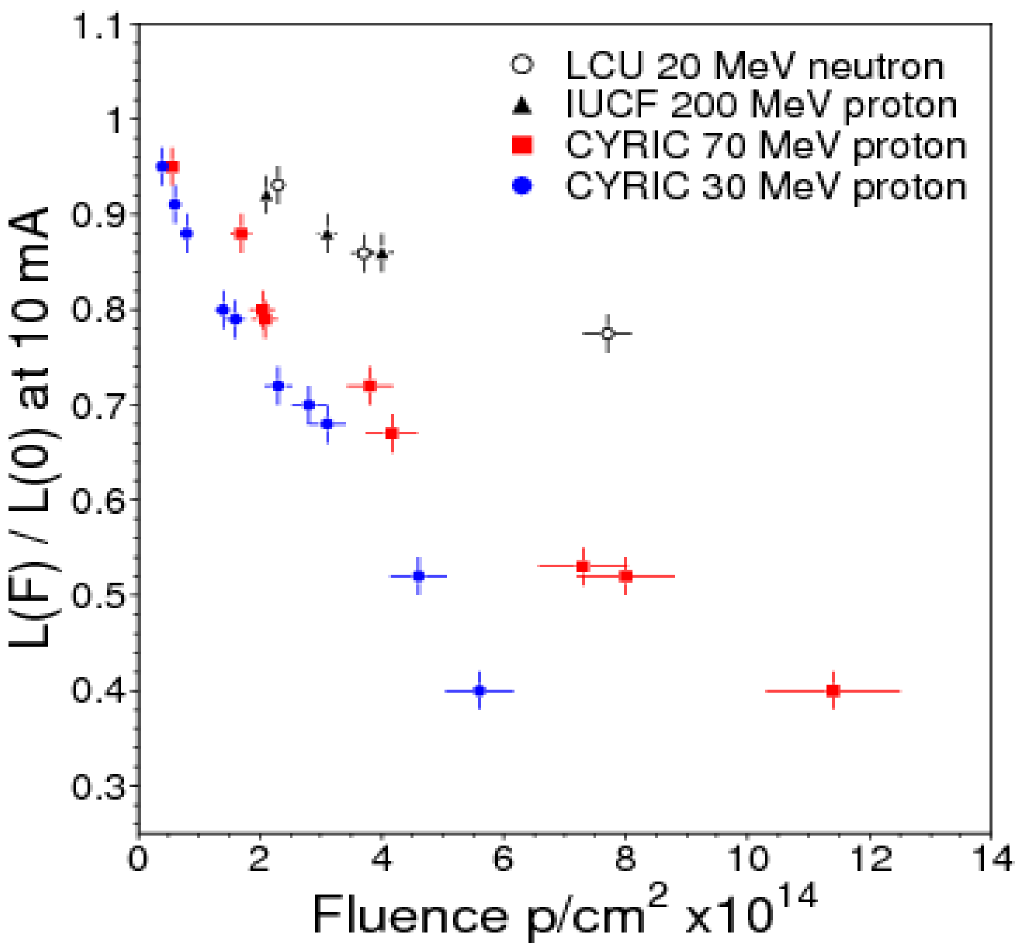


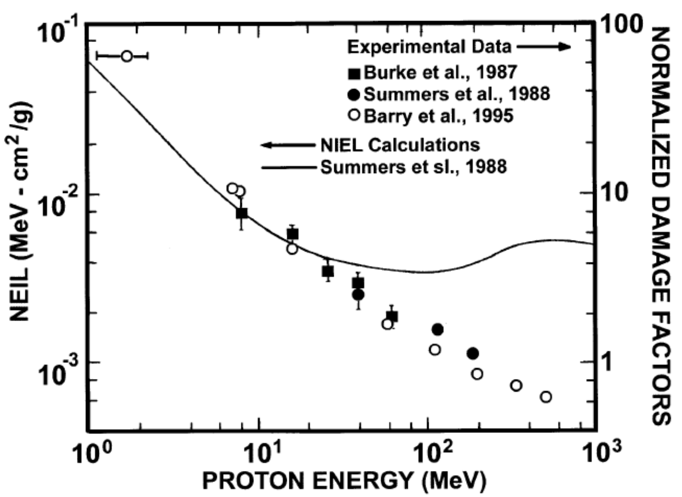




VCSEL rad-hardness summary

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





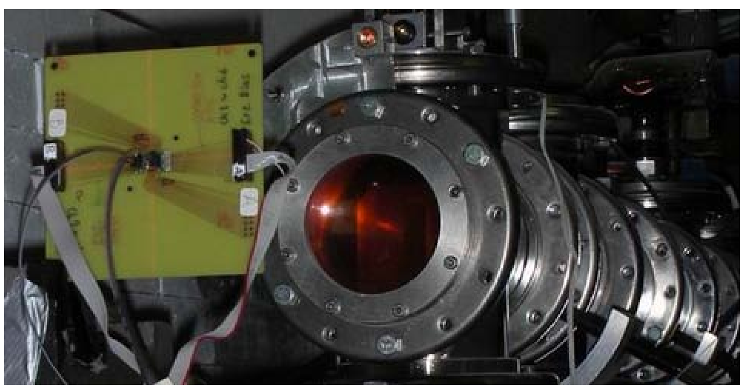
GaAs solar cell

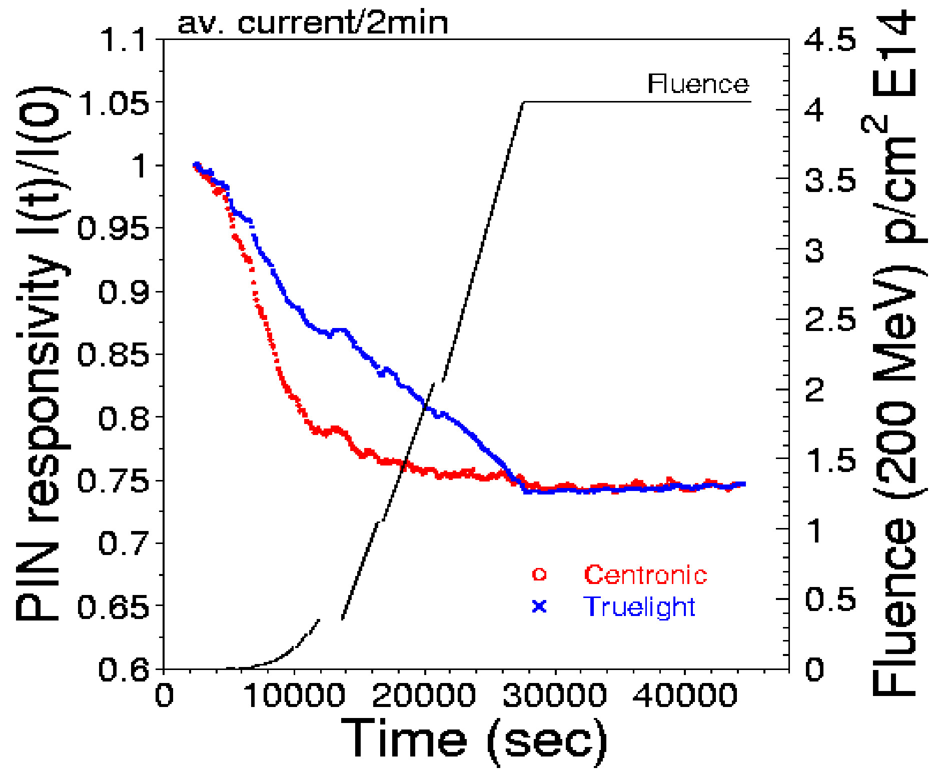
