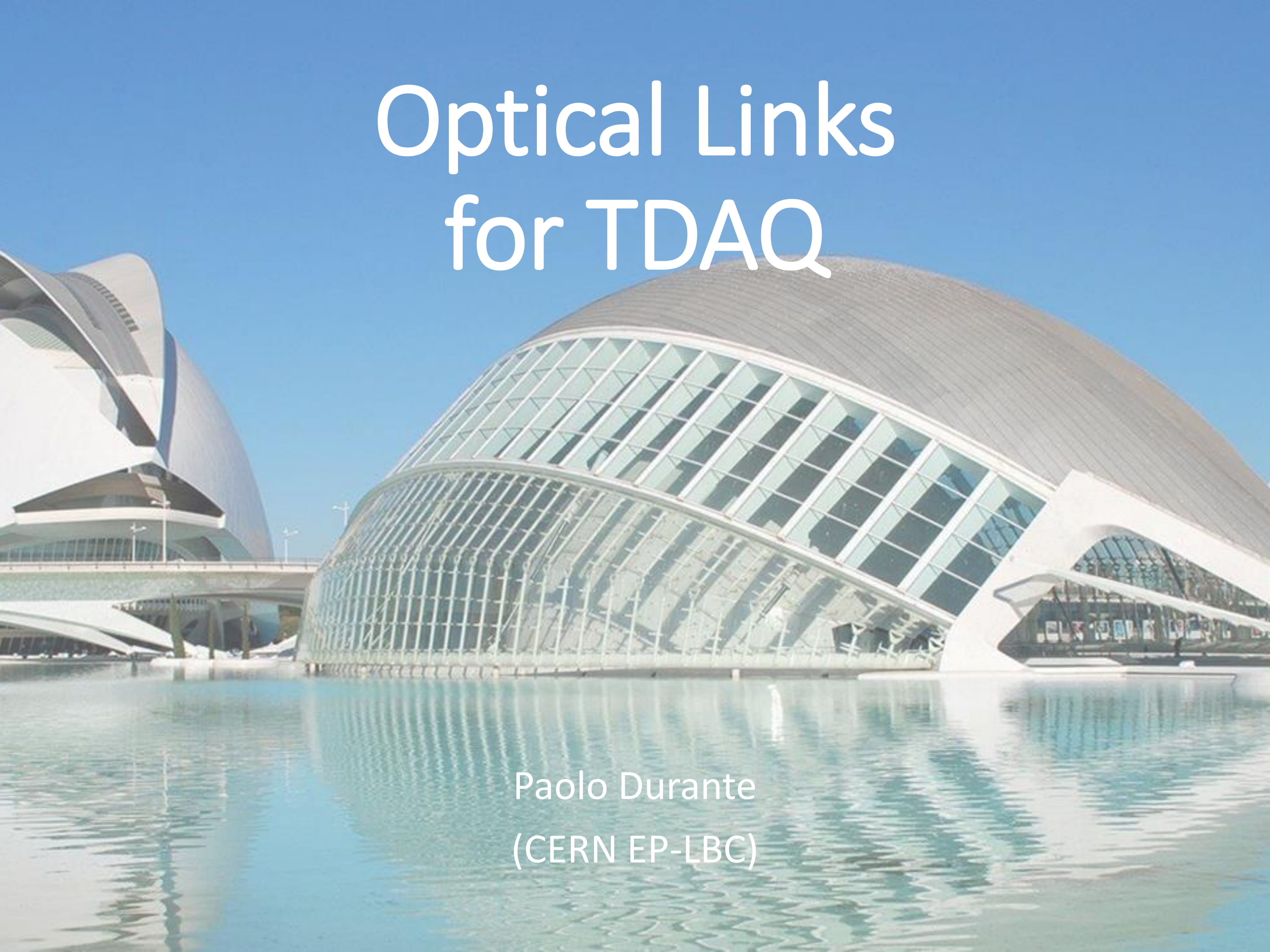
# Optical Links for TDAQ



Paolo Durante
(CERN EP-LBC)

# Outline

- Fundamental concepts
- Electro-optical assemblies
- Applications
  - CERN Versatile Link / Versatile Link PLUS
- Installation / Commissioning

# Safety first!

- Class 1
  - Safe
- Class 1M
  - Safe if not magnified
- Class 2
  - Safe if you blink!
    (e.g. laser pointers)
- Class 2M
  - As 2M, if not magnified
- Class 3R
  - Low risk, be careful (typical tx)
- Class 3B
  - Do not look directly (CD, DVD)
- Class 4
  - Permanent eye damage (cutter)

# Why optical fibers (vs. copper)

**PROs**

- Cheap material (silica)
- High rates (Tb/s)
- Low weight
- Long range (1000s Km)
- No interference
- Improving technology

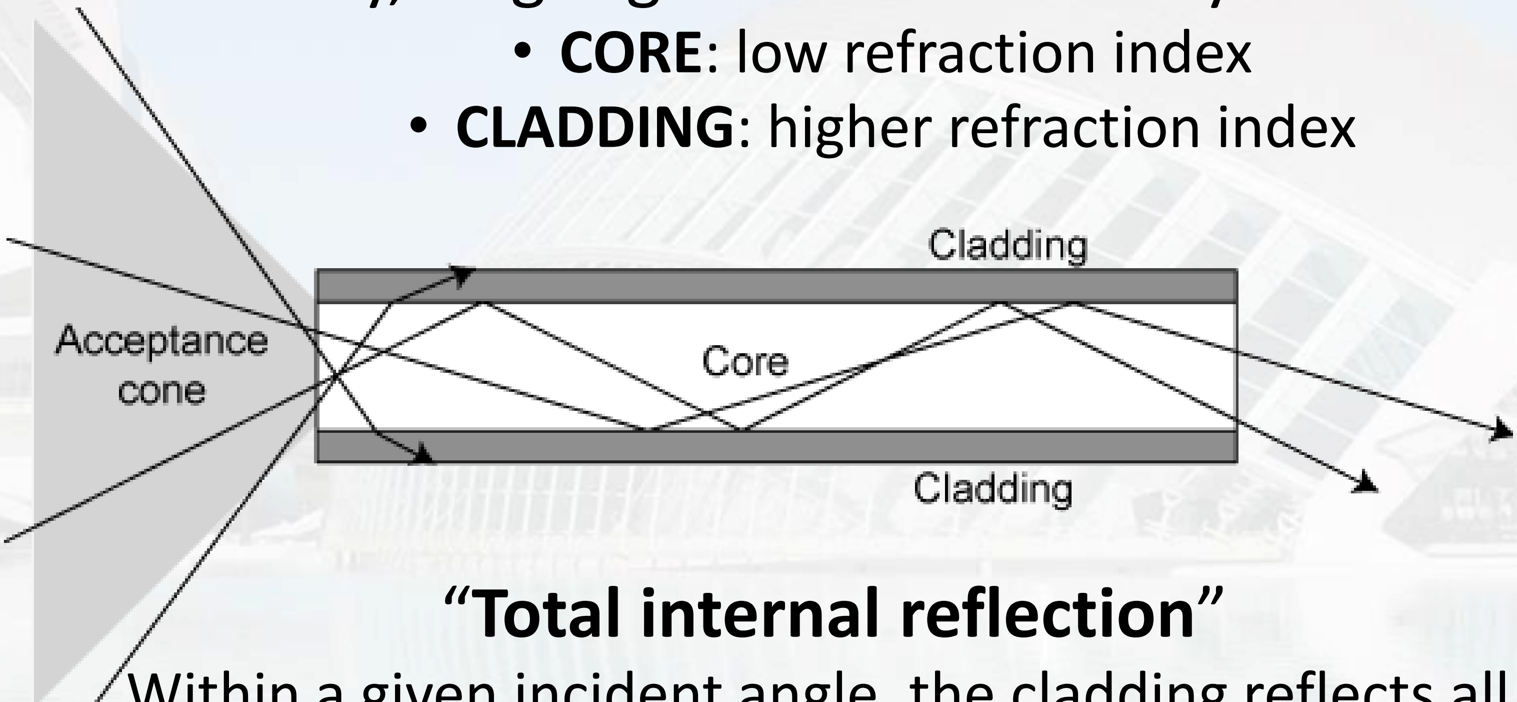
**CONs**

- Expensive technology
- System complexity
- Mechanical fragility
- Installation complexity
- Termination complexity

# How optical fibers work

Essentially, a light guide with a two layer structure

- **CORE**: low refraction index
- **CLADDING**: higher refraction index

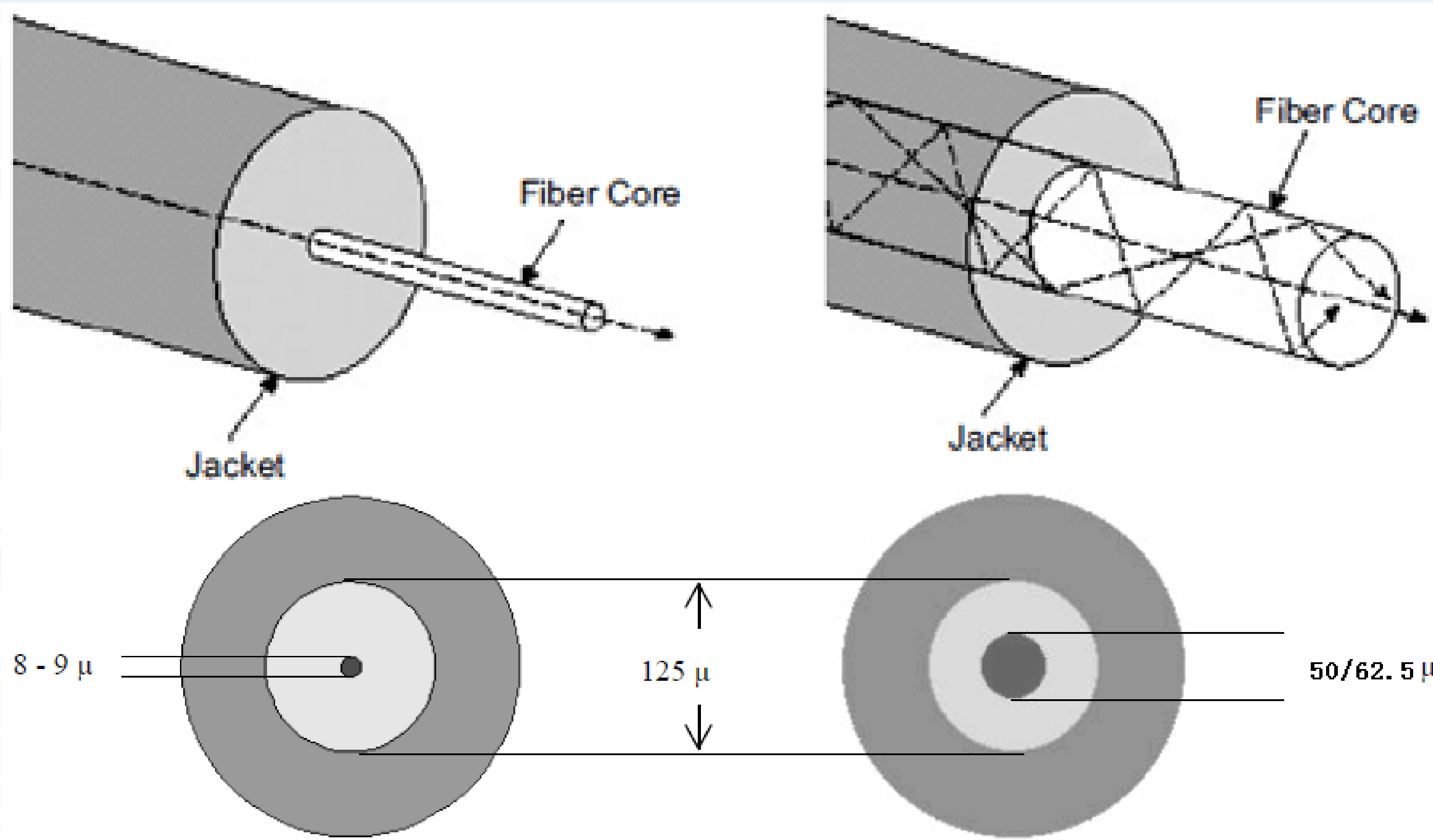



“**Total internal reflection**”

Within a given incident angle, the cladding reflects all light back into the core

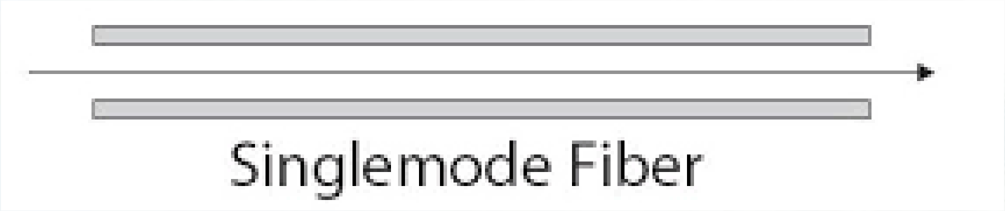
# “Single-Mode” vs. “Multi-Mode”

**Single-Mode Fiber (SMF)** **Multi-Mode Fiber (MMF)**



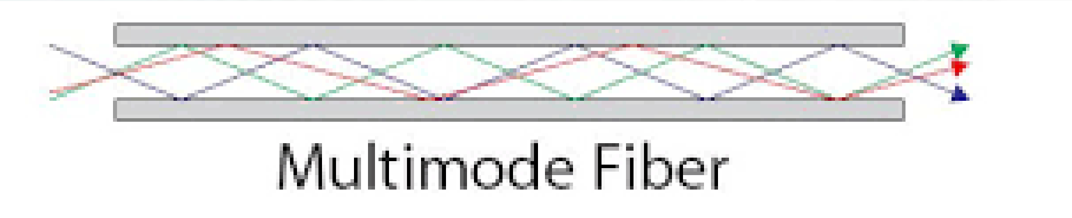
# Single-Mode fiber (SMF)

- Smaller core diameter (8-10 µm)
- Higher bandwidth and longer range
- No “modal dispersion”
  - ~80 Km unamplified
  - 1000s of Km amplified
- Very expensive and precise laser transmitters

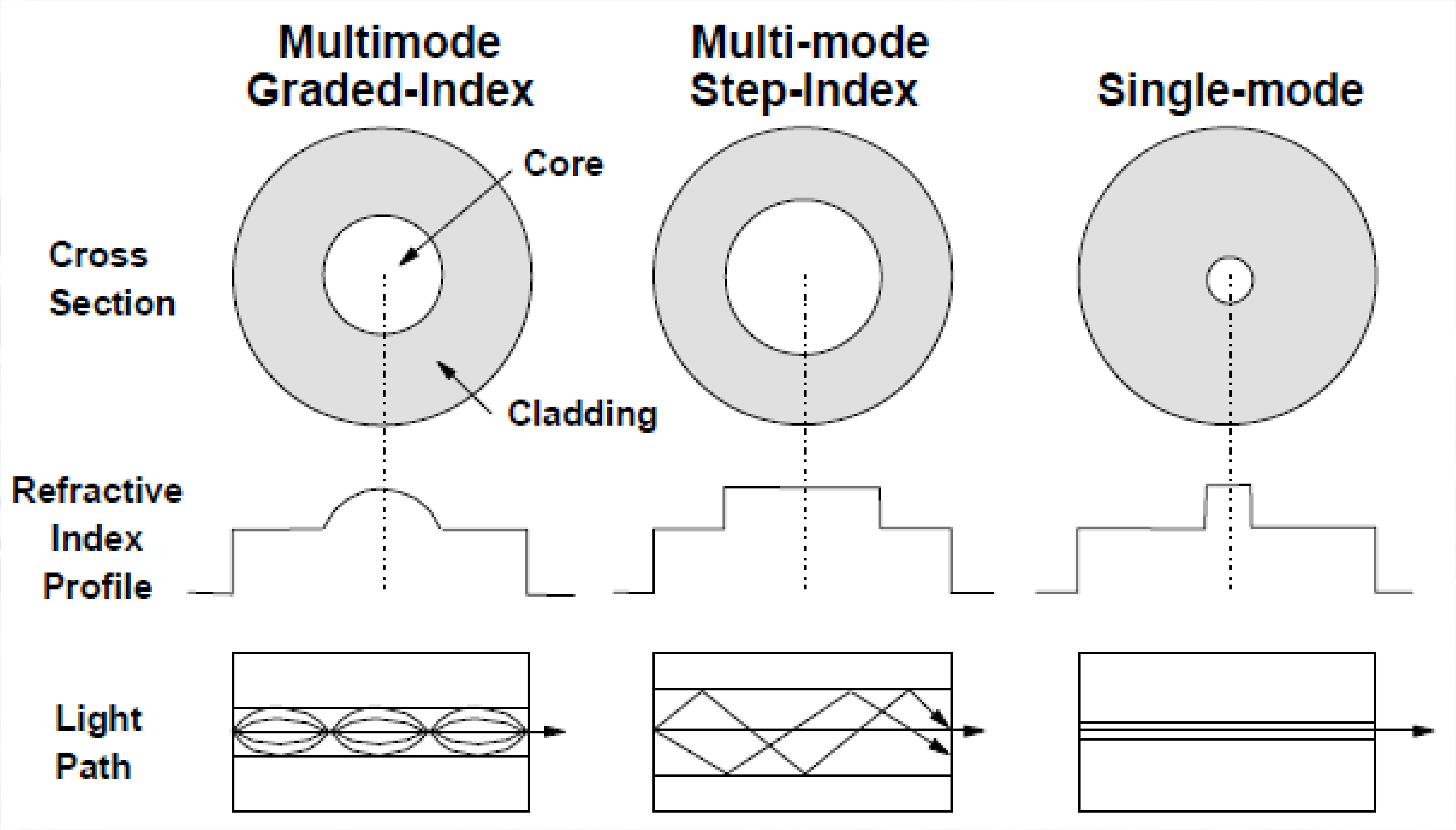


# Multi-Mode Fiber (MMF)

- Much wider core (~50 µm)
- Much more forgiving wrt light quality & alignment
- Attenuation influenced by “modal dispersion”
  - Multiple propagation modes allowed in the light guide
  - Range limited to hundreds of meters
  - Less on graded-index wrt step-index fibers
- Light sources are considerably cheaper



# Graded-index vs. Step-index fiber



# OM3 vs. OM4


**OM3**

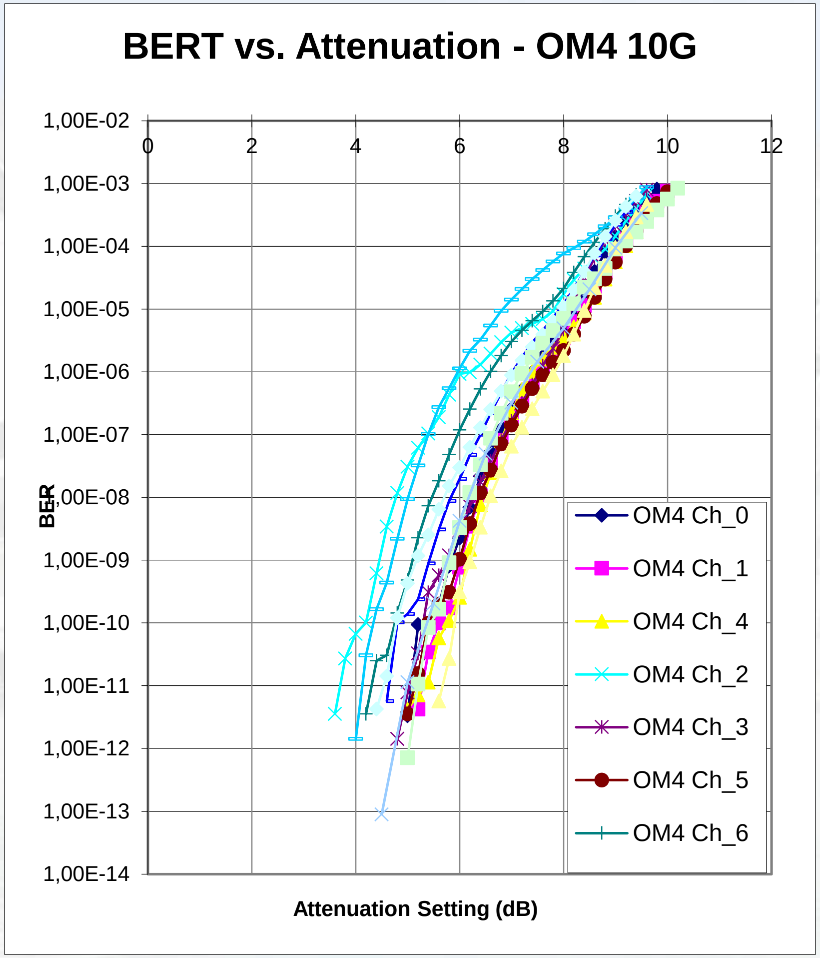
- <3.5 dB/Km @850nm
- EMB: 2000 MHz x km
- 1000m @1 Gb/s
- 300m @10 Gb/s
- 100m @100 Gb/s

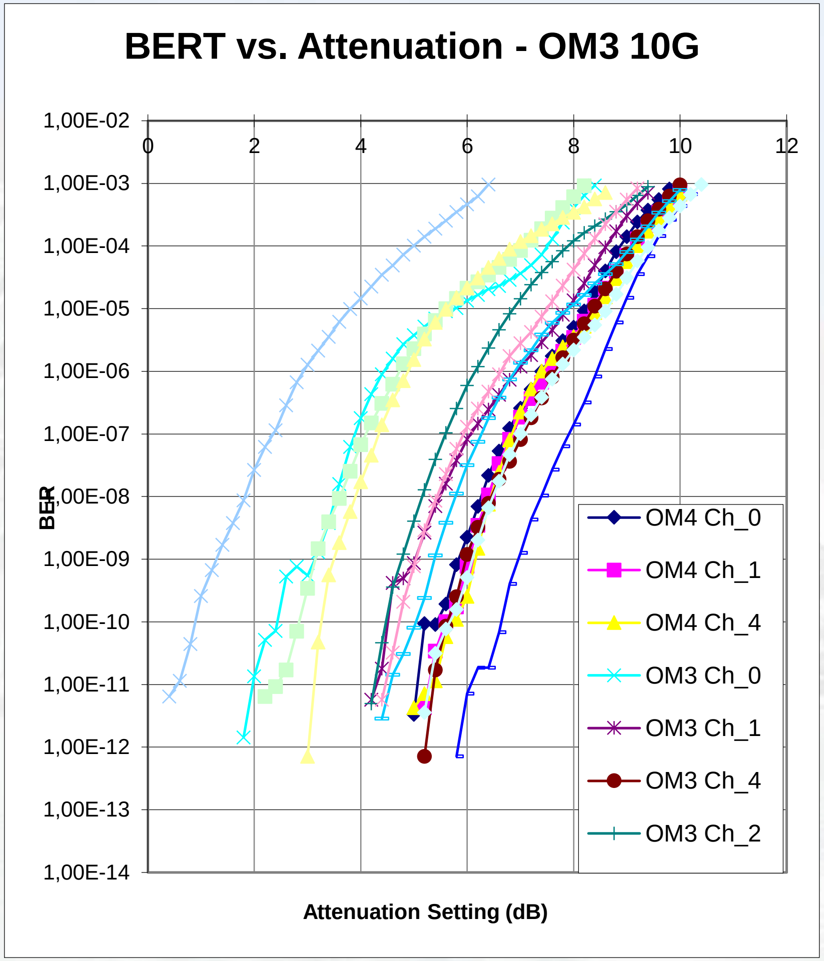
**OM4**

- <3.0 dB/Km @850nm
- EMB: 4700 MHz x km
- 1000m @ 1 Gb/s
- 500m @ 10 Gb/s
- 150m @ 100 Gb/s
- Higher cost

EMB = Effective Modal Bandwidth = max data rate at a given distance (constant)

# OM3 vs. OM4 Bit Error Ratio (BER)

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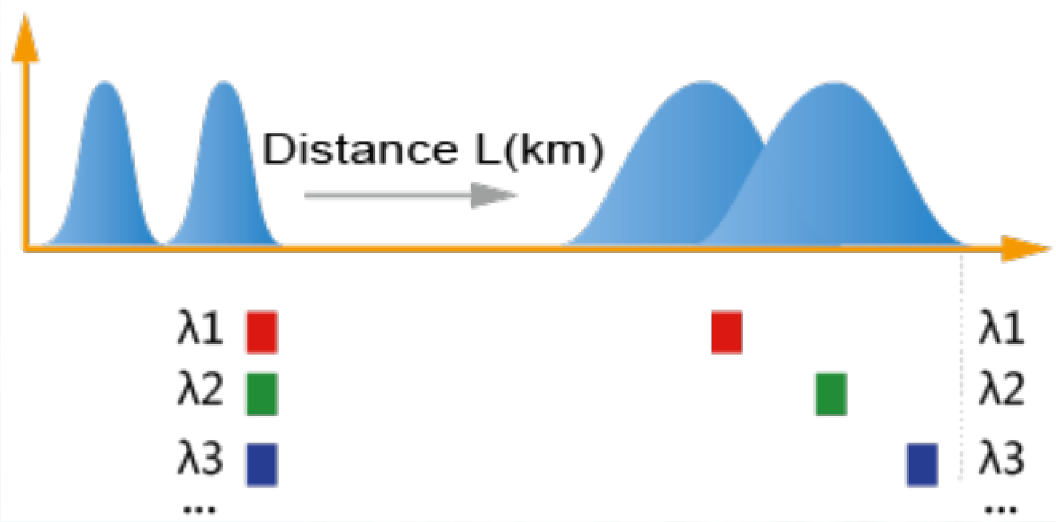
Ethernet: BER < $10^{-12}$

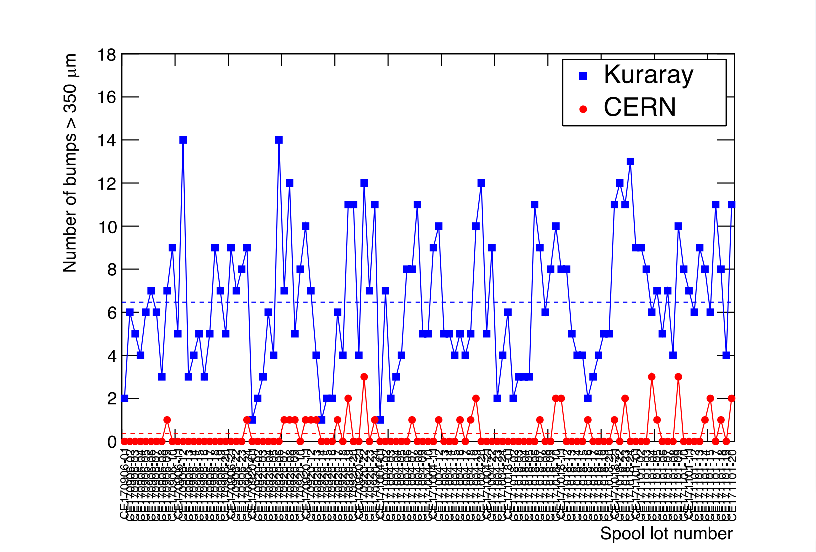
# Chromatic Mode Dispersion (CMD)

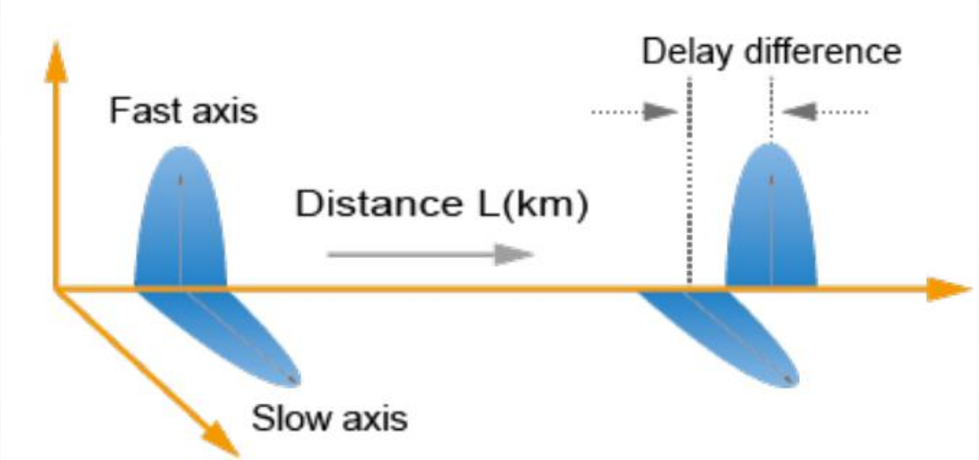
- Dispersion spreads out pulse shapes
- Different wavelengths (colors) propagate in a non vacuum at different speeds
- CMD is worse at higher data rates ($f^2$)



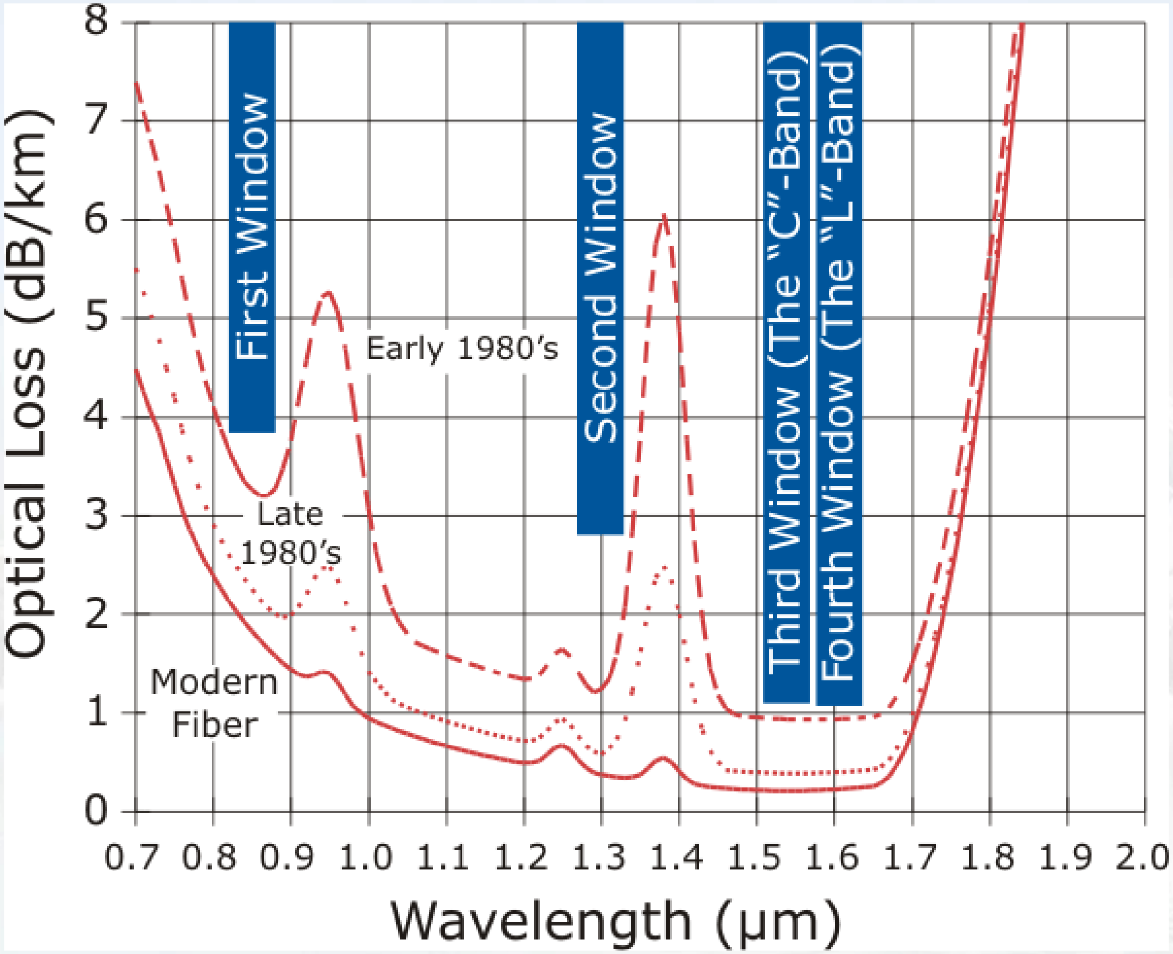
# Polarization Mode Dispersion (PMD)

- Real optical fibers are not perfectly cylindrical
- Light with different polarization propagates at different speeds



# Optical fiber transmission bands



# Optical fiber transmission bands

- "First Window" – 850 nm
  - Highest attenuation, "short range" (~100 m)
- "Second Window" – 1310 nm
  - "O-band", kilometer range
- "Third Window" – 1550 nm
  - "C-band", "Conventional band", long-reach DWDM
- "Fourth Window" – 1590 nm
  - "L-band", "Long band"

# Optical attenuation

- As light propagates in a fiber, its intensity decreases
  - Scattered by defects in the glass
  - Absorbed by impurities and converted to heat
- Attenuation is measured in “Decibels”
  - 1/10 = -10 dB
  - 1/100 = -20 dB
- Optical power often expressed in “dBm”
  - 0.5 mW = -3 dBm
  - 1 mW = 0 dBm
  - 2 mW = 3 dBm
  - 100 mW = 20dBm
- Combining losses/gains expressed in dB = addition

# Other causes for attenuation

- Insertion loss
- Return loss
- Bending loss
- Dirt
- Radiation induced “darkening”

# Insertion loss

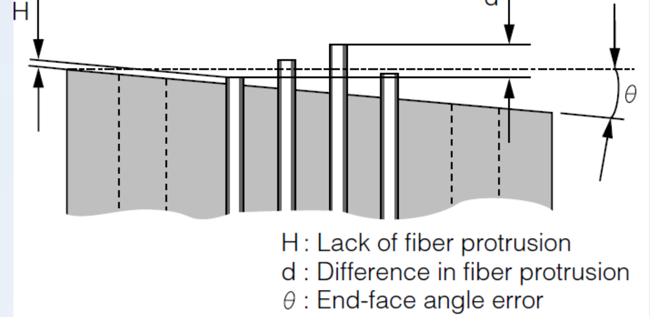
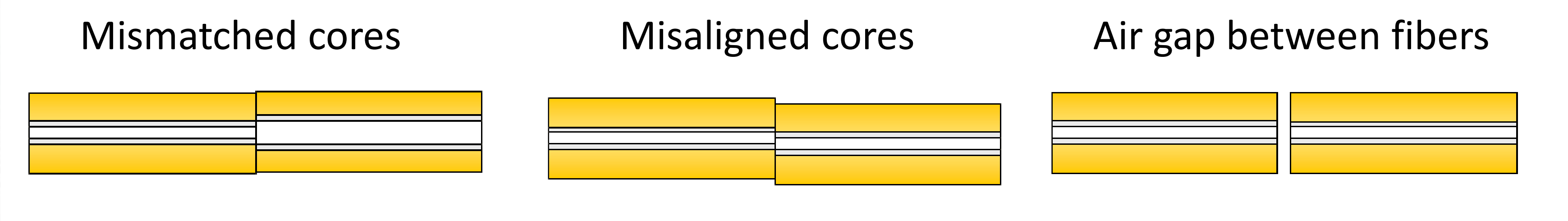
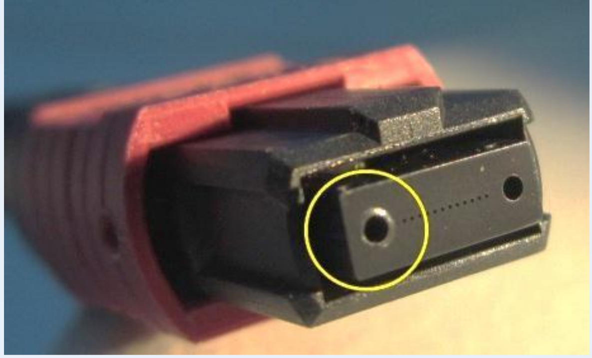


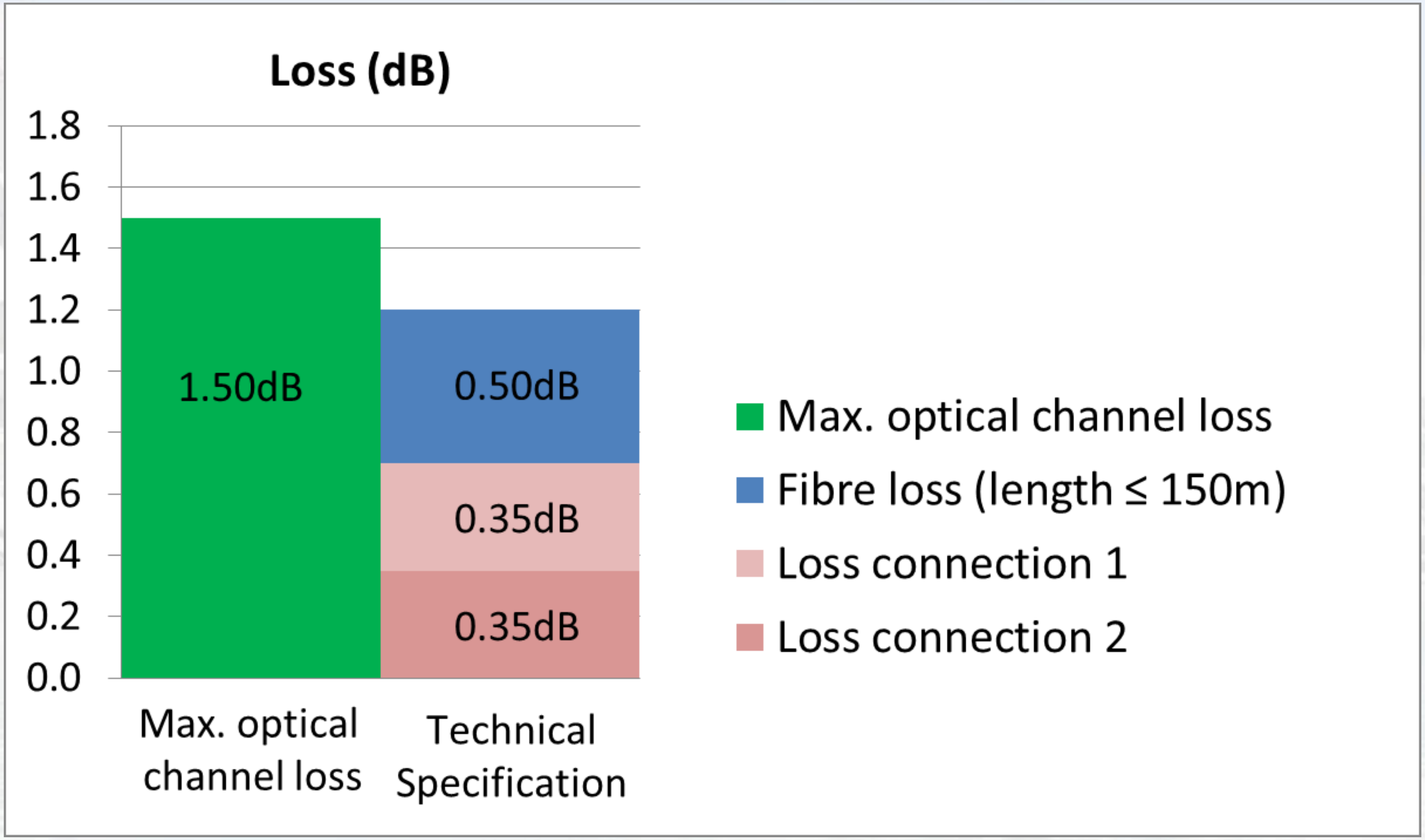

Fig. 9. Factors Affecting Physical Contact.

- Number and quality of connectors and splices
- Standard < 0.60 dB (typ. 0.20 dB)
- «Elite» < 0.35 dB (typ. 0.10 dB)
- 40G OM3: 1.5dB total connector loss budget
- 40G OM4: 1.0dB total connector loss budget



# Connector loss budget

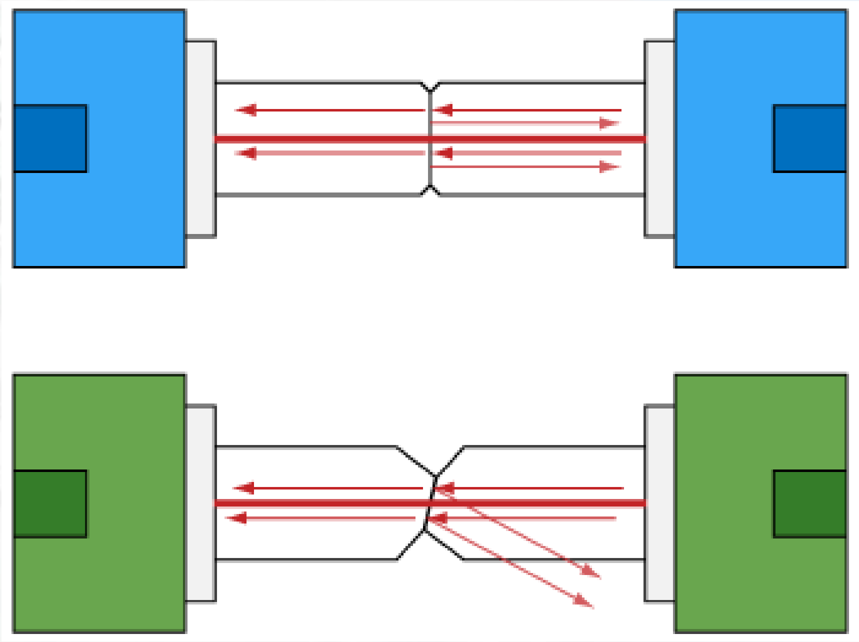




$$\mathrm{ORL(dB)} = 10\log_{10}\frac{P_\mathrm{i}}{P_\mathrm{r}}$$

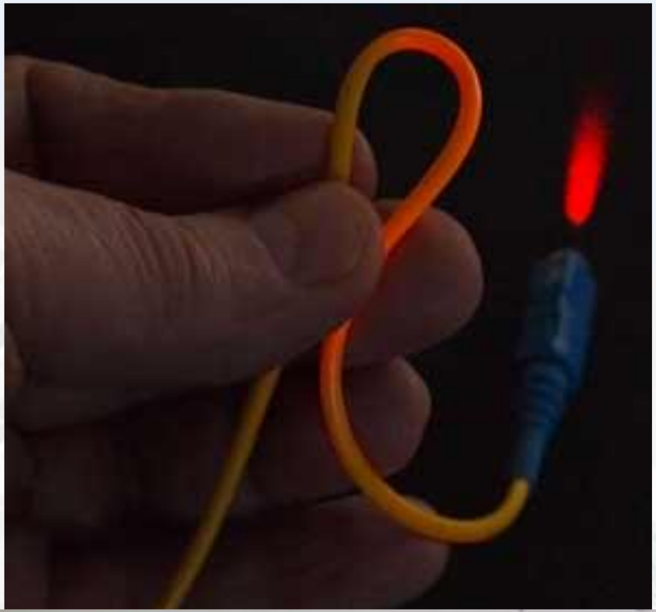
# Return loss

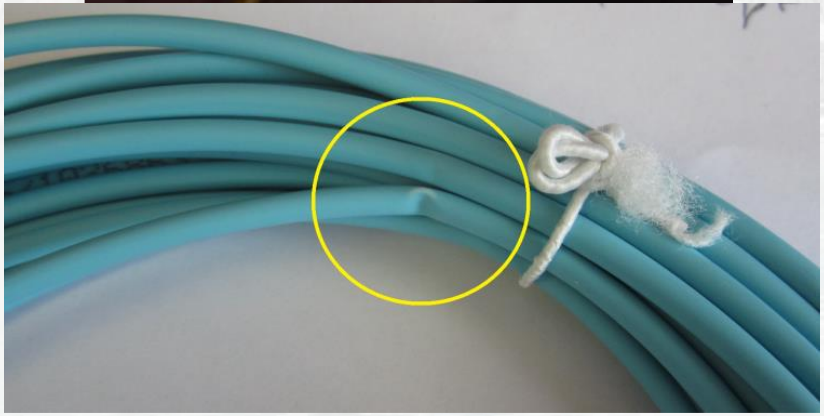
- Incident / reflected power [dB]
- (Ultra) Physical Contact (UPC) blue
  - (< -30 dB) < -55 dB ORL
- Angled Physical Contact (APC) green
  - 8° angle
  - < -65 dB ORL
  - For high-power emitters
- Are incompatible!



# Bending loss

- Total internal reflection depends on critical angle
- Small bend radius causes light leaks
- Bend-insensitive fibers exist
  - Higher *n* cladding
  - Short range (patch panels)
- Don’t kink!

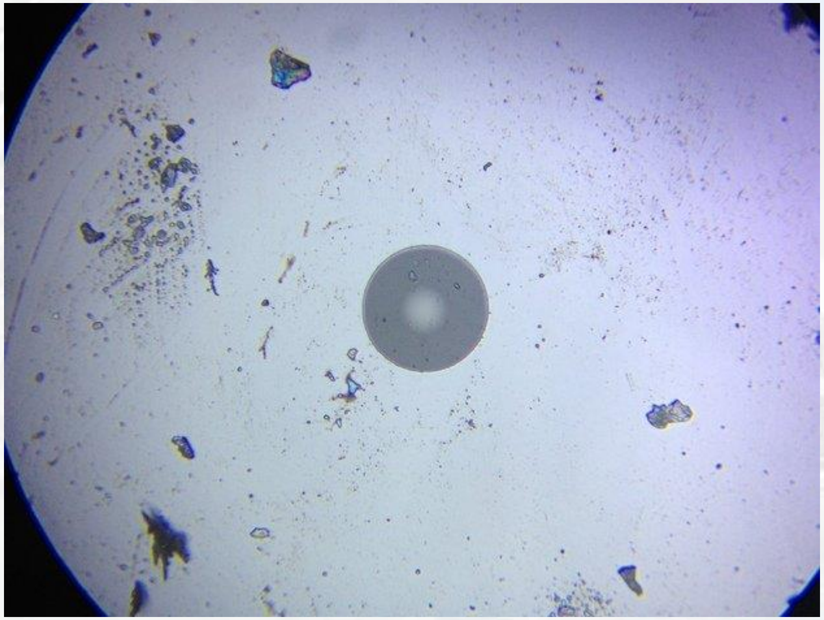




# Dirt induced loss

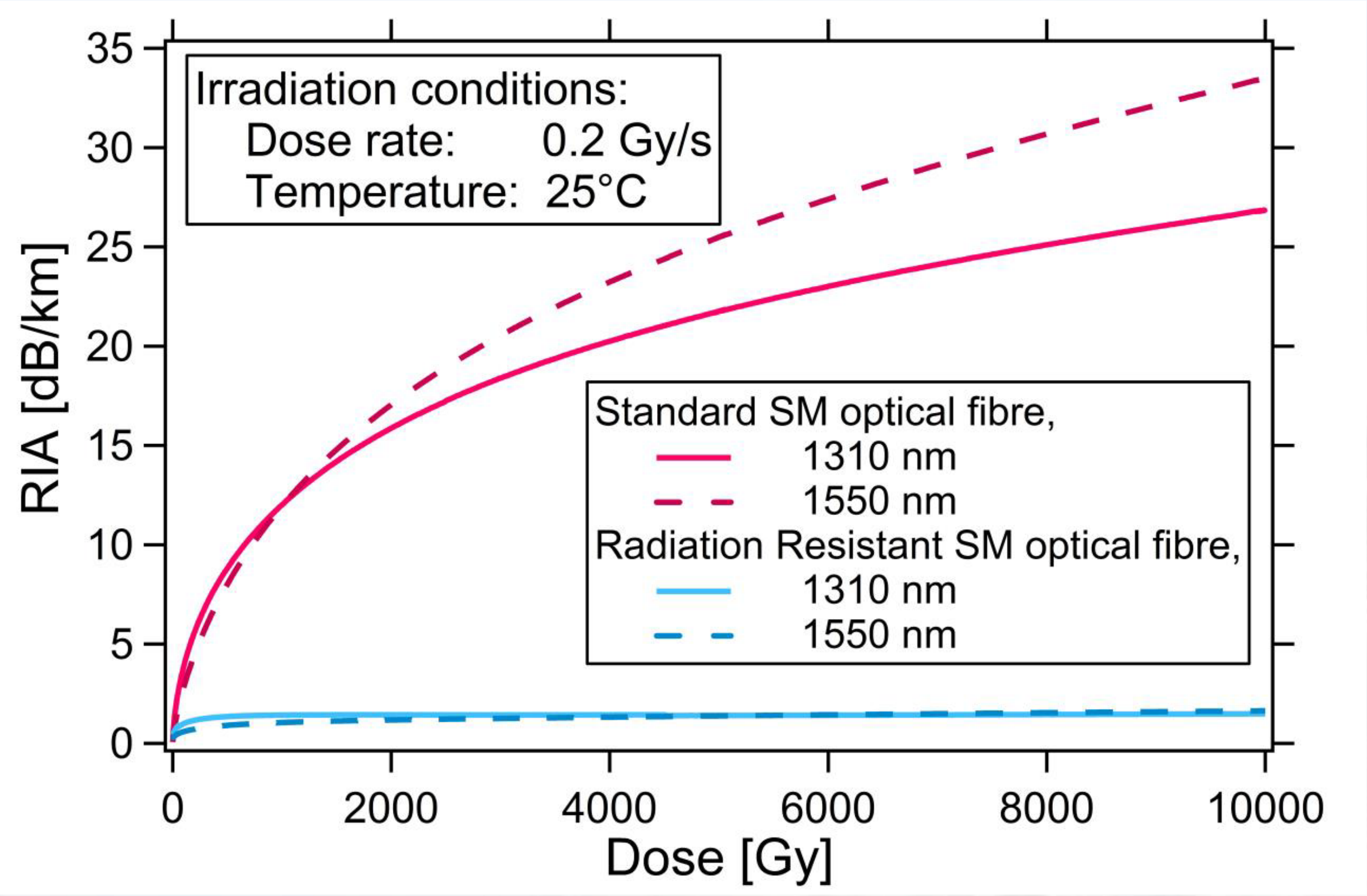
- A µm speck of dust can completely (or partially) cover the core
- Insertion force can dent the optical interface
- Don’t leave fibers exposed
- Clean **both sides** before mating
  - Cleaning cassettes
  - Insertable tape rolls

# Optical fiber visual inspection



# Radiation induced loss

Use rad-hard fibers with special doping and manufacturing processes



# Other definitions

- Transmitter launch power
  - dBm power @ λ
- Optical Modulation Amplitude (OMA)
  - $\mathrm{OMA} = P_1 - P_0$
- Extinction ratio
  - $r_e = \frac{P_1}{P_0}$
- Receiver sensitivity
  - Min. received power @ BER target
- Dynamic range
  - (Worst-case max input power - Sensitivity)

# Outline

- Fundamental concepts
- **Electro-optical assemblies**
- Applications
  - CERN Versatile Link / Versatile Link PLUS
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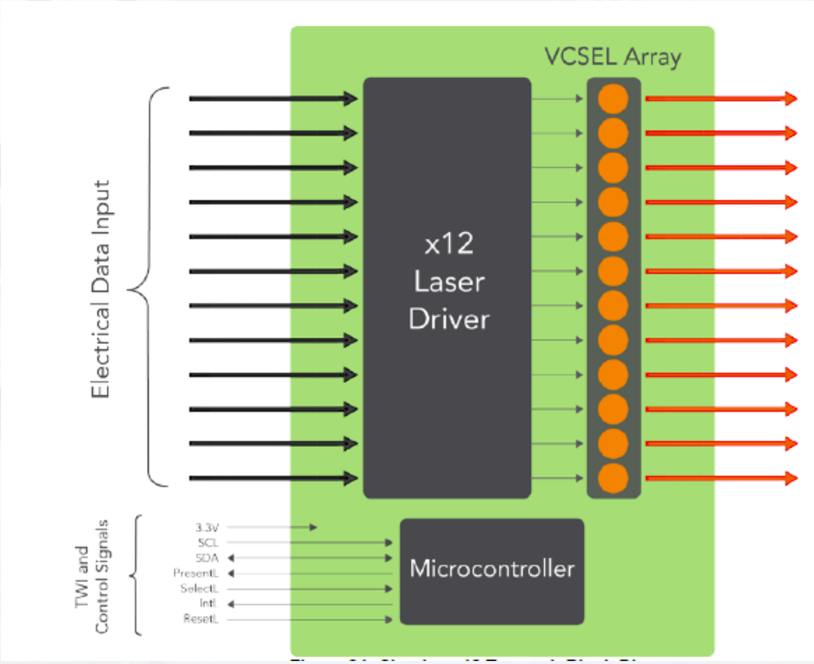
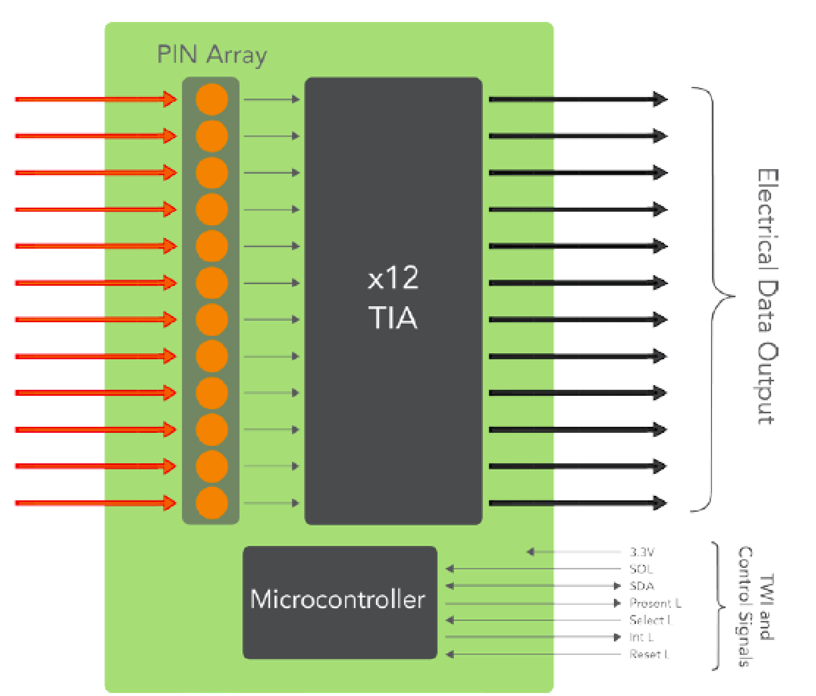
# Vertical-Cavity Surface-Emitting Laser (VCSEL)

**Tx**

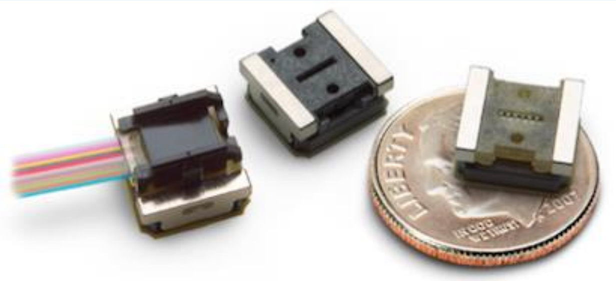


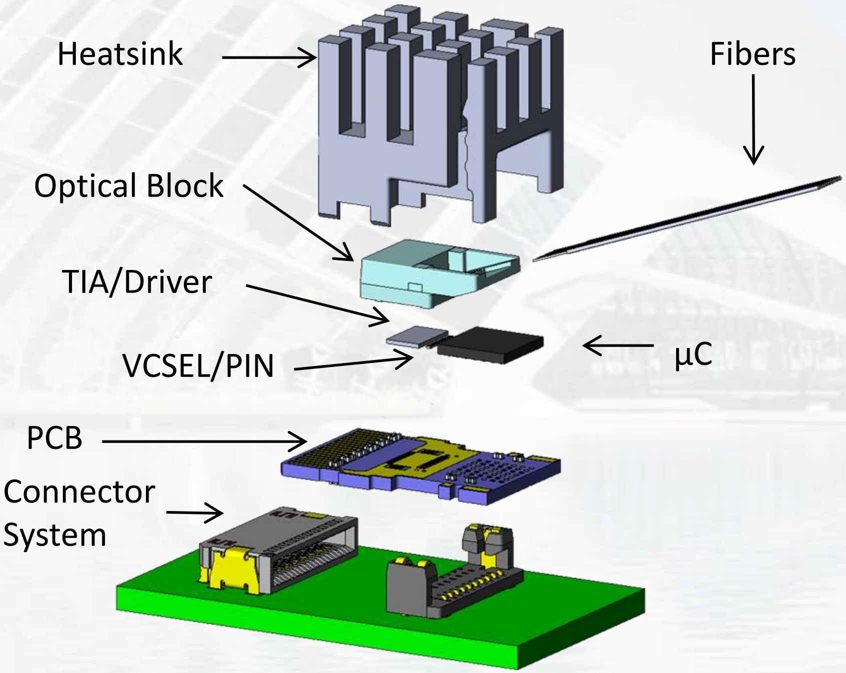

**Rx**



# VCSEL optical engine assembly

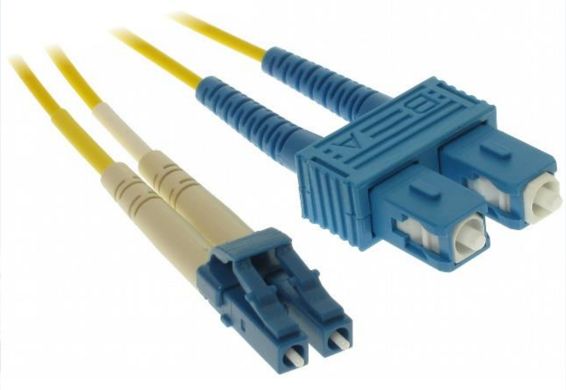
- Can be integrated with other circuitry
- Can be packed in dense 1D and 2D arrays
- Can be tested pre-dicing
- High quantum efficiency -> low power
- Good optical coupling via MO interfaces (e.g. PRIZM® LightTurn®)

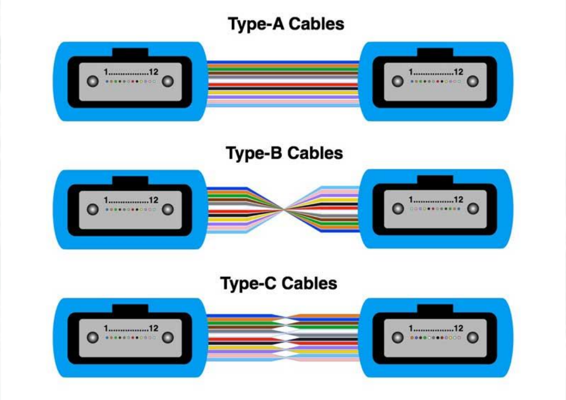


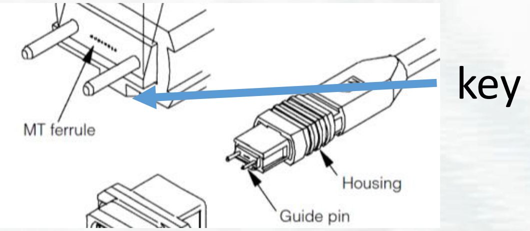


# Optical connector assemblies

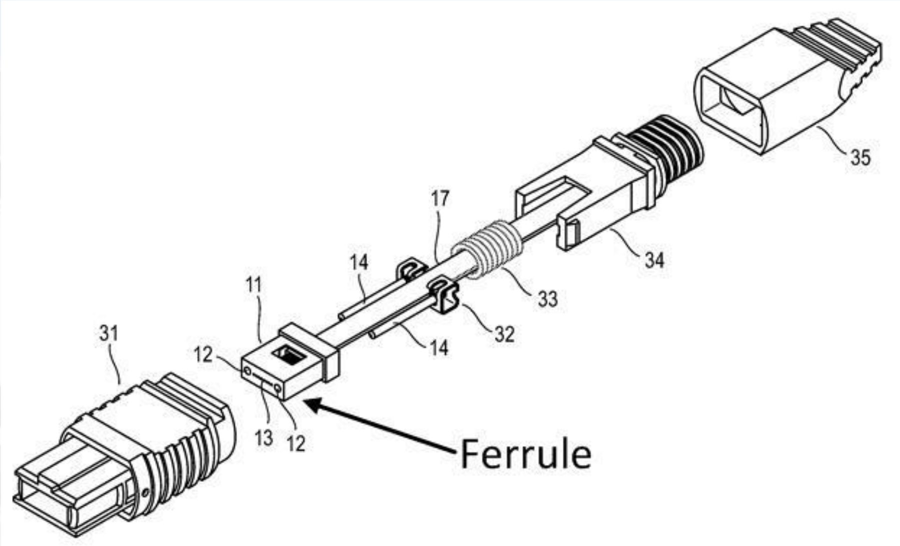
- Form factors
  - SC (x1, x2, obsolete)
  - LC (x1, x2)
  - MPO (x12, x24, x48)
  - MTP (high-quality MPO)
- Polarity
  - Straight (A)
  - Crossover (B)
  - Flipped-pairs (C)
- Gender
  - Male
  - Female

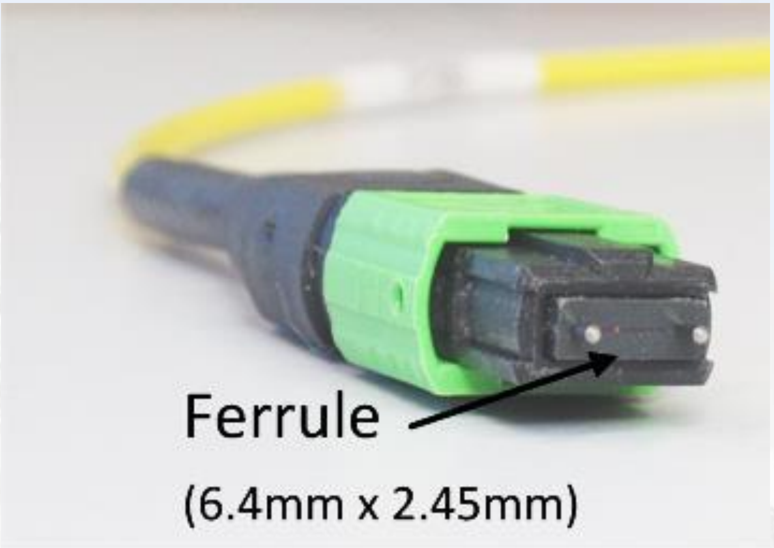


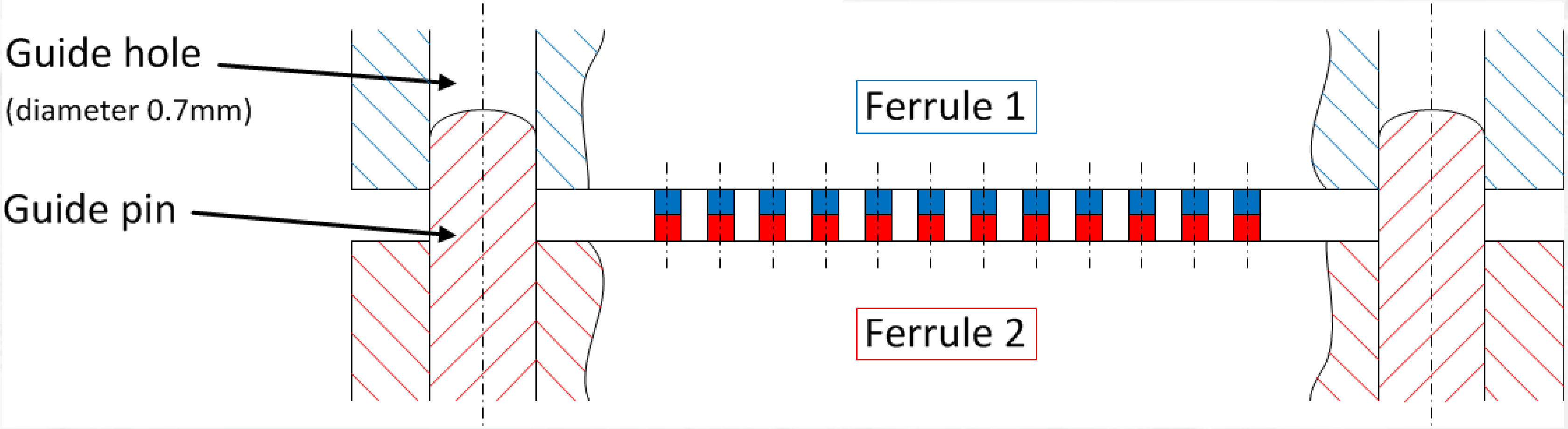


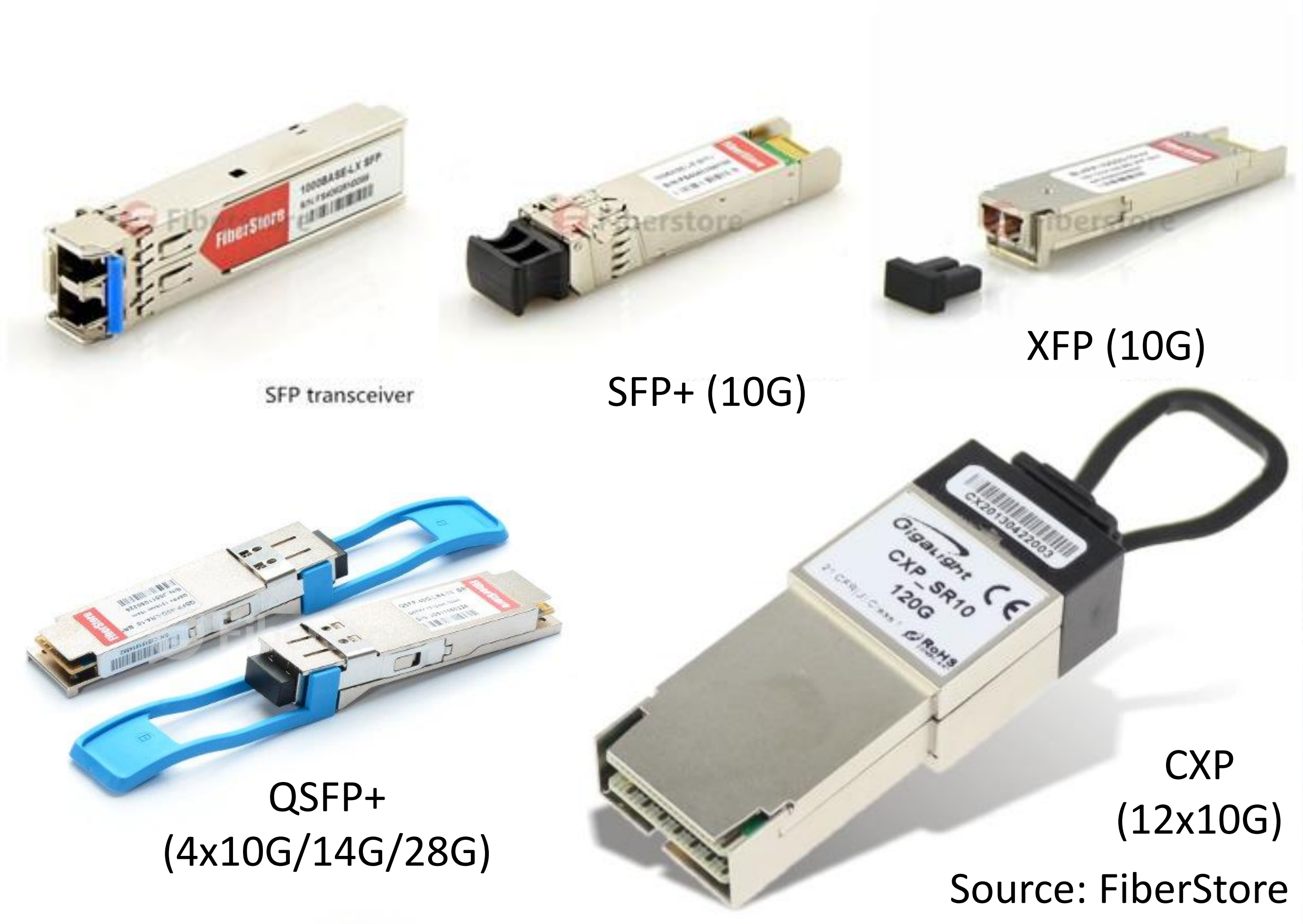

# MTP/MPO optical assembly



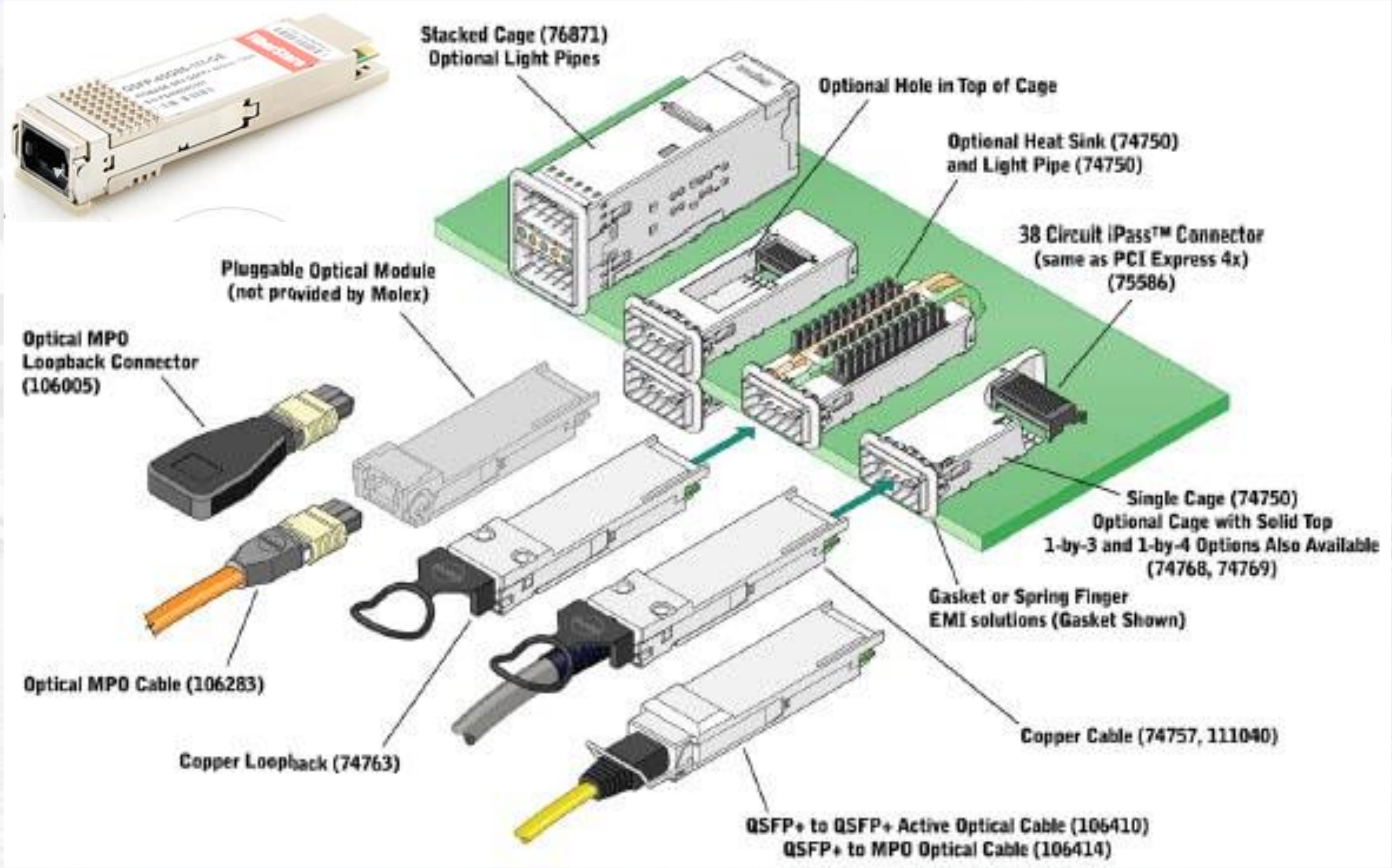
# Electro-optical form factors



# Quad Small Form-factor Pluggable

4x bidirectional connections at 10, 14 (“QSFP+”), 25 and 28G (QSFP28)

Next-generation networks might even need x8 connectivity (QSFP-DD)

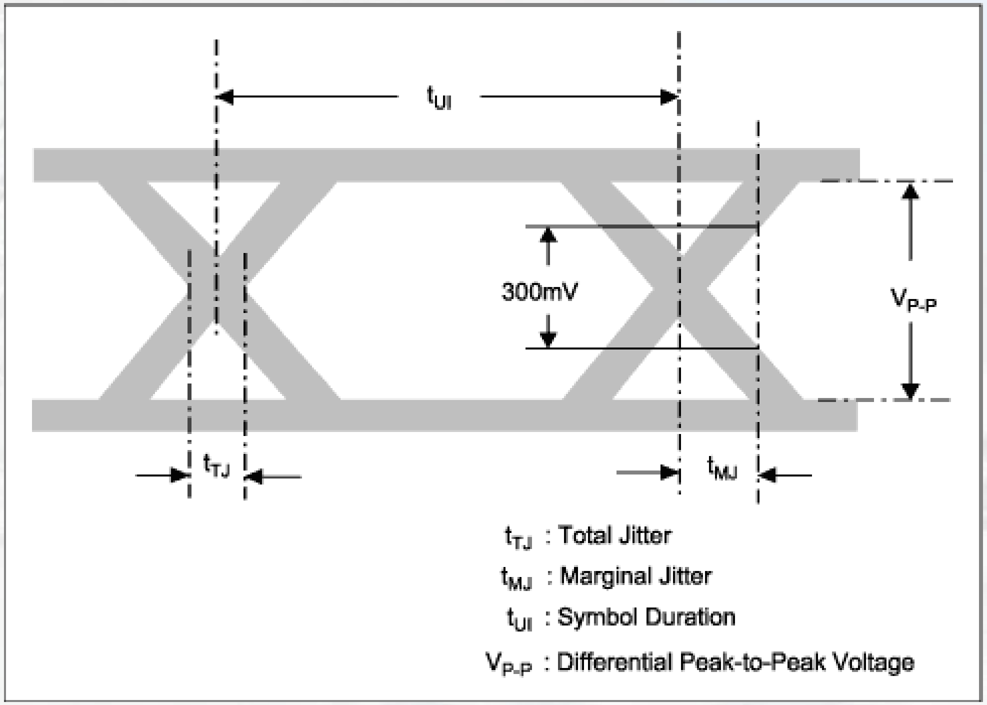


# Active Optical Cables (AOC)

- Great for point to point connections, when length is known in advance
- Handled (almost) like a copper cable, no optical connector or cleanliness related problems
- Cheaper than discrete optics
- Available in “Octopus” breakouts

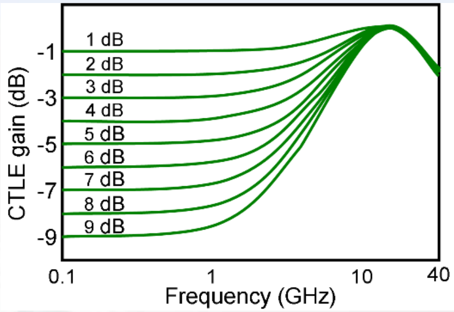
# Eye diagram

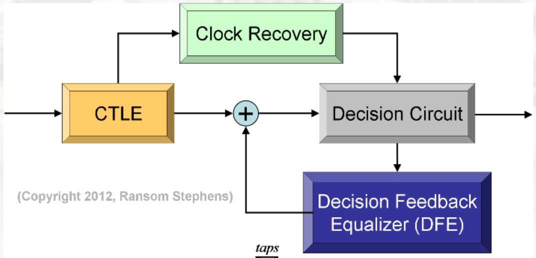
- I→V (trans-impedance amplifier)
- Superimpose all possible binary transitions
- Quickly quantify noise and inter-symbol interference (ISI) effects
- Many standards mandate minimal eye parameters



# Signal optimization techniques

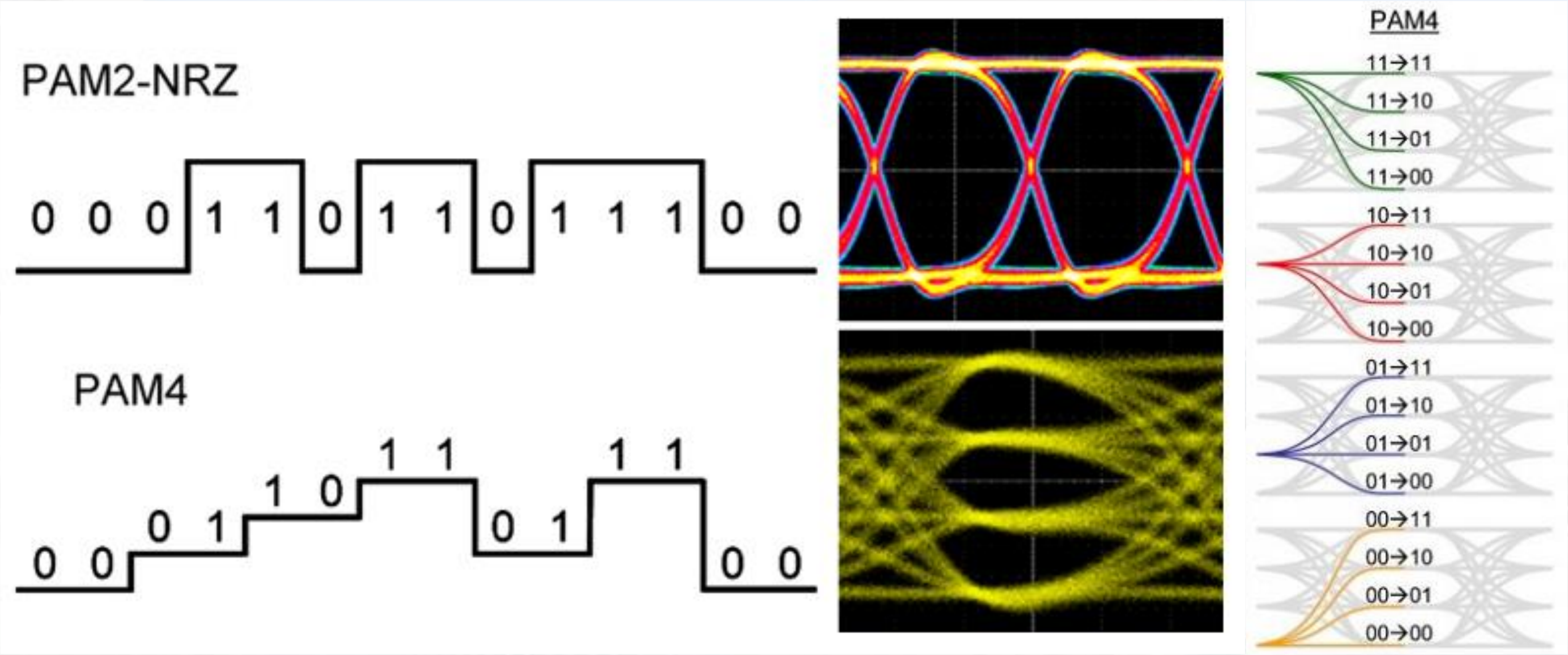
- Pre-emphasis (already used at 10G)
- Tx FFE (Feed Forward Equalization)
  - Emphasis of high-speed content to combat frequency dependent attenuation in channel
- Rx CTLE (Continuous Time Linear Equalization)
  - De-emphasizes low frequency, peak at Nyquist, filters off high frequency
- Rx CDR (Clock and Data recovery)
  - Used together with CTLE or other equalization
- Rx DFE (Decision Feedback Equalization)
  - Non-linear, feedback from decision circuit
  - Power hungry…
- PAM4 Modulation (56G and up)




$$\mathrm{DFE}(n) = \sum_{m=0}^{taps} c_m s(n - m - \tau)$$

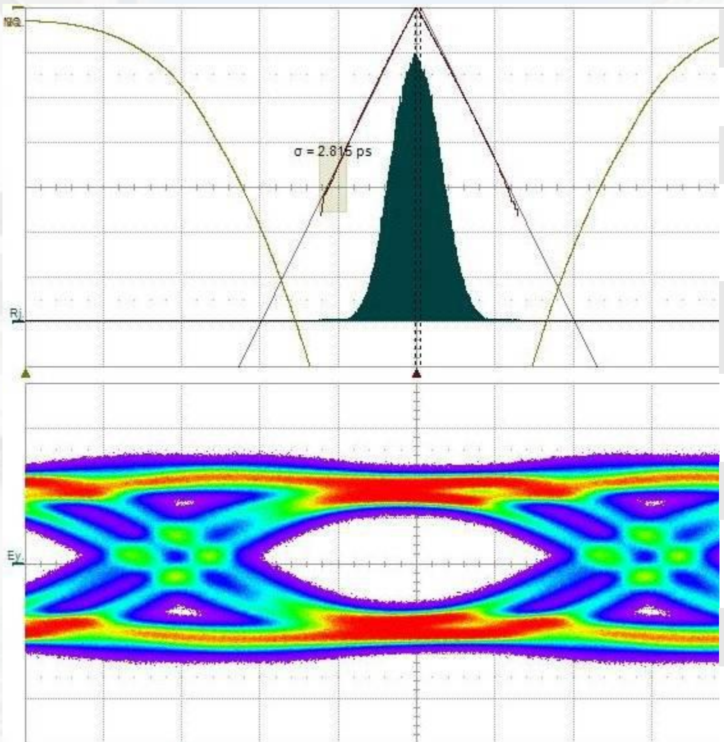
# Modulation: PAM2 vs. PAM4



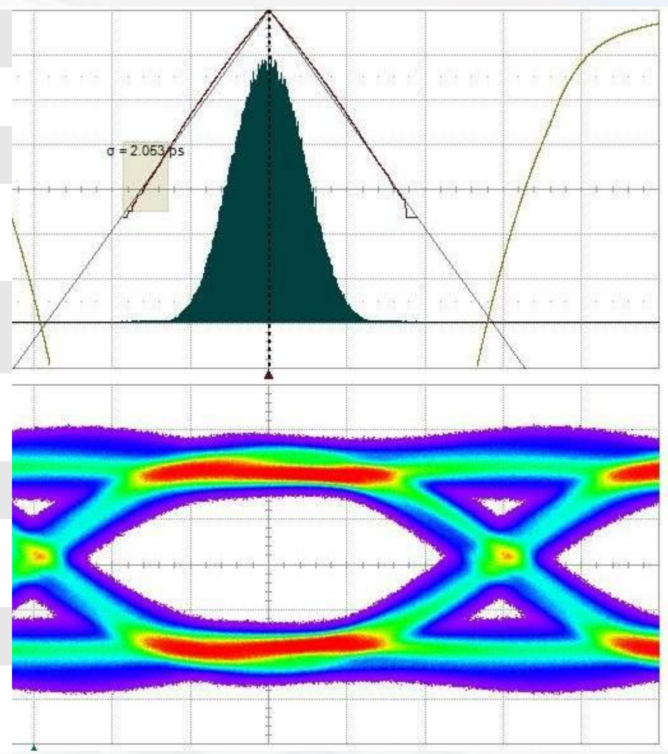
# Example: 10GBASE-R

**No de-emphasis nor equalization on optical drivers**

**With de-emphasis and equalization**




| Eye aperture | |
|---|---|
| 0.29 | 0.54 |
| BER | |
| $<10^{-15}$ | $<< 10^{-16}$ |
| Tot. jitter @ $10^{-12}$ | |
| 62.7ps | 39.3ps |
| Random jitter | |
| 3.13ps | 2.25ps |
| ISI | |
| 25.5ps | 13.6ps |




https://indico.cern.ch/event/297003/

# Physical layer naming (Ethernet)

e.g.: “10GBASE-R”

1. **Data rate:** *10*, *100*, *1000*, *10G*, *100G*…
2. **Signaling:** *base*(band), *broad*(band), *pass*(band)
3. **Medium:** *T* = twisted pair (copper), *S* = 850 nm short wavelength (multi-mode fiber), *L* = 1300 nm long wavelength (mostly single-mode fiber), *E or Z* = 1500 nm extra long wavelength (single-mode), *B* = bidirectional fiber (mostly single-mode) using WDM, *P* = passive optical (PON), …
4. **Encoding:** *X* = 8b/10b, *R* = 64b/66b, …

# Forward Error Correction (FEC)

- Insert "redundant" information before transmission
- Receiver can detect if errors occurred, and where
- Receiver can computationally fix errors, up to a design limit dependent on the algorithm
- 1st generation FEC (Reed-Solomon)
  - 6% overhead for ~6 dB BER gain
- 2nd generation FEC (EFEC)
  - 7% overhead for 8~9 dB BER gain
- 3rd generation FEC (SD-FEC)
  - 20-25% overhead for 10~11 dB BER gain
- FEC is now **mandatory** in most high speed standards, like 100GbE and beyond

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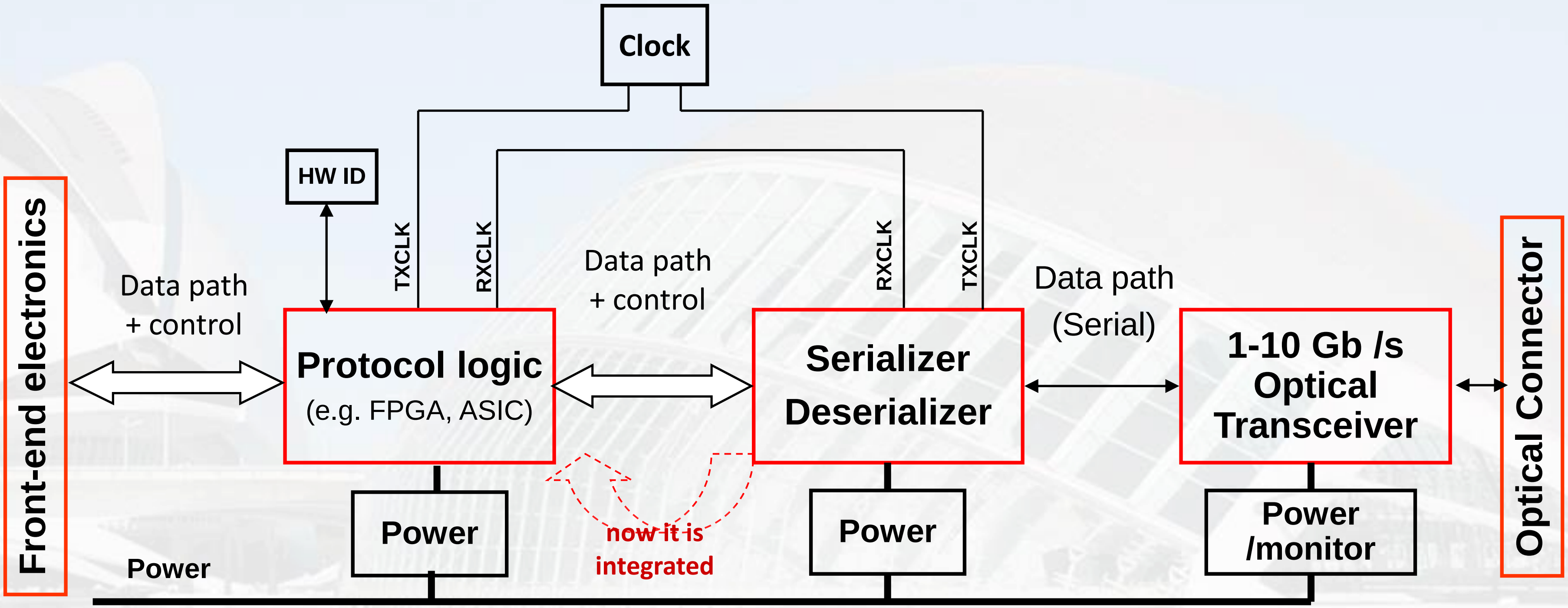
# System integration



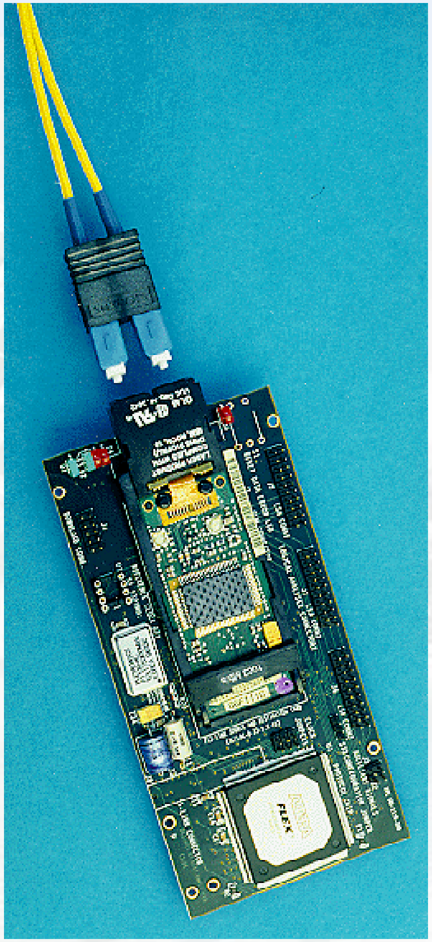

- FIFO like parallel interface
- Simplex, half-duplex, or duplex

- Physical Coding (e.g. 8B/10B)
- Link Control, Data Framing,
- Flow Control
- Error Detection

- E/O conversion

# Example: S-LINK

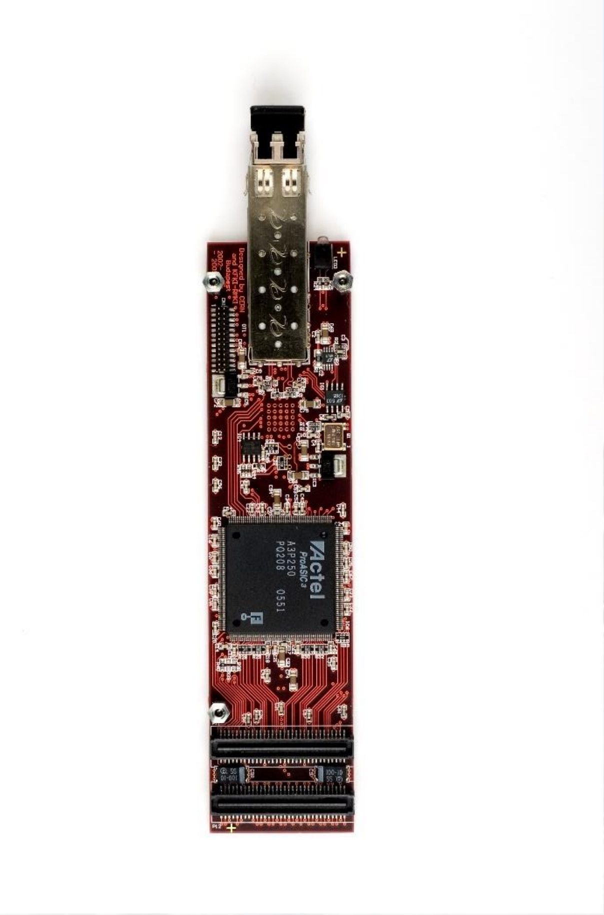
- Defined in 1995
- Duplex
- PCI interface
- 32-bit: ≤ 132 MB/s
- 8-bit: ≤ 64 MB/s
- Dual SC
- MMF
  - 50/125: 2 km
  - 62.5/125: 0.7 km
- OPB: 0.25 dB



**http://cern**.ch/HSI/**s-link**

# Example: DDL

- Defined in 1997
- Duplex
- PCI Interface (RORC)
- 2.125 Gb/s (max. 2.5 Gb/s)
- 850 nm
- MMF: 50µm or 65µm
- Up to 500m



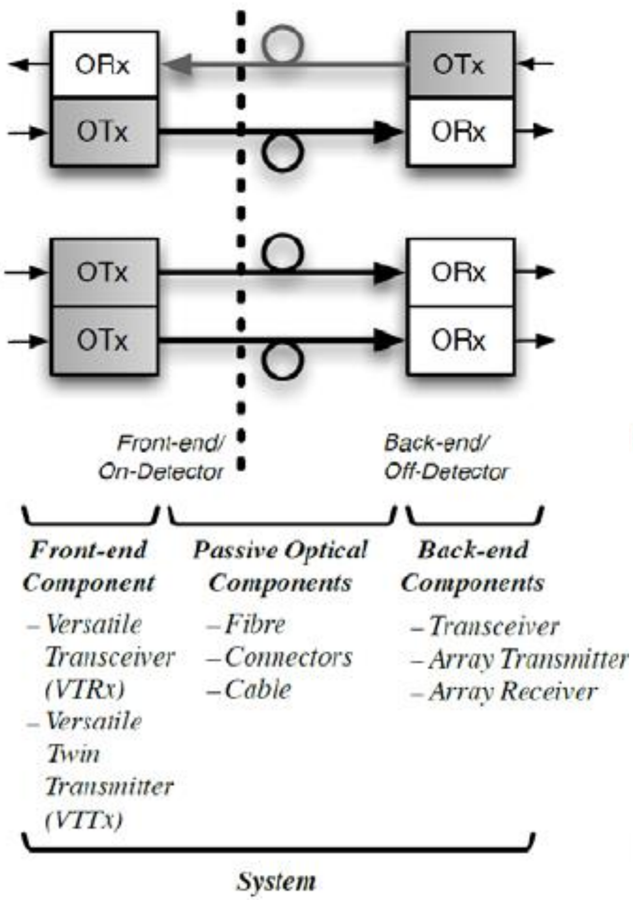
**http://cern.ch/ddl**

# Example: Versatile Link

- **3.2 Gbit/s** or **4.48 Gbits/s** user bandwidth
- Optional FEC
- SFP-like form factor
- Deterministic latency in both directions
- Radiation hard – qualified for:
    - 1 MRad total dose
    - 5e14 neq/cm²
- FE interface: 10 to 40 **E-links:** SLVS based with 320, 160 or 80 Mbit/s
- "Low"-power
    - <1.5W, 2.2W Worst-case


Courtesy: Paulo Moreira and Versatile link team
https://espace.cern.ch/project-versatile-link/public/default.aspx

# Versatile Link project




**VTRx and VTTx versions**

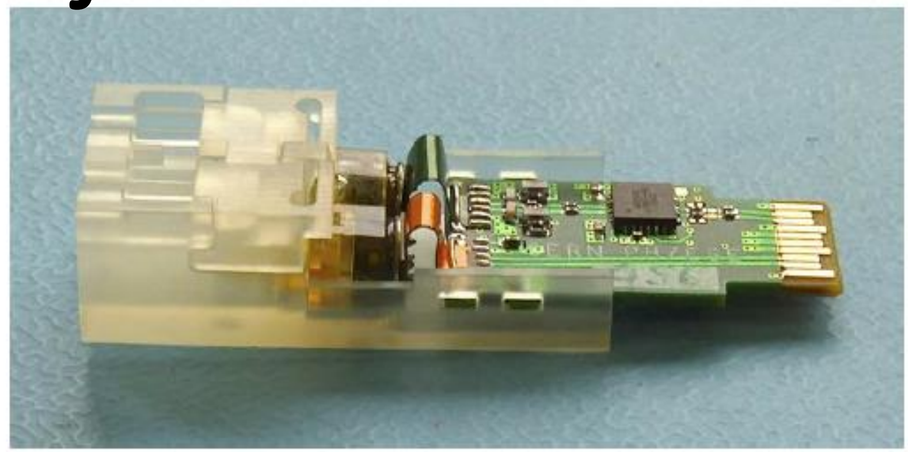


Figure 2: Photograph of a fully assembled VTRx

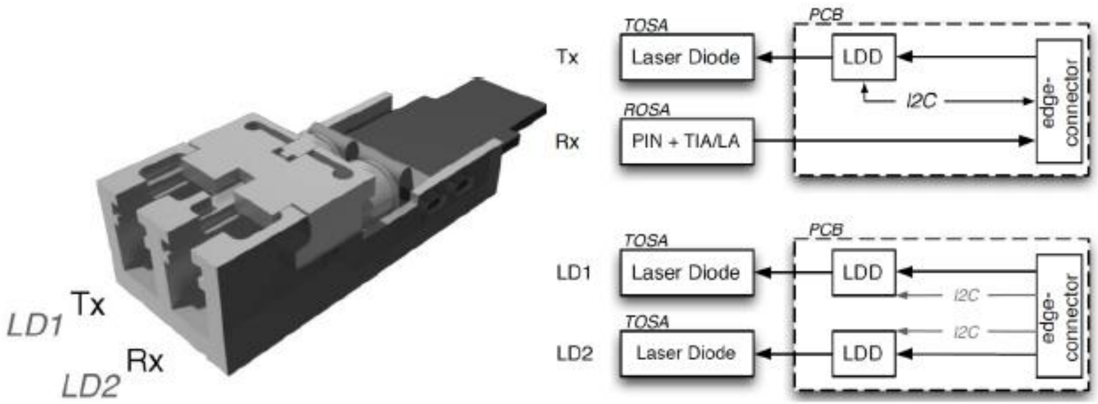
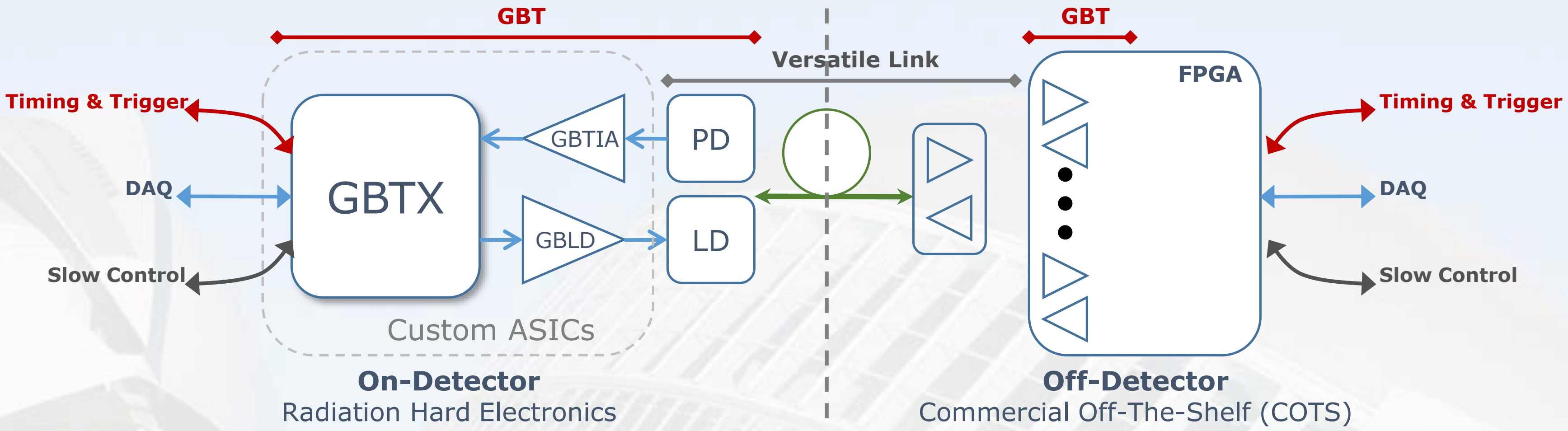



Figure 3: Sketch and blockdiagram of VTRx and VTTx modules

https://espace.cern.ch/project-versatile-link/public/default.aspx

# GBT architecture



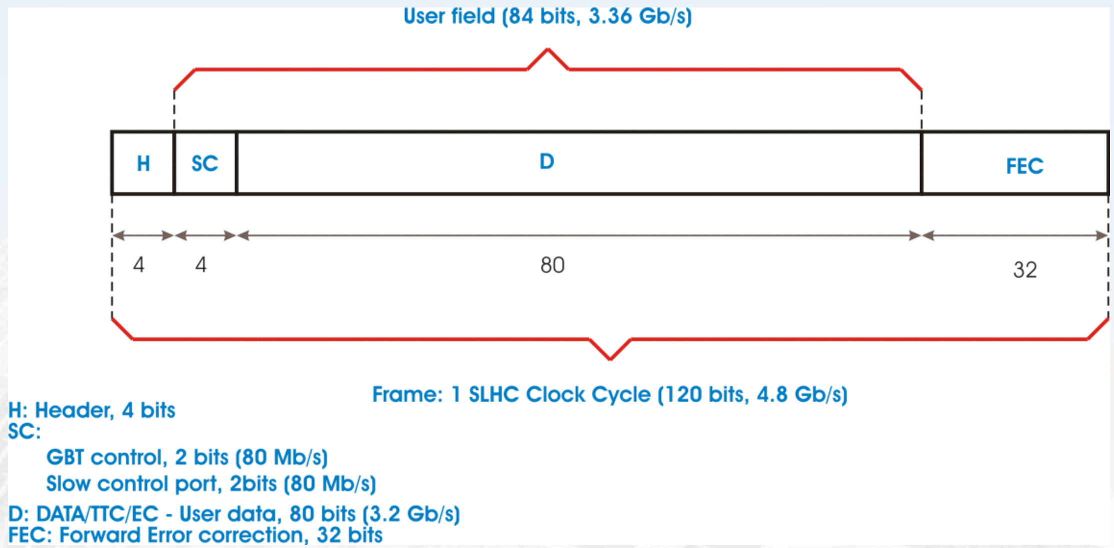

- **A Single Link for:**
  - **Readout (DAQ)**
    - High speed unidirectional (up-link)
    - Trigger data (up-link)
  - **Timing Trigger and Control (TTC)**
    - Clock reference and synchronous control (down-link)
    - Trigger decisions and control (down-link)
    - Low and fixed latency
  - **Experiment control (SC/DCS/ECS)**
    - Modest bandwidth (bidirectional link)

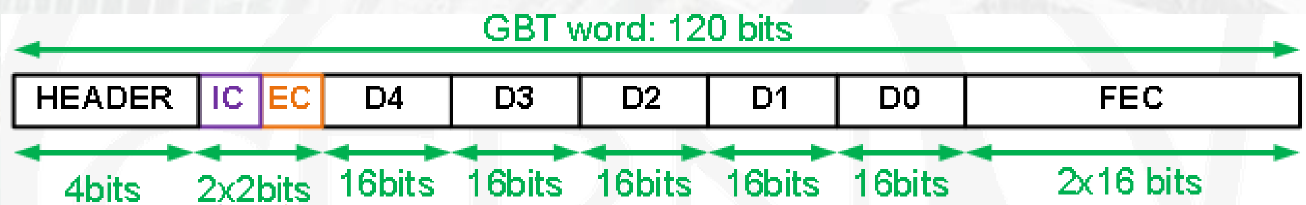
- **Custom ASICs in the detectors:**
  - Radiation Tolerant: Total dose & Single Event Upsets
- **Commercial components in the control room**
  - FPGAs used to implement multi-way transceivers

https://espace.cern.ch/GBT-Project/default.aspx

# GBT packet format

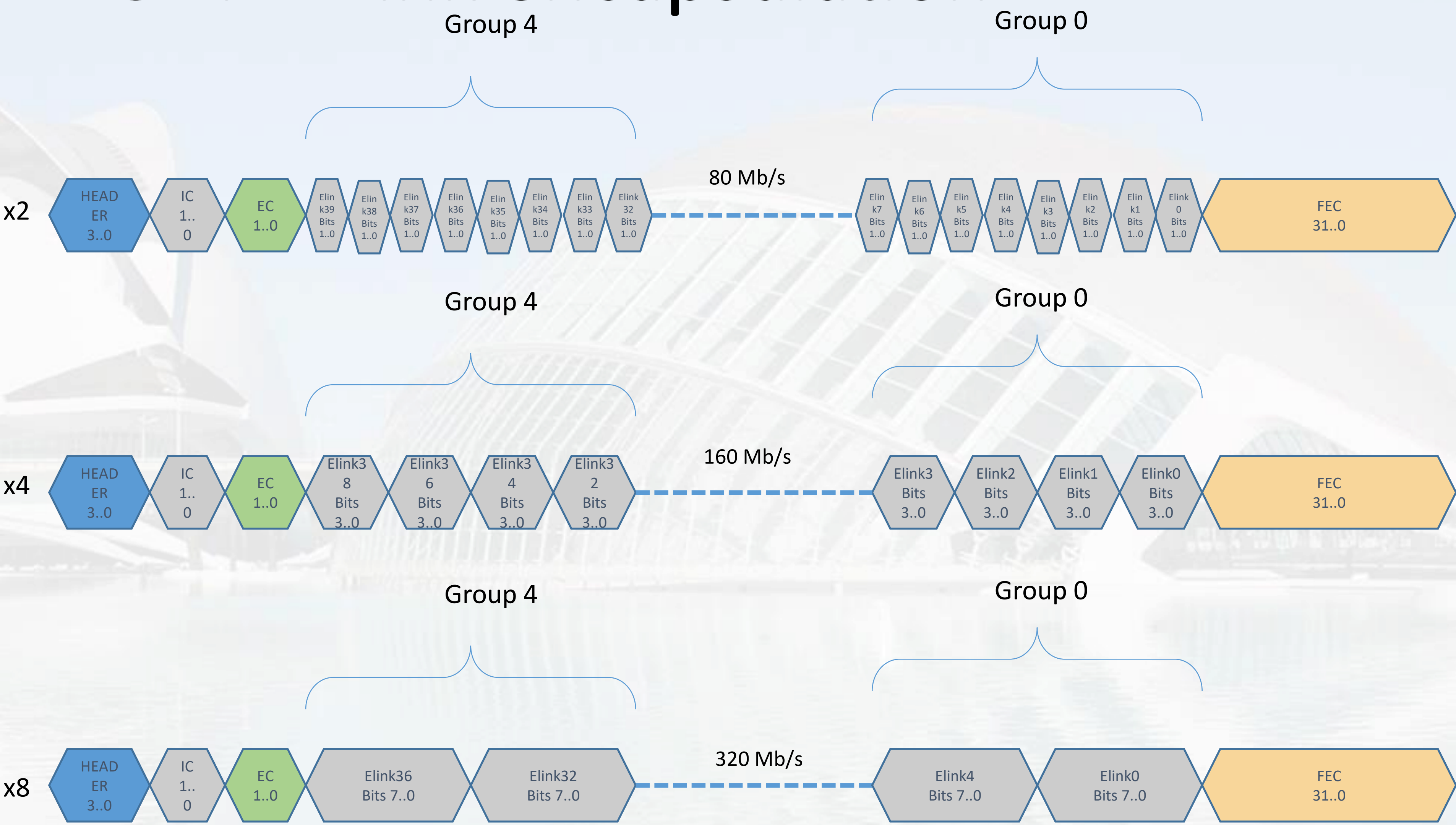
- Fixed frame length: 120bits
  - Frame transmission rate: 1/25ns
  - Data transmission rate: 4.8 Gbps
- Fixed bandwidth allocation:
  - Trigger path: 640 Mbps
  - Control path: 160 Mbps
    - 1 internal e-link (for GBT management)
    - 1 external e-link (for GBT-SCA chip)
  - Data path: 2.56 Gbps
    - 8 e-links @ 320 Mbps
    - 16 e-links @ 160 Mbps
    - 32 e-links @ 80 Mbps



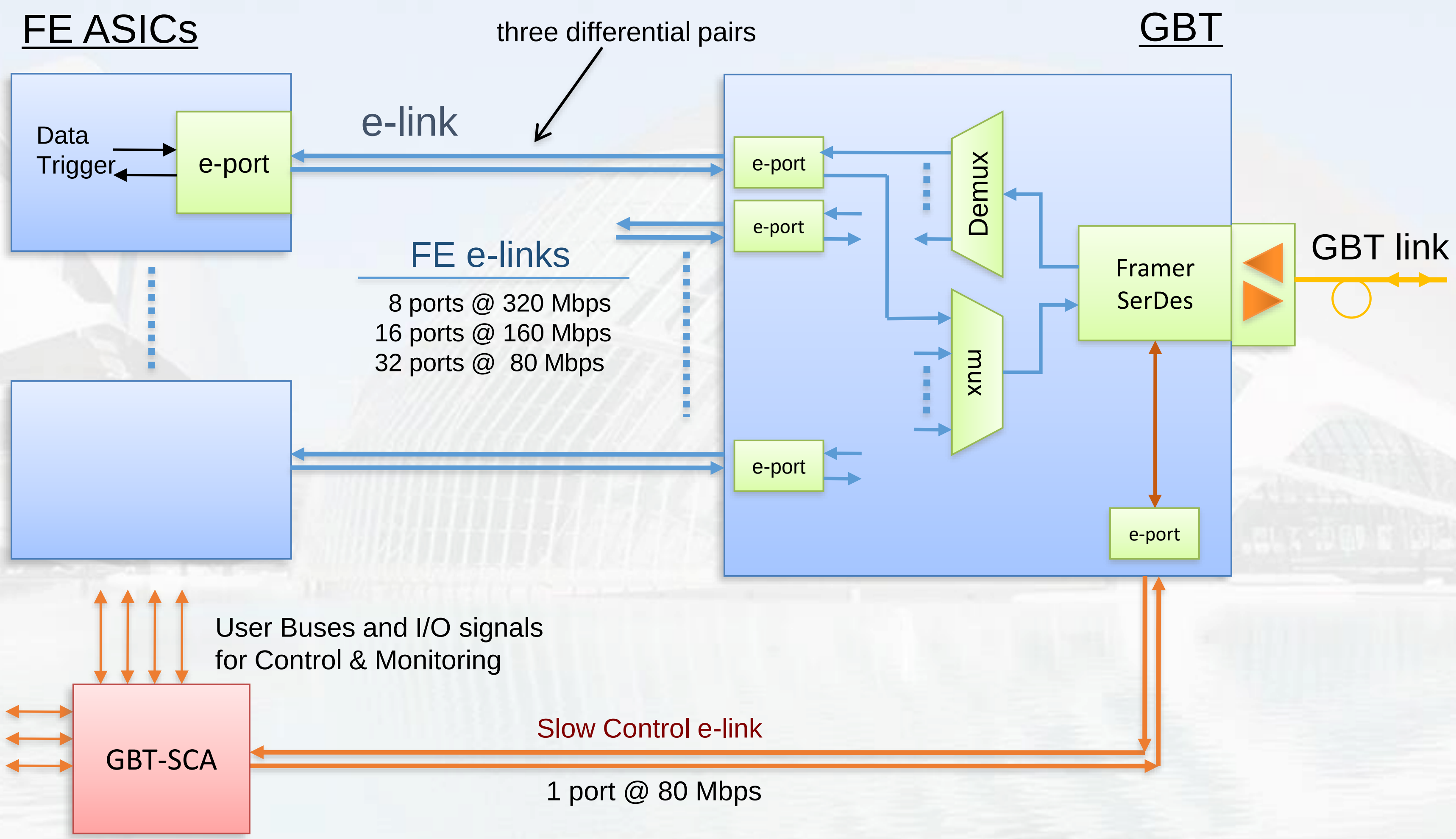




- Data flow:
  - Symmetrical, Bi-directional data transmission.
  - Transmission of GBT-frames is continuous.
  - Data from e-link ports are muxed/demuxed in the GBT-link stream.
  - GBT data path is unaware of the e-link transfer protocol.

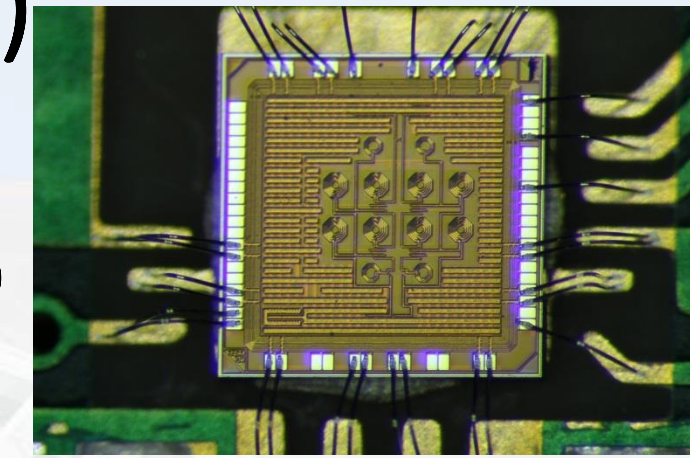
# GBT E-Link encapsulation



# GBT-Frontend interconnection

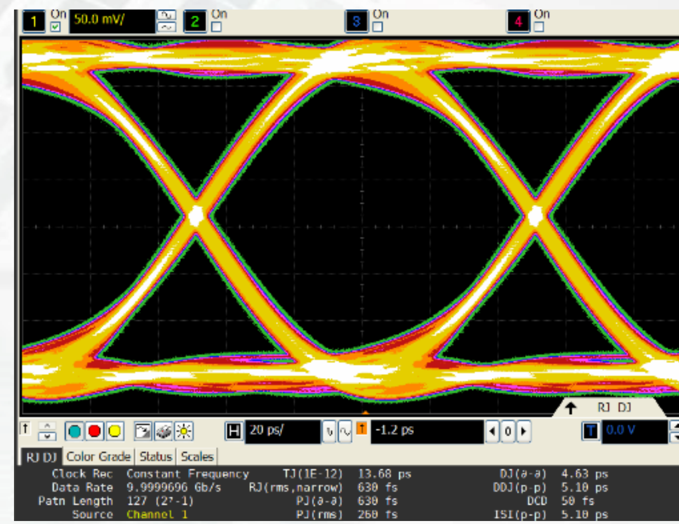


# Low-Power GBT (lbGBT)



- Data rates:
  - 2.5 Gb/s for down links (1.28 Gb/s FEC12)
  - 10 Gb/s for up links (7.68 Gb/s FEC12 or 8.96 FEC5)
- Lower power:
  - ~300 mW @ 5.12 Gb/s (Low-power)
  - ~400 mW @ 10.24 Gb/s (High-speed)
  - compare to ~2W for regular GBT
- How:
  - 130 nm → 65 nm
  - Vdd: 1.5 V → 1.2 V
  - Simpler SCA
- Multi-purpose
  - DAQ / Trigger / Control
- Pre-production in 2020

Electrical Eye Diagram @ 10 Gb/s




https://indico.cern.ch/event/799025/contributions/3486153/attachments/1901196/3138449/lpGBT20190903.pdf

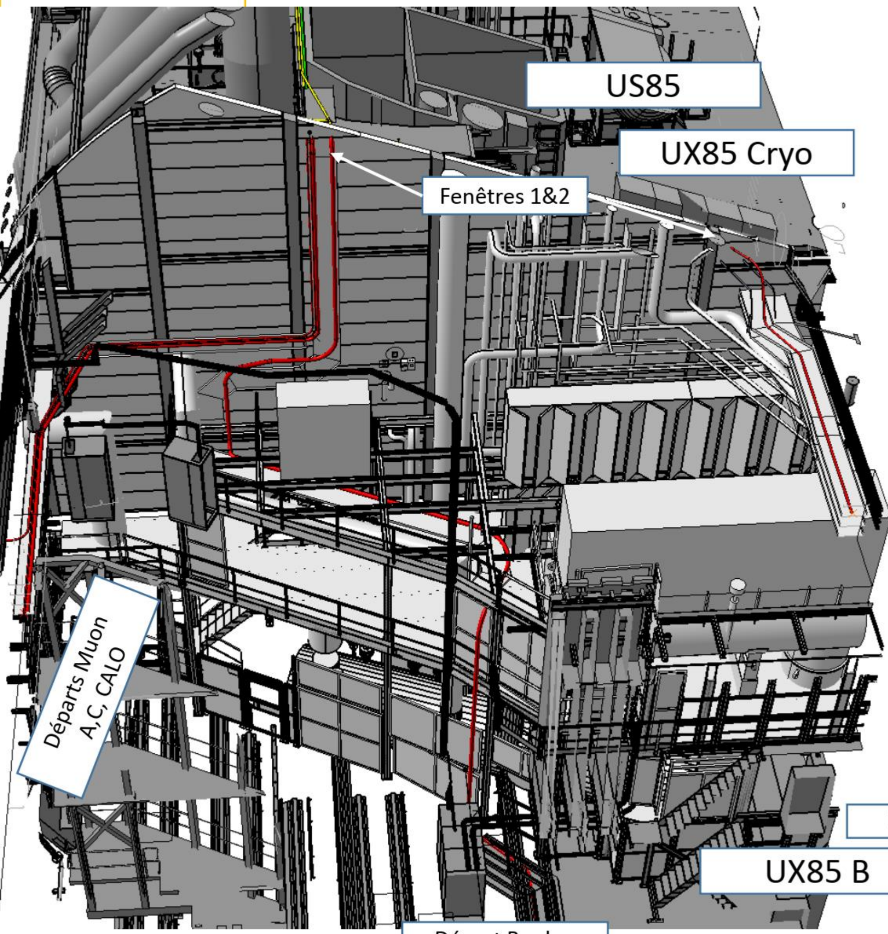
# Outline

- Fundamental concepts
- Electro-optical assemblies
- Applications
  - CERN Versatile Link / Versatile Link PLUS
- **Installation / Commissioning**

# Installation

**45 out of 19.008 fibers damaged during installation (0.24%)**

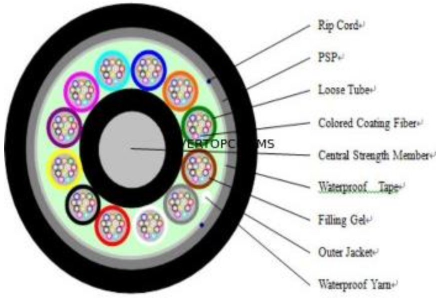
Fibres: BUNKER




Passage des fibres avant de rejoindre le chemin de câbles vertical vers fenêtre 1.

Cheminement vertical, avant de passer dans la zone C. Ca va être modifié


L'entrée des fibres dans la zone Cryo. EN-EA à vérifier

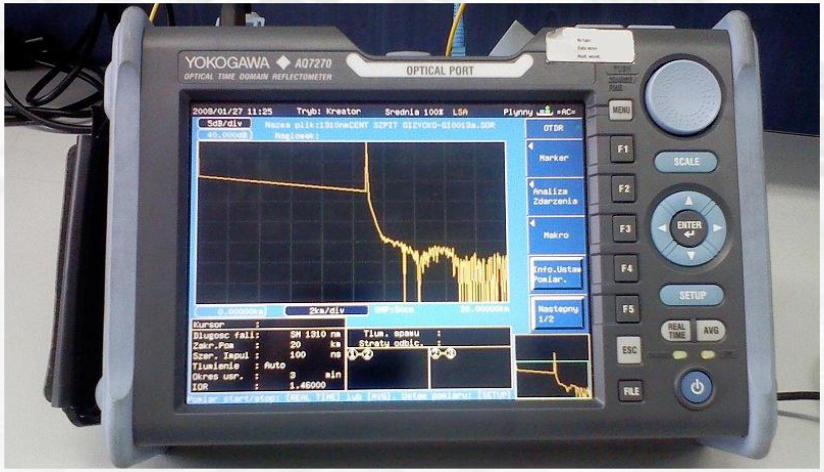


# Optical Power Meter (Light meter)

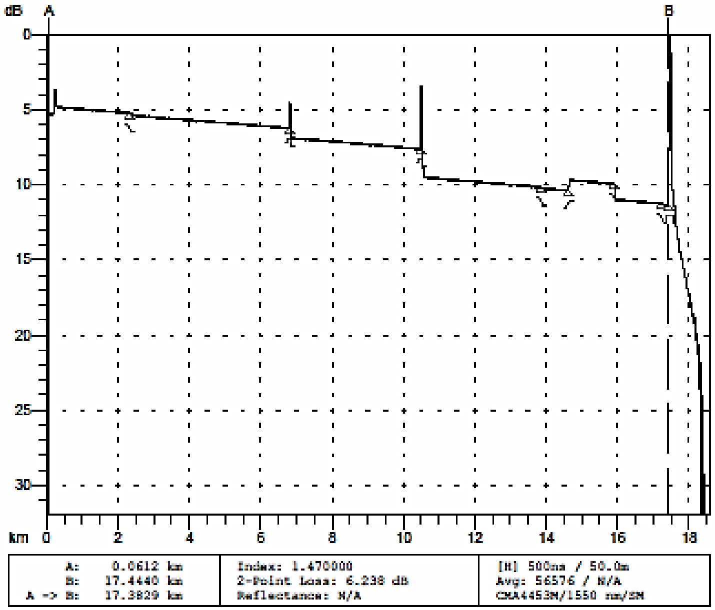
- Actually two devices
  - Optical reference
  - Receiver module
- Measures the “brightness” of the signal [dBm] or [mW]
- Automated (re)-calibration
  - Measure either absolute power or relative loss
- MPO polarity detection
- Scan one entire MPO bundle at once

# Optical Time-Domain Reflectometer (ODTR)

- Indispensable tool to test fiber installations
- Inject a train of light pulses in fiber strand
- Analyze light that is reflected back
- Characterize fiber path
  - Locations of fiber splices
  - Locations of fiber breaks
  - (As distance from probe)
  - Overall attenuation of fiber

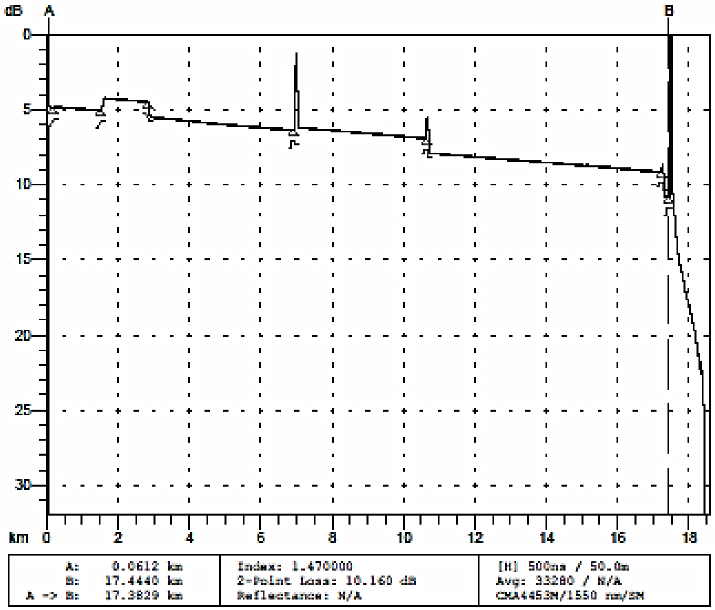


# Example ODTR output




| Feature #/Type | Location (km) | Event-Event (dB) | (dB/Km) | Loss (dB) | Refl (dB) |
|---|---|---|---|---|---|
| 1/N | 2.3310 | ?? | ?? | 0.12 | |
| 2/R | 6.8035 | 0.91 | 0.203 | 0.64 | -58.19 |
| 3/R | 10.4907 | 0.72 | 0.196 | 1.86 | -48.24 |
| 4/N | 13.8639 | 0.70 | 0.206 | 0.06 | |
| 5/N | 14.6205 | 0.14 | 0.188 | -0.71 | |
| 6/N | 15.9114 | 0.26 | 0.205 | 1.06 | |
| 7/N | 17.2350 | 0.25 | 0.193 | 0.08 | |
| 8/E | 17.4491 | 0.05 | 0.211 | >3.00 | >-33.55S |

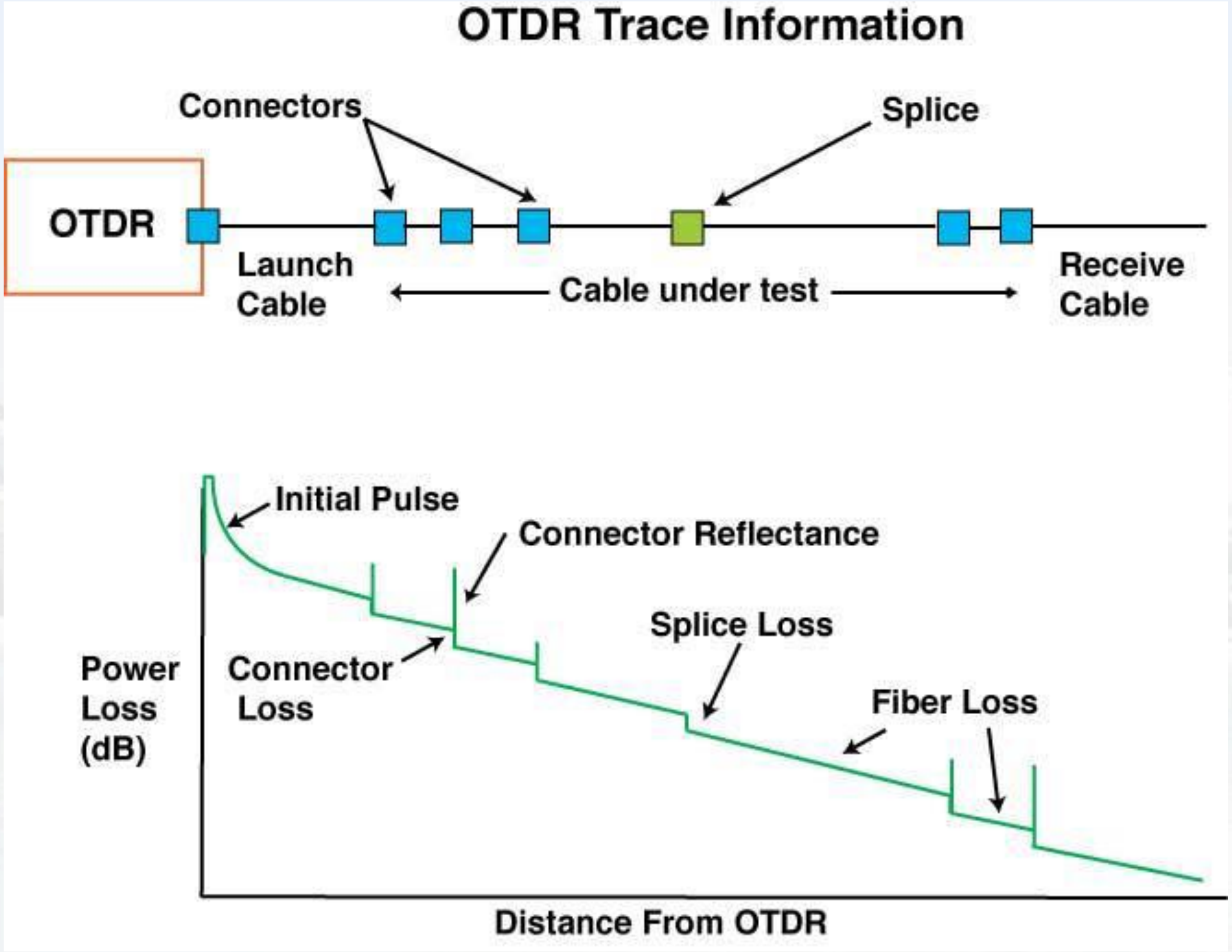
Overall (End-to-End) Loss: ??




| Feature #/Type | Location (km) | Event-Event (dB) | (dB/Km) | Loss (dB) | Refl (dB) |
|---|---|---|---|---|---|
| 1/N | 0.1937 | 0.02 | 0.121 | -0.06(2P) | |
| 2/N | 1.5194 | 0.24 | 0.184 | -0.82 | |
| 3/N | 2.8327 | 0.26 | 0.197 | 0.99 | |
| 4/R | 6.9421 | 0.90 | 0.219 | -0.21 | >-46.37 |
| 5/R | 10.6396 | 0.75 | 0.203 | 0.96 | -56.69 |
| 6/R | 17.2269 | 1.28 | 0.194 | 1.61 | -61.90 |
| 7/E | 17.4512 | 0.04 | 0.184 | >3.00 | >-34.48S |

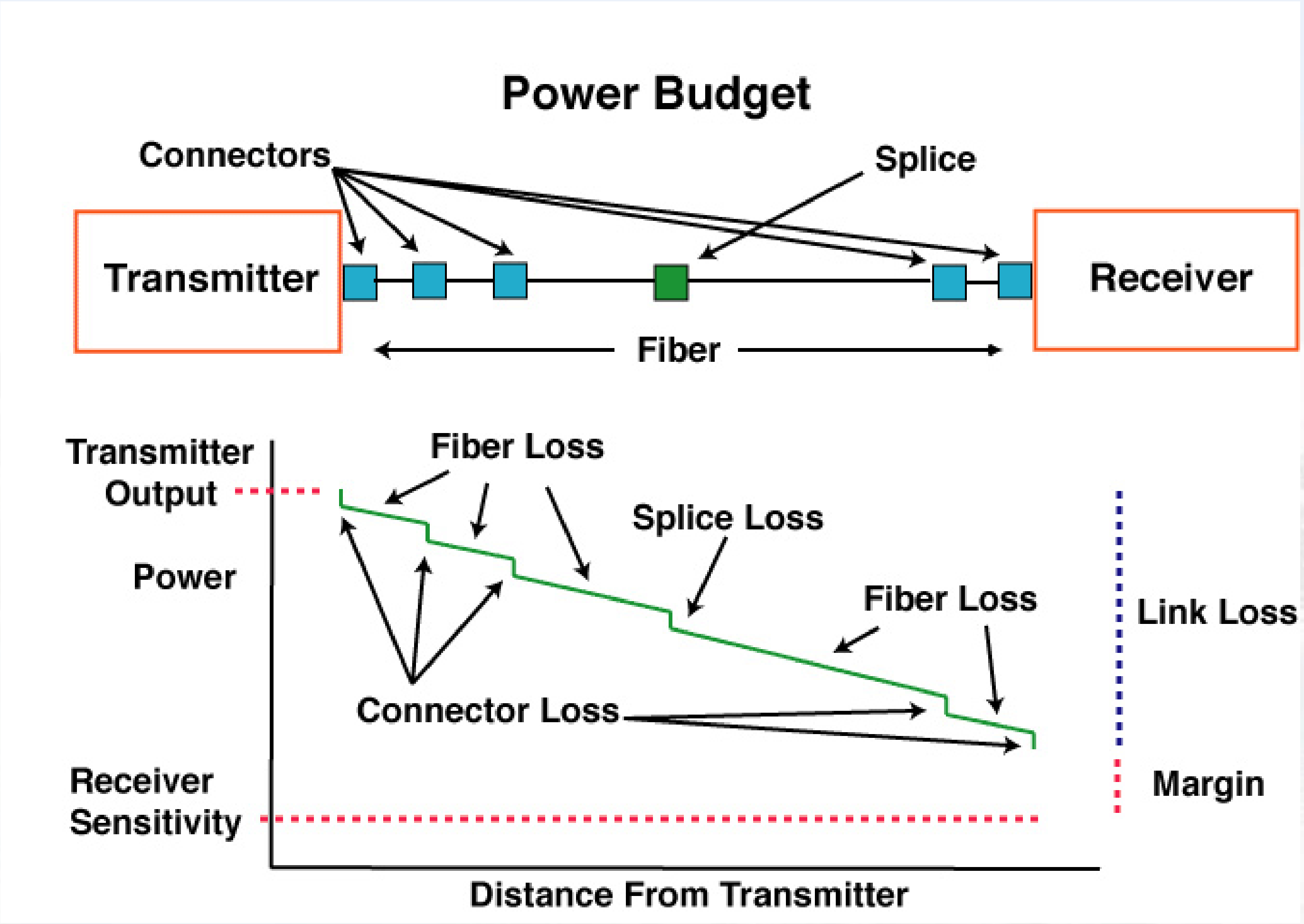
Overall (End-to-End) Loss: 5.97 dB

# ODTR output diagram



# Plan your optical budget…

Always include safety margins!



# …and plan your cabling