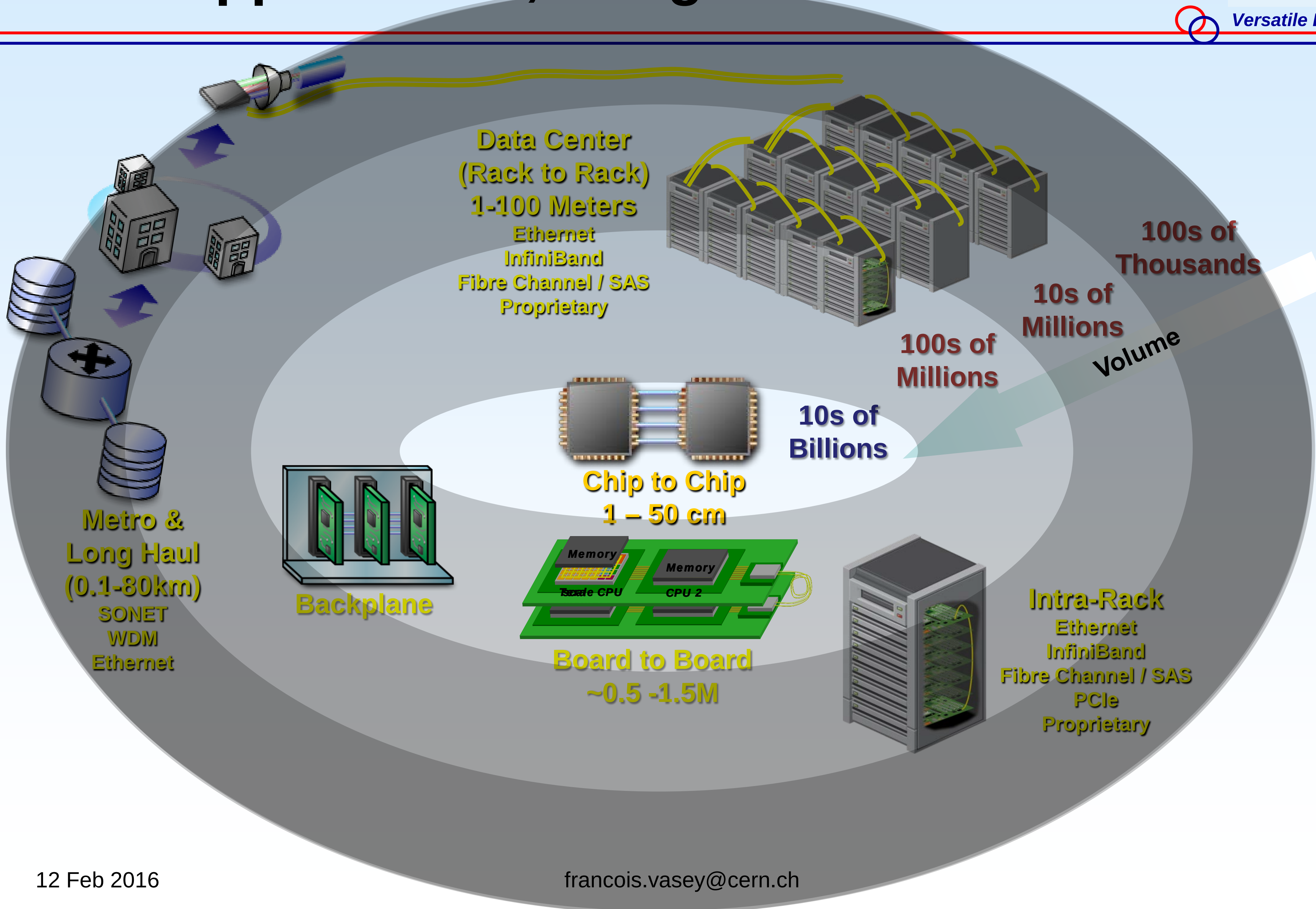
Optical Links for High Energy Physics

Versatile Link

Francois Vasey, CERN

Applications, Ranges and Volumes

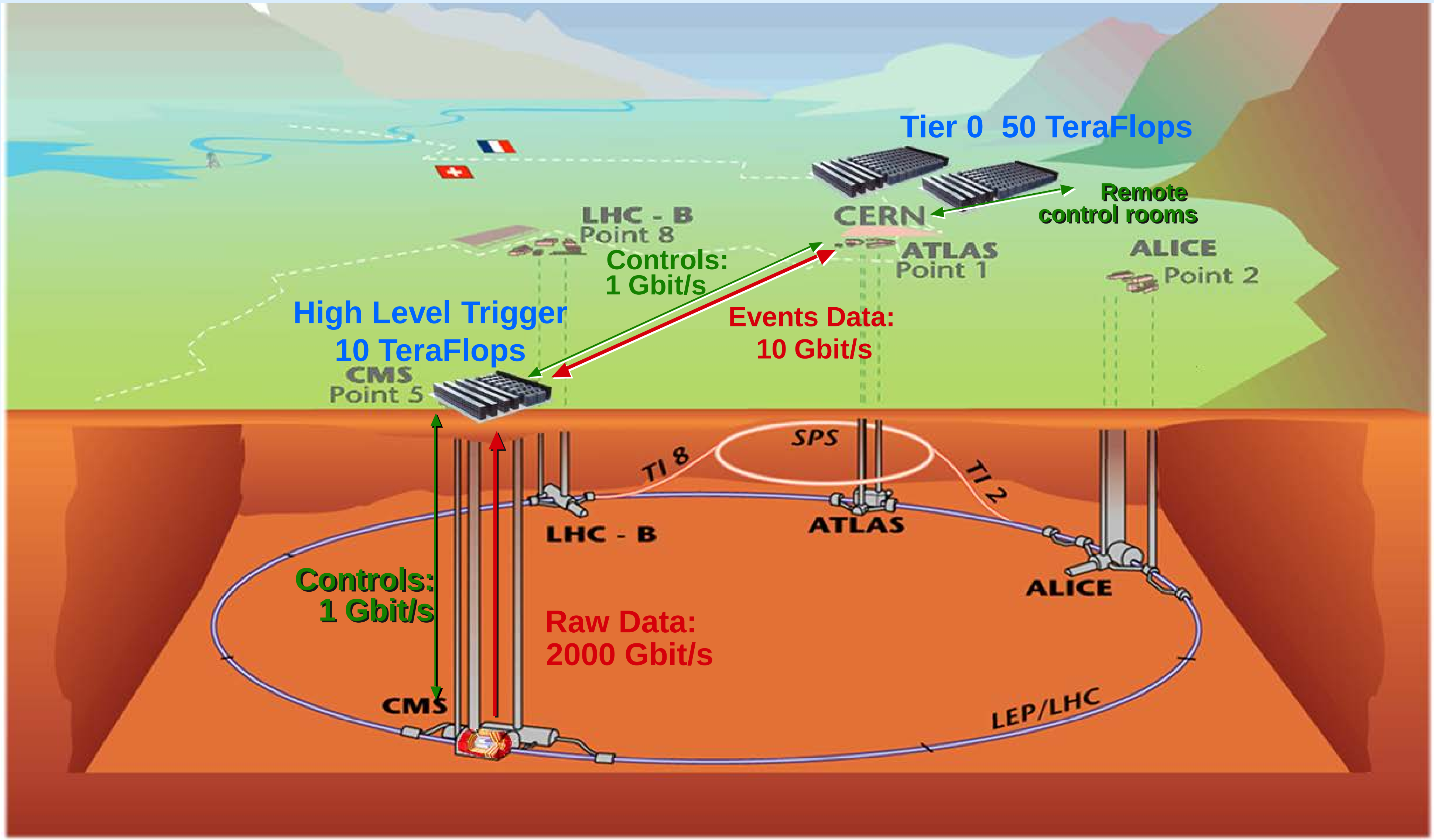
Versatile Link



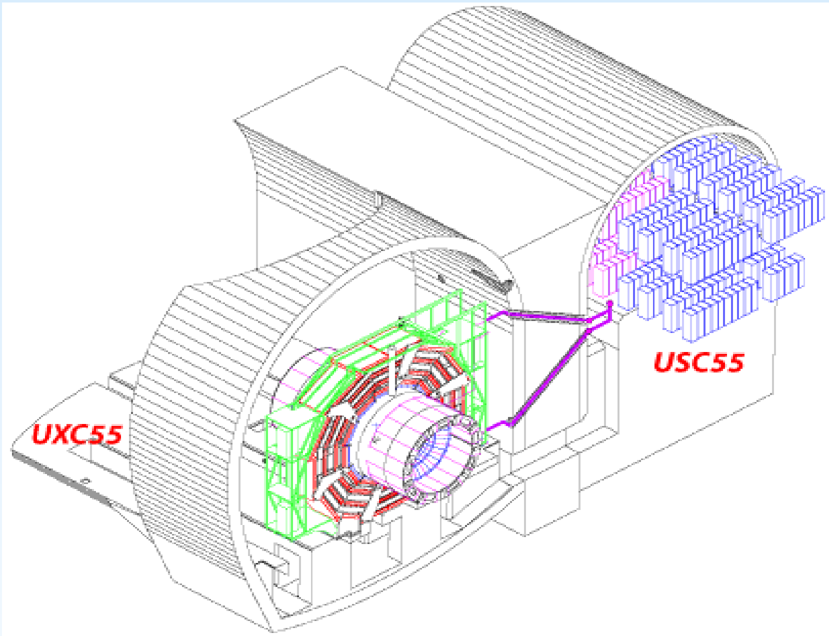
The LHC experiments at CERN

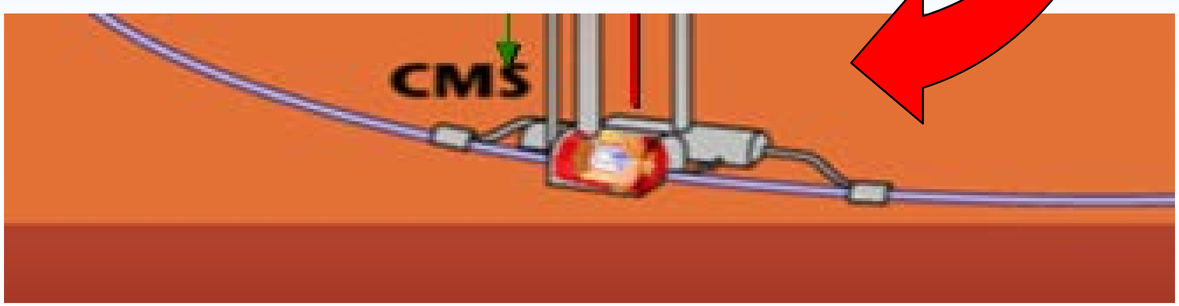
Versatile Link

A typical dataflow: The Example of CMS

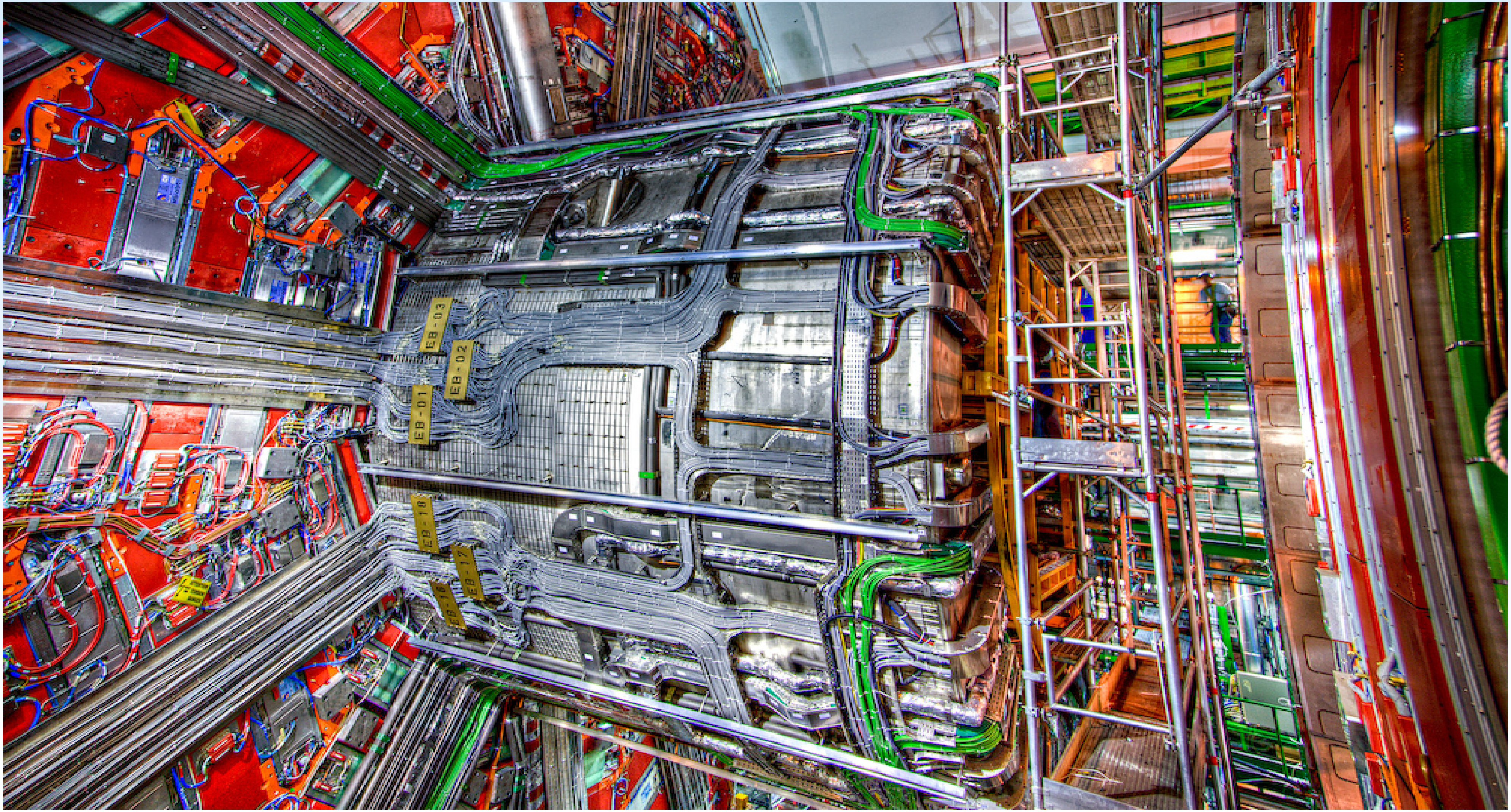


The Front-End Optical Links

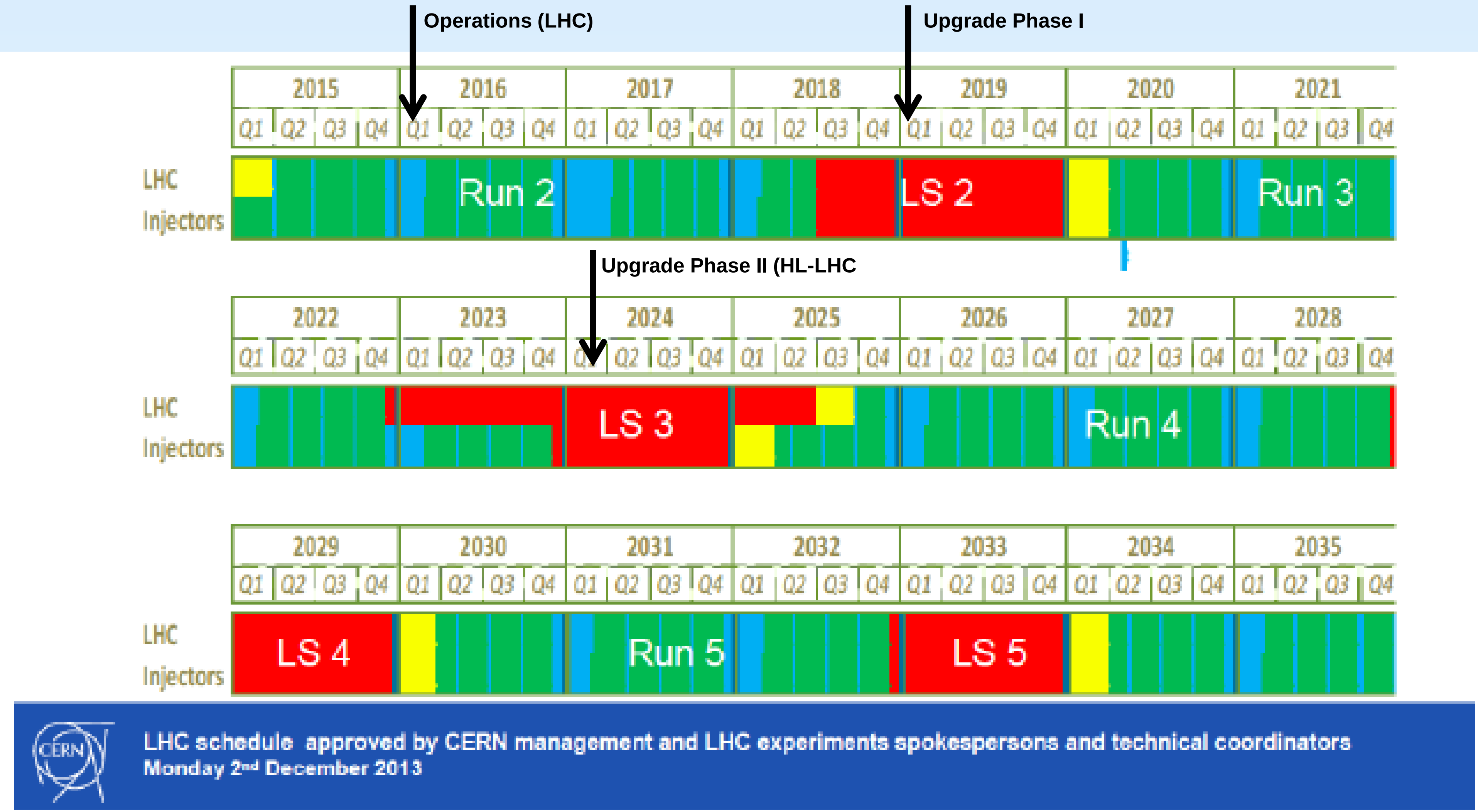




CMS Central Wheel



LHC Schedule Drives Experiments Upgrades



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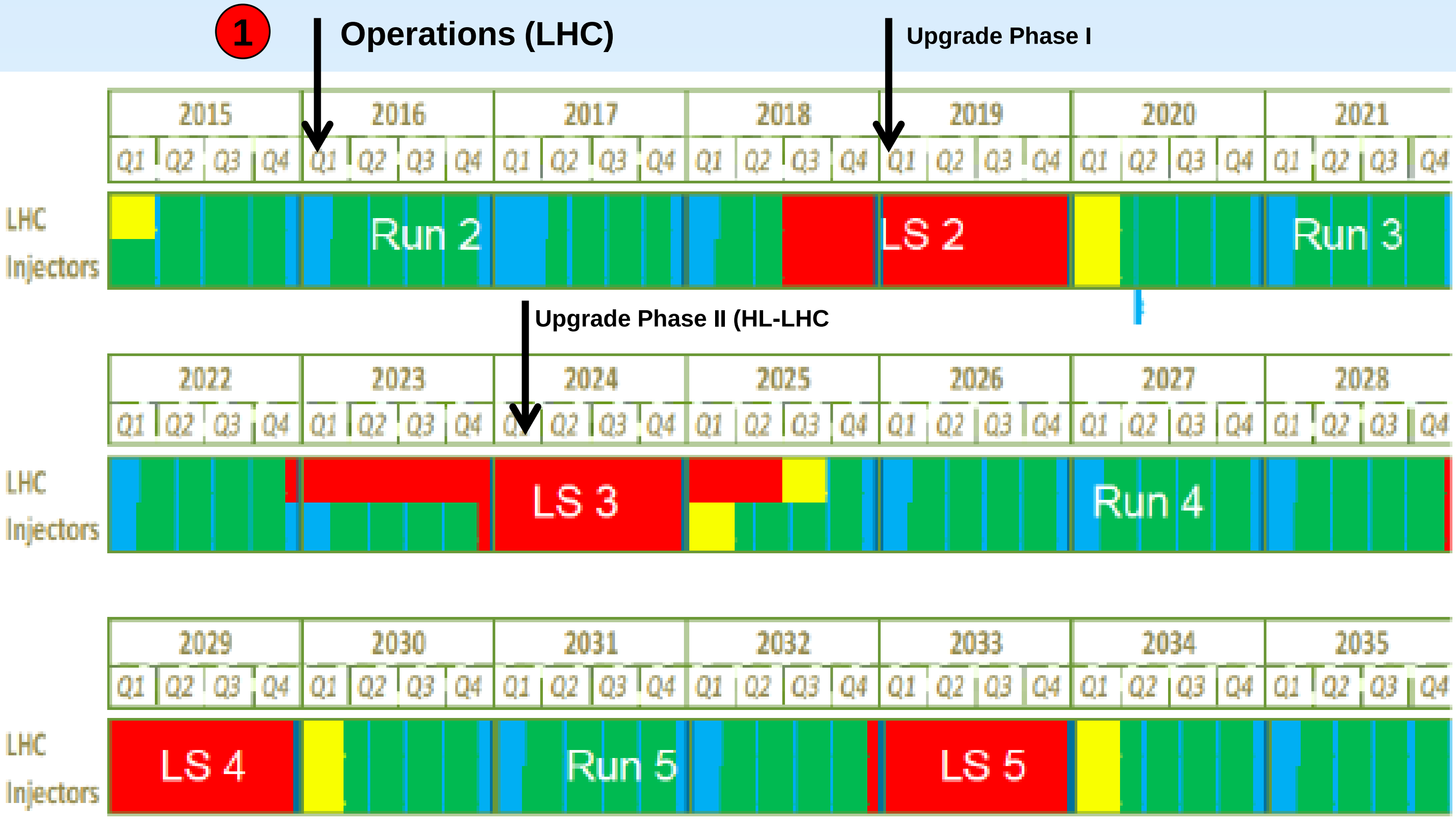
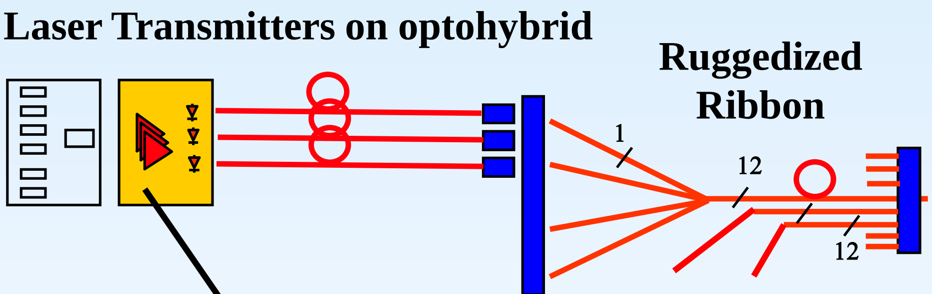
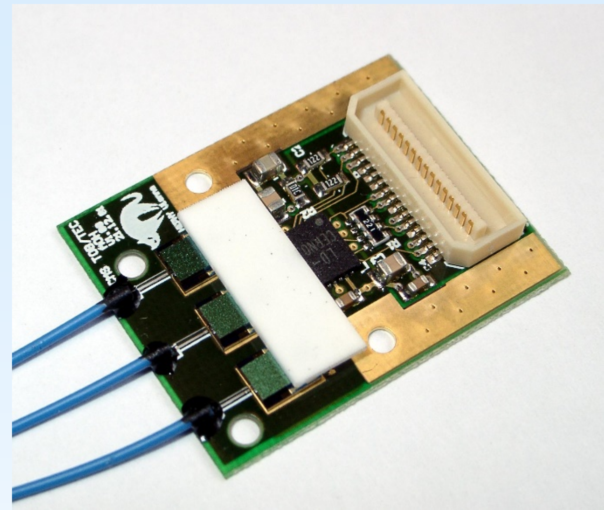
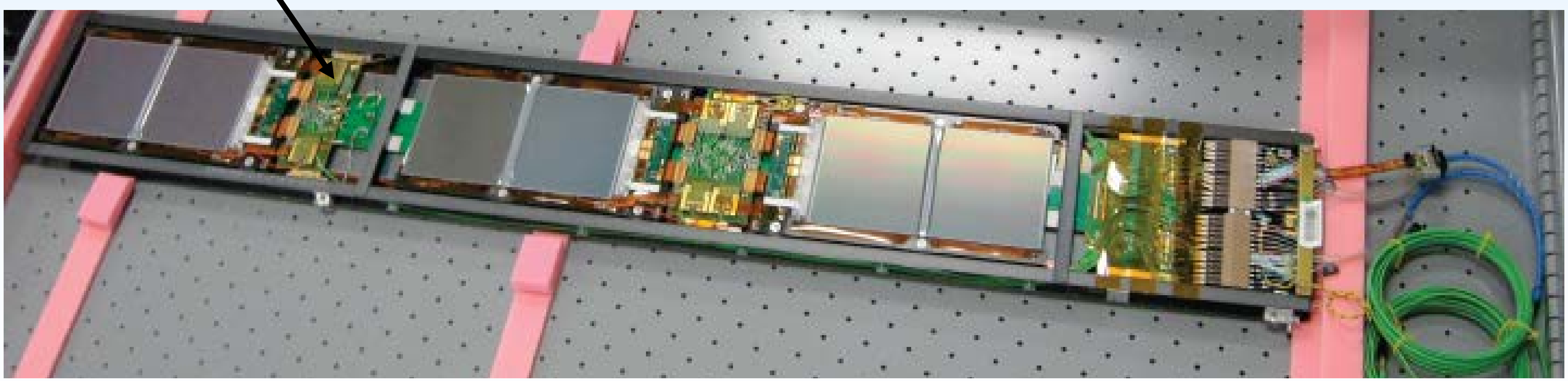


LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

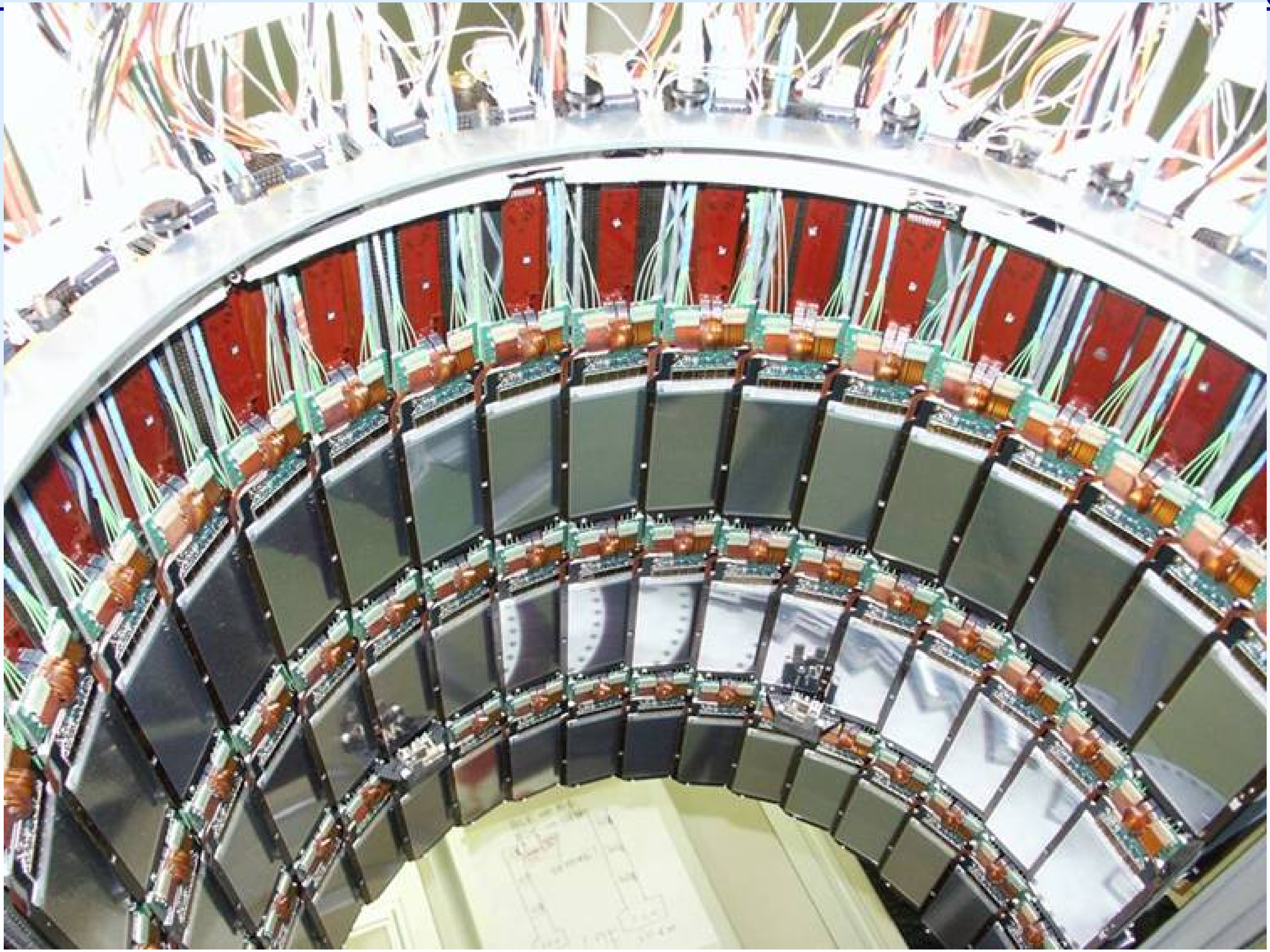
CMS Tracker TOB rod



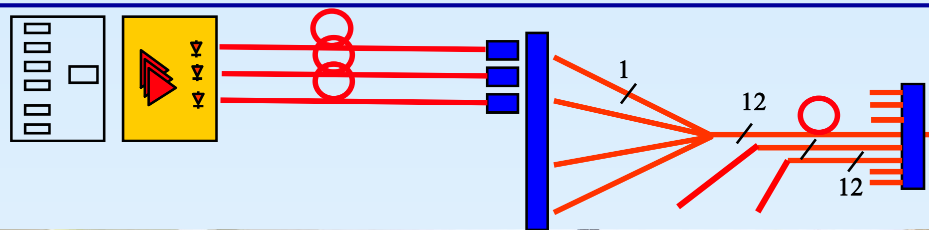


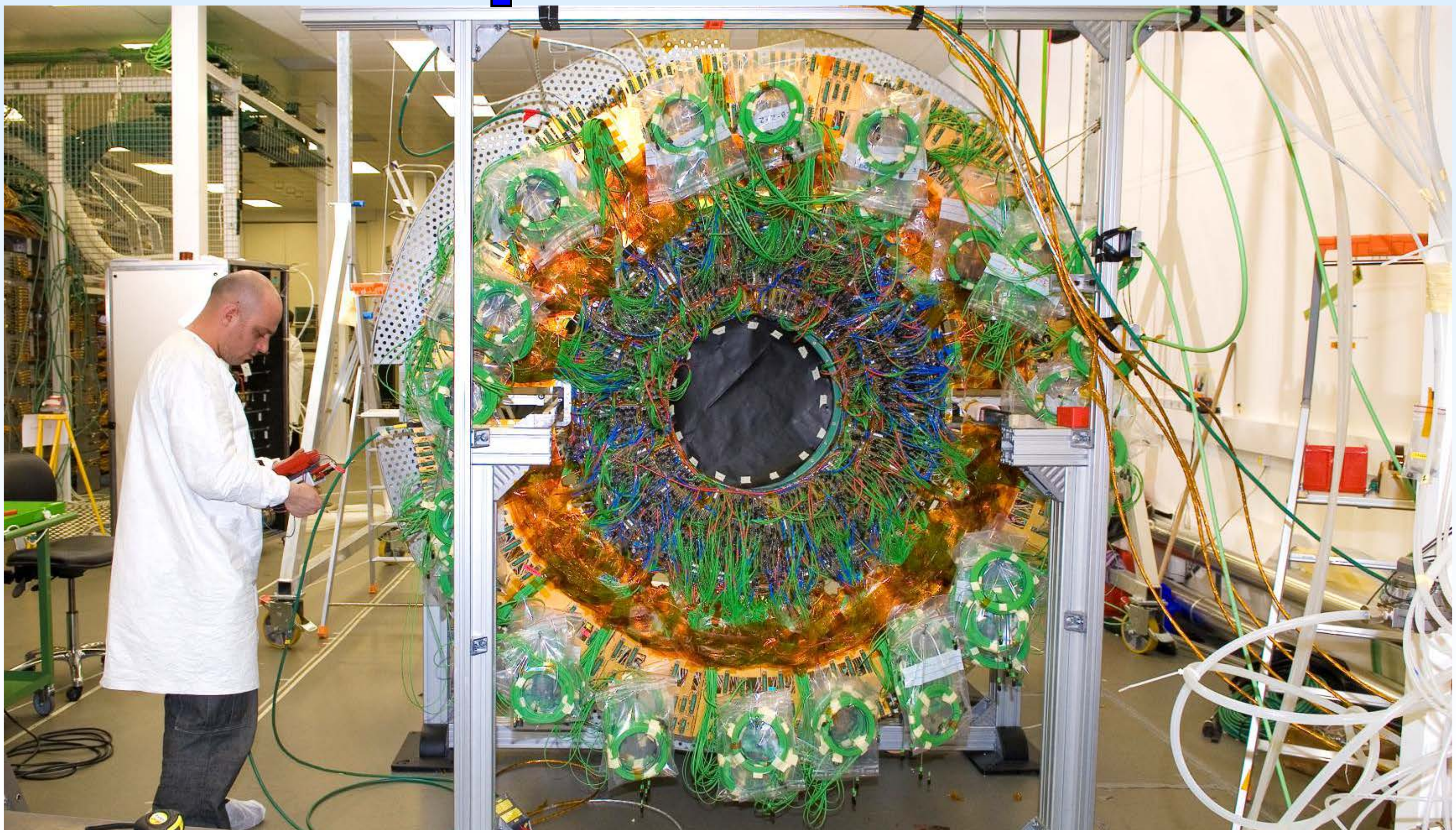


CMS Tracker TIB layer 4

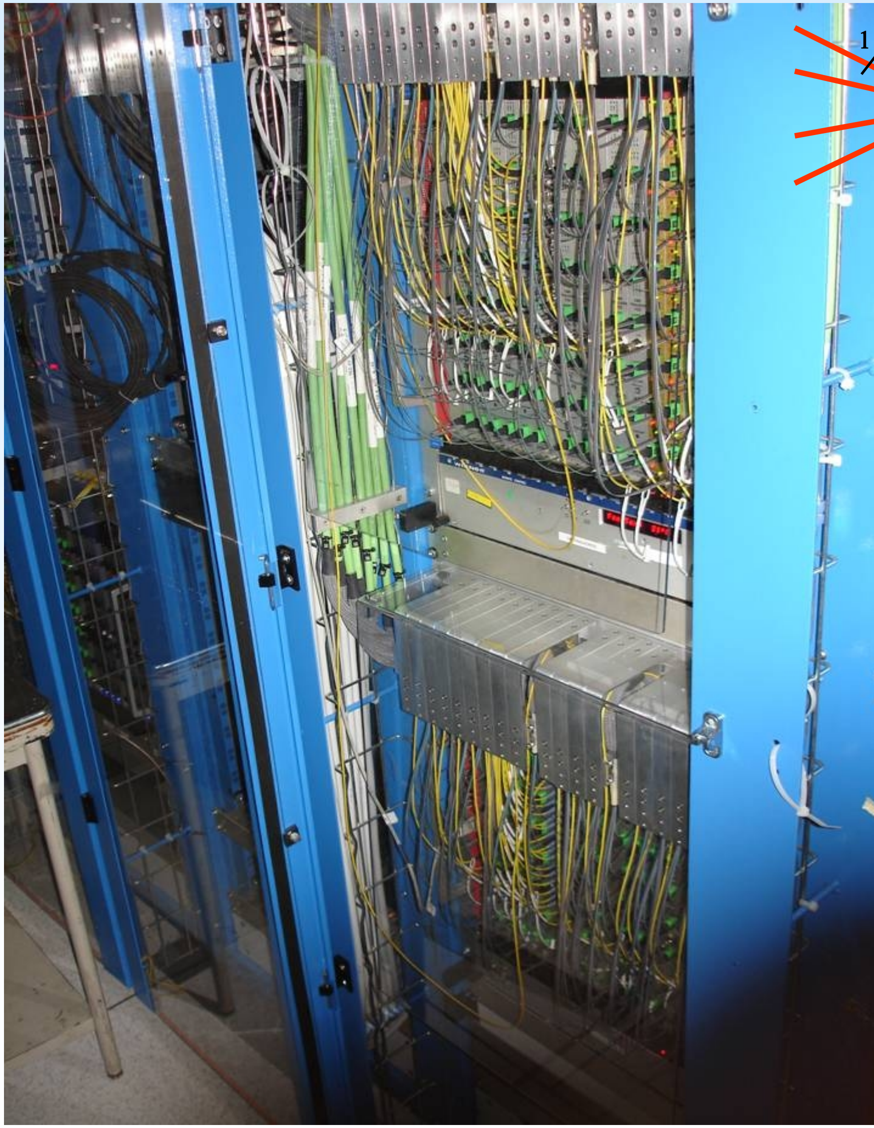


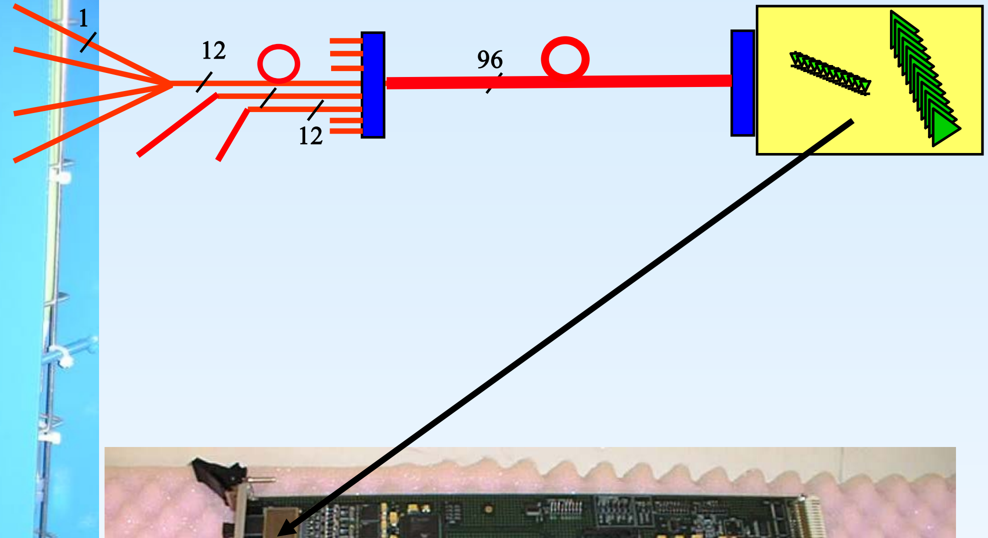
CMS Tracker TIB patch panel

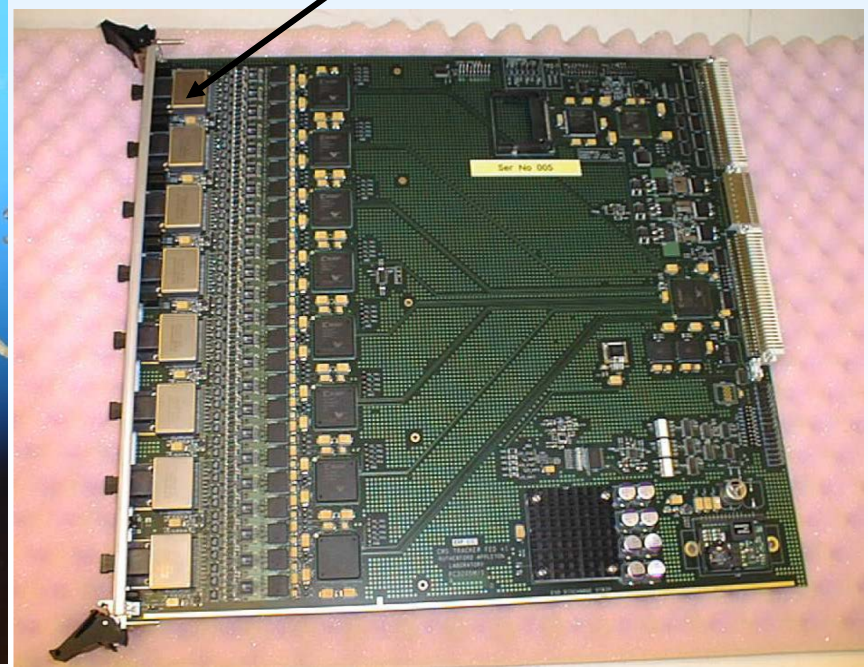




CMS Tracker FED

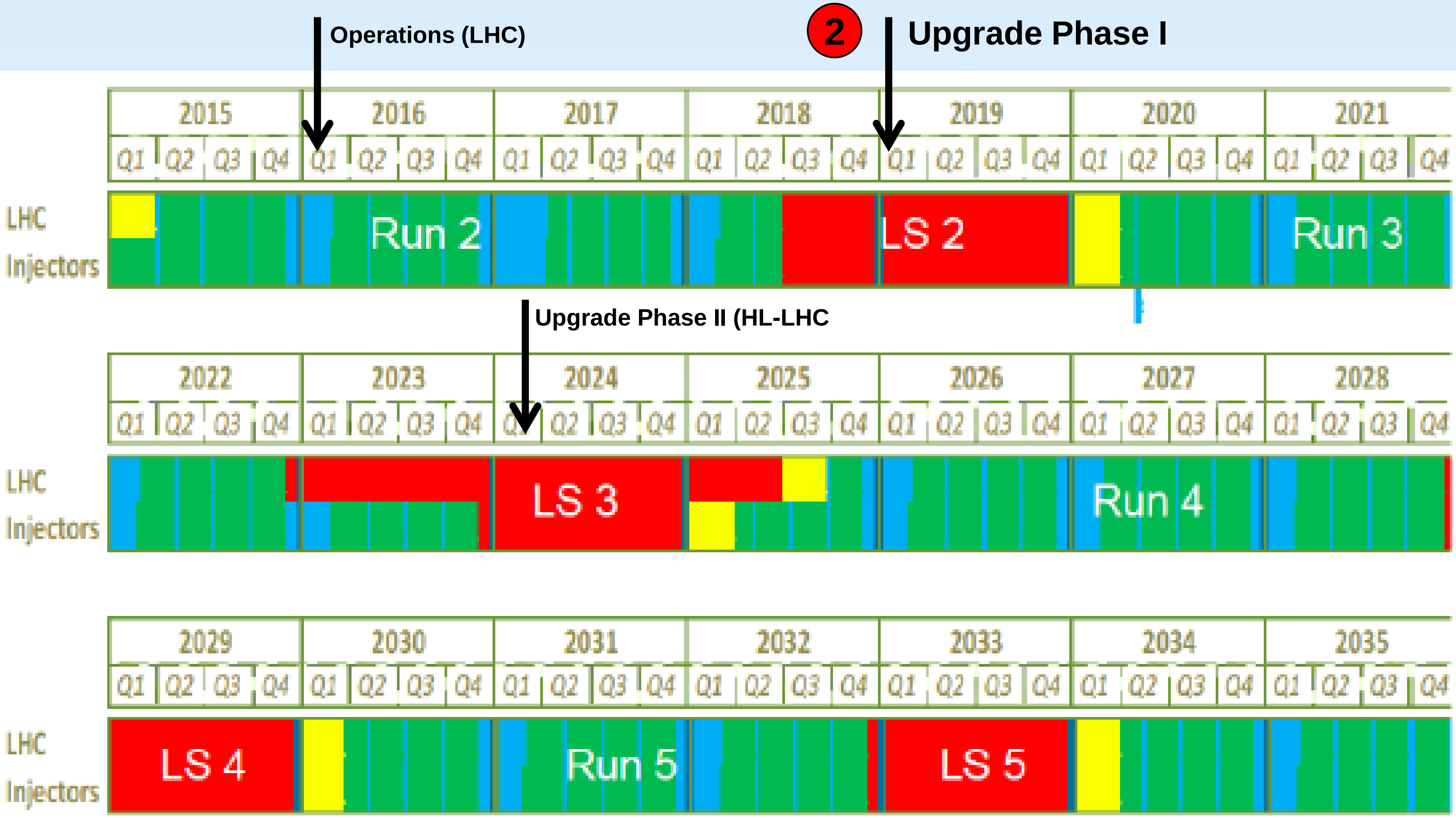