Srour, IEEE TNS 50, 653 (2003)

Proton damage to Epi Si PIN, degradation

IUCF 200 MeV proton, to $4x10^{14}$ p/cm^2

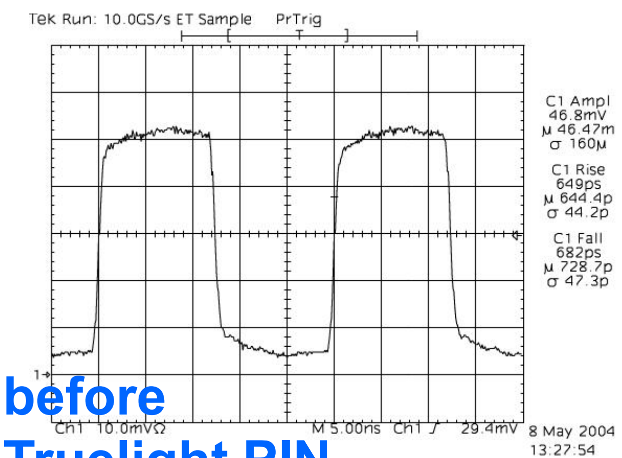
- **DC Laser light to Epi PINs**
- **Online current measurement**
- ➔ Responsivity
  dropping fast in early fluence





Proton damage to PIN, wave-form

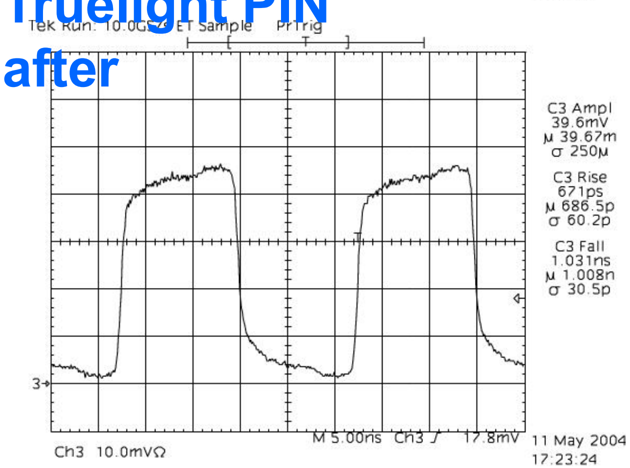
- ➢ Wave form at full depletion, after 4×10^{14} (200 MeV) p/cm^2
- ➔ rise/fall time < 1 ns (20%-80%)

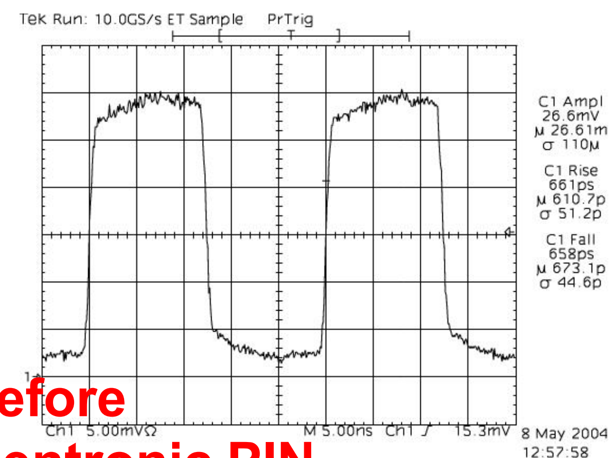


before

Truelight PIN

after

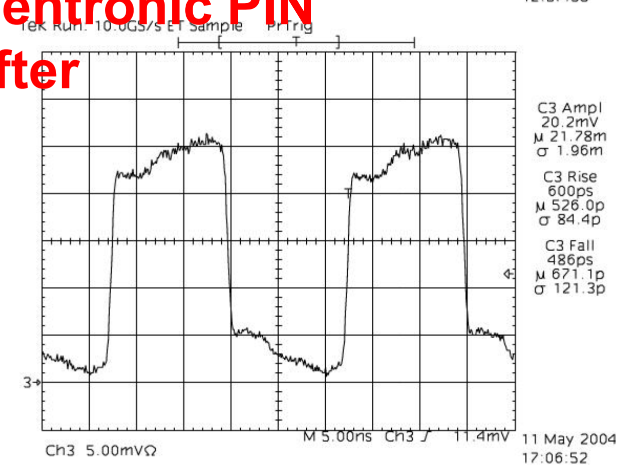




before

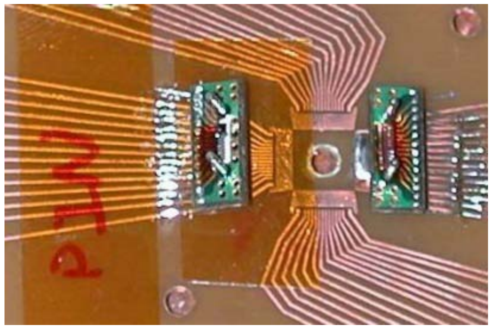
Centronic PIN

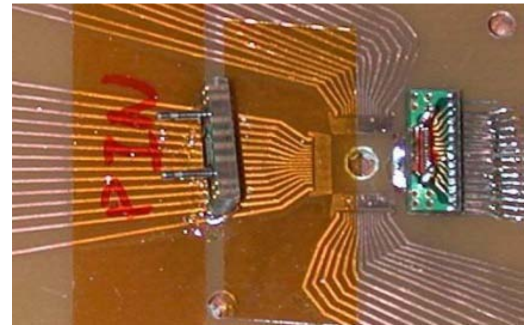
after

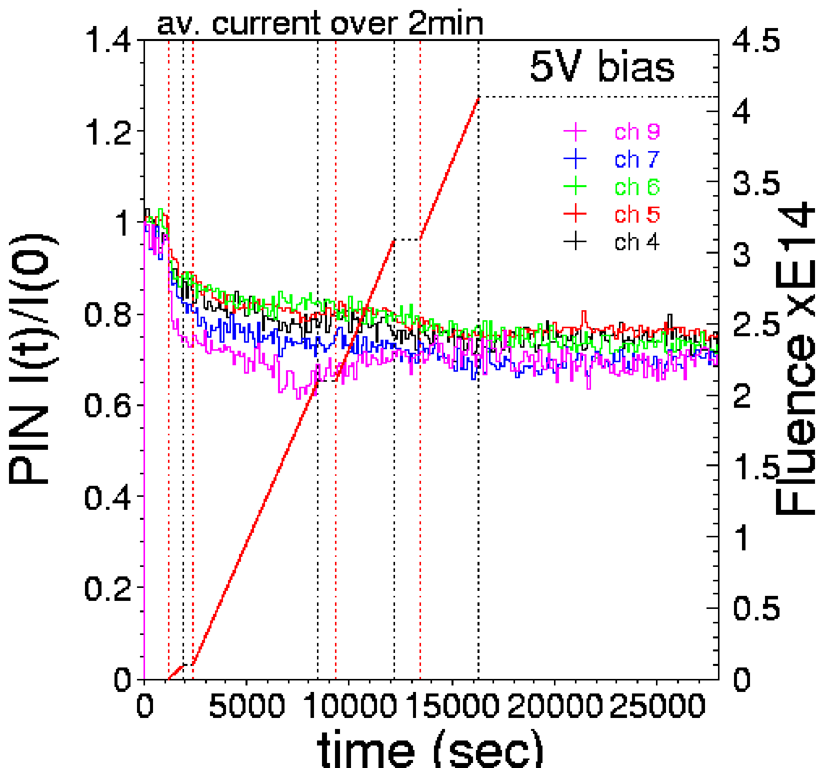


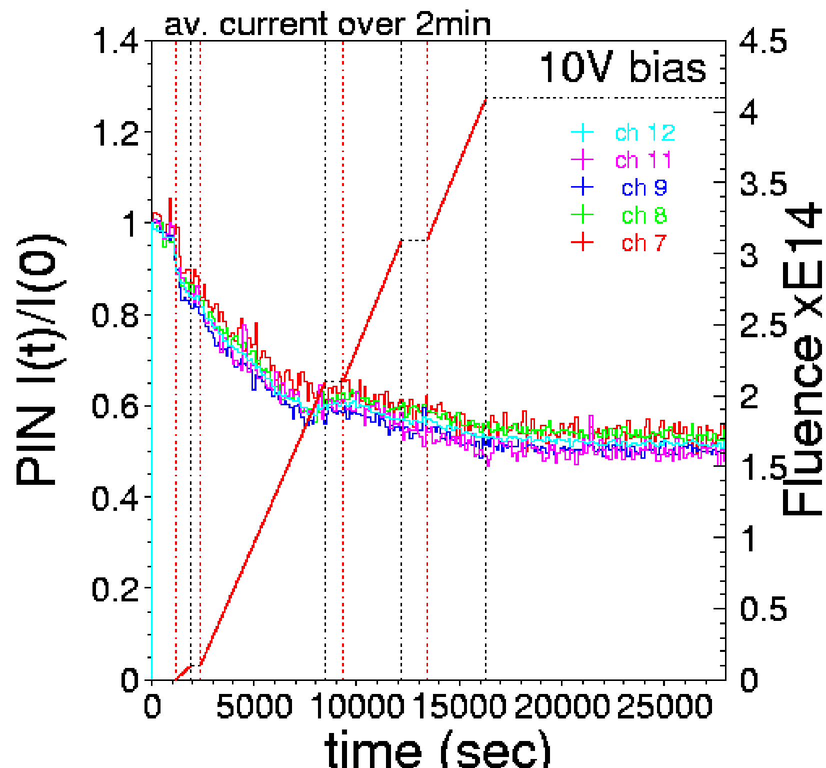
Proton damage to PIN, orientation matters

PIN face parallel to beam ➔ twice damage





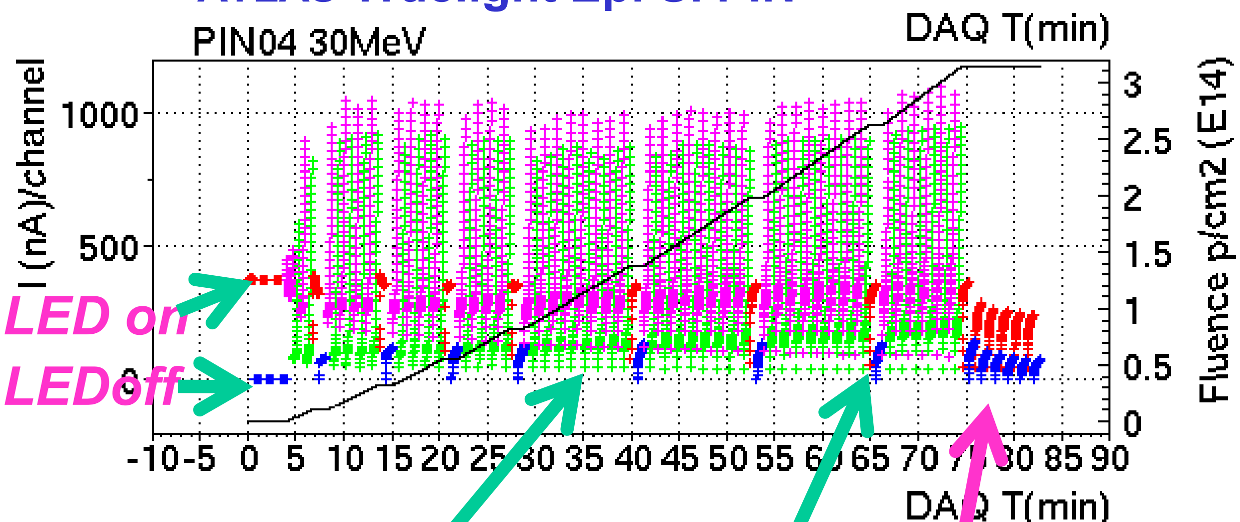




PIN responsivity, dark current

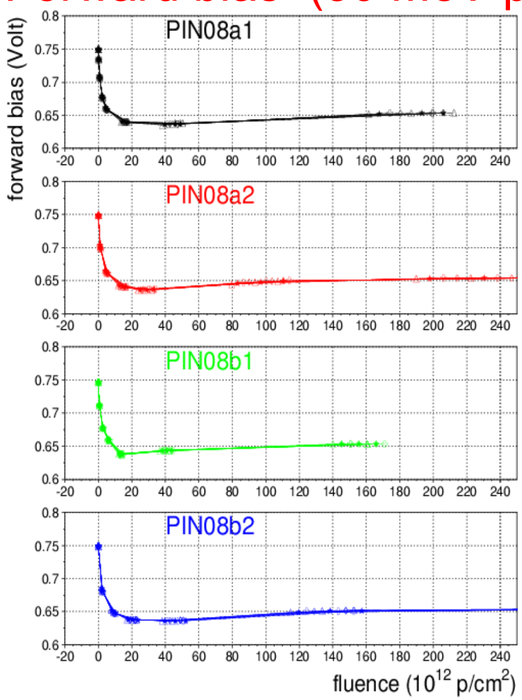
- Tohoku 30 MeV proton
- Control beam on/off
  LED light on/off
- Online PIN V_R scan

ATLAS Truelight Epi Si PIN



beam on, *beam off*

Forward bias (30 MeV p)



Each strip is a 0-20V scan

Beam off: + LED on + LED off

Beam on: + LED on + LED off

Quick recovery
expelling dark current

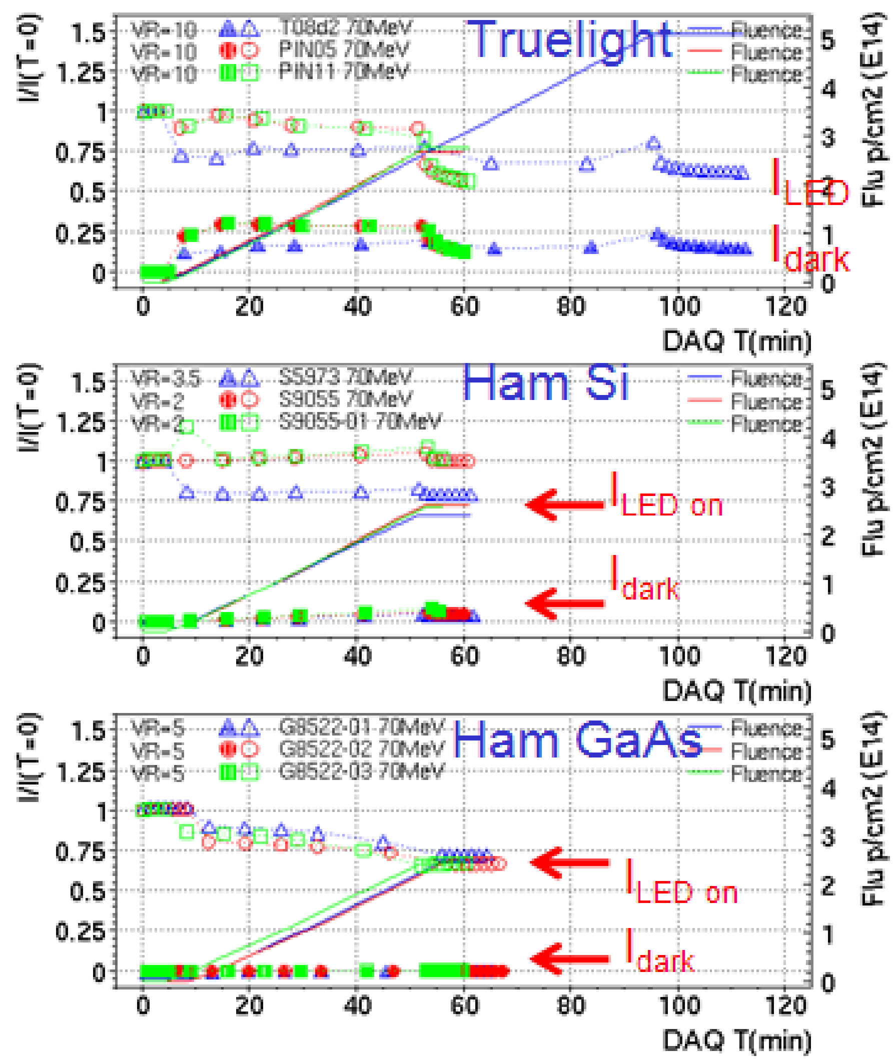
PIN proton damage, summary

Degradation of responsivity (I/L) proton 2E14

	V_R	fc	diam.	I/L	30 MeV		70 MeV	
	Vol	GHz	µm	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

- 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

70 MeV proton

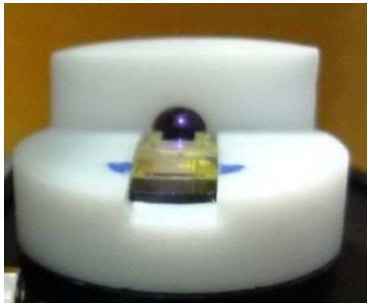


Radiation hardness of commercial devices

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

Rad-hardness of USB Optical Engine light-coupling material

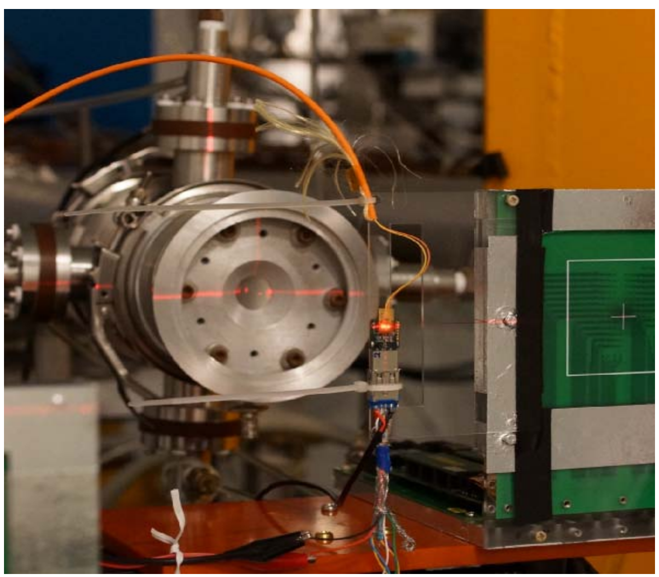
- **Light coupling prism receptacle**
  Material: PEI (polyetherimide), as for the TOSA/ROSA tip
  optical quality surface
- **Co^{60} gamma ray, Total-Ionizing-Dose**
  at INER Taiwan
  flux: 3.5 kGy/hr, total: **117 kGy**
  ➔ NO LOSS !!
  for light transmission
  within the 2% systematic error

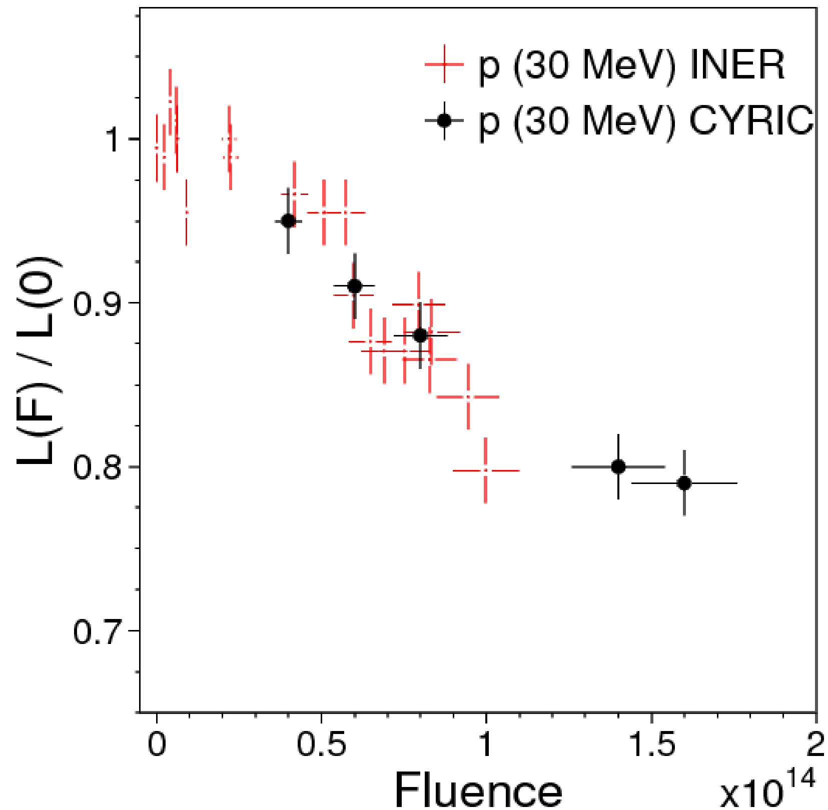


Proton to VCSEL, Optical IC

- **Proton Irradiation**
  INER 30 MeV proton beam
  flux of 3.5×10^{10} p/cm^{2}s, to a total $\mathbf{1.2 \times 10^{14}}$
  equivalent to $\mathbf{8.9 \times 10^{14}}$ n(1MeV)/cm^{2}s

- **Irradiation measurement**
  FOCI module DC biased
  VCSEL mid-level DC light





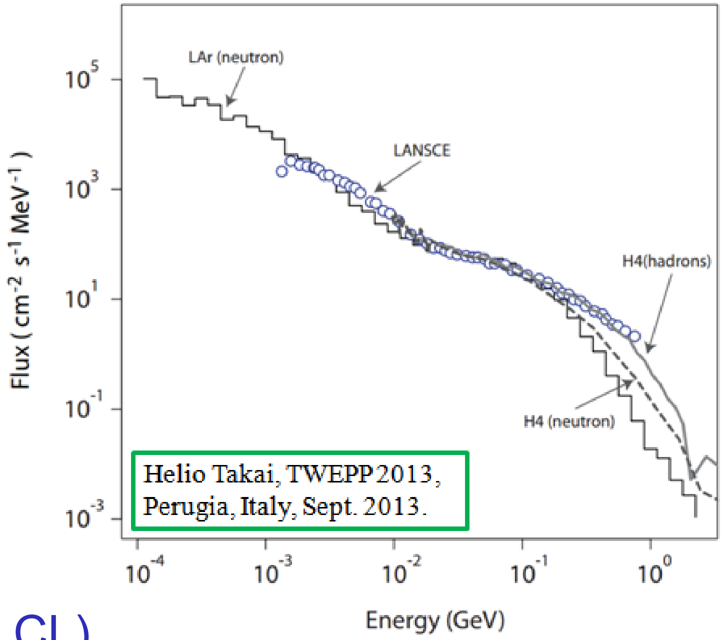
LANSCE neutron test

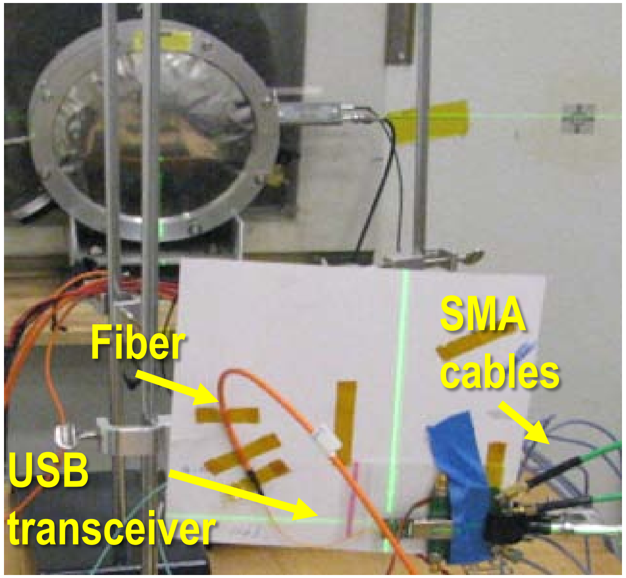
- Beam profile similar to ATLAS
- **USB transceiver in Bit-Err-Rate**
  Straitix II GX, PRBS 2^7-1 bit pattern
  TX path, RX path tested separately

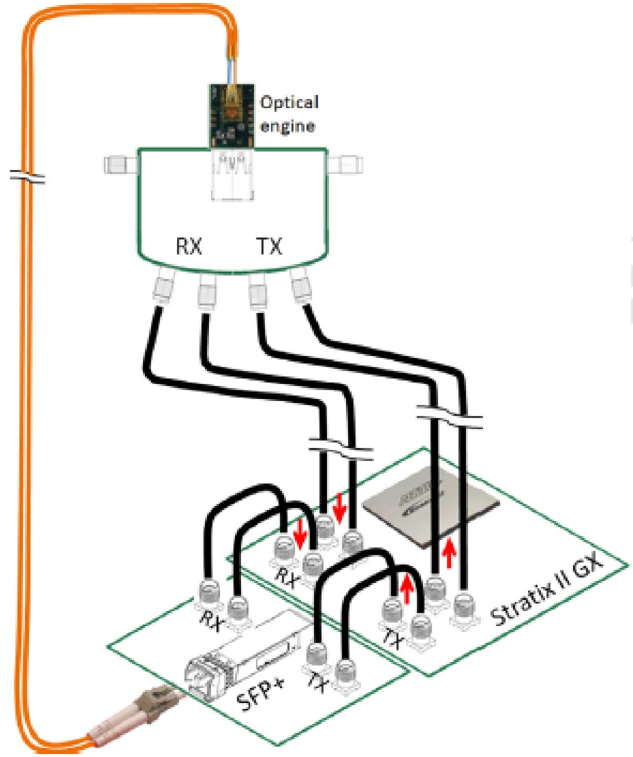
  neutron flux 2.9×10^5 n/cm^{2}s
  over 1.5 days to 3.8×10^{10} n/cm^2

  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



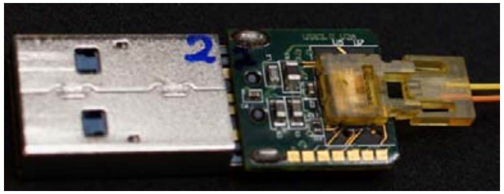


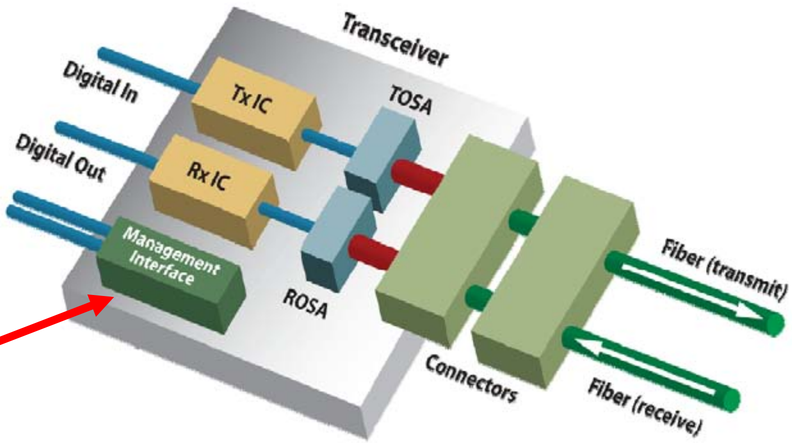


Rad-hardness of Transceiver IC

- Sub micron CMOS process is rad-hard
- Avoid vulnerable components

- USB optical chip runs well under irradiation
  power-cycle failed initialization
  ➔ OTP (one-time programmable memory corrupted)





Configuration corrupted after irradiation

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/cm^2/s)	Fluence (n/cm^2)	# errors	σ (cm^2)
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

SMU, TWEPP2012

Summary

- Fiber-optics advancing rapidly for IT industry
  - ➔ New commercial devices are compact and faster
  - ➔ Rad-hard drivers to be developed HEP applications
  - ➔ Quality Control, Rad-hard tests for lifetime assurance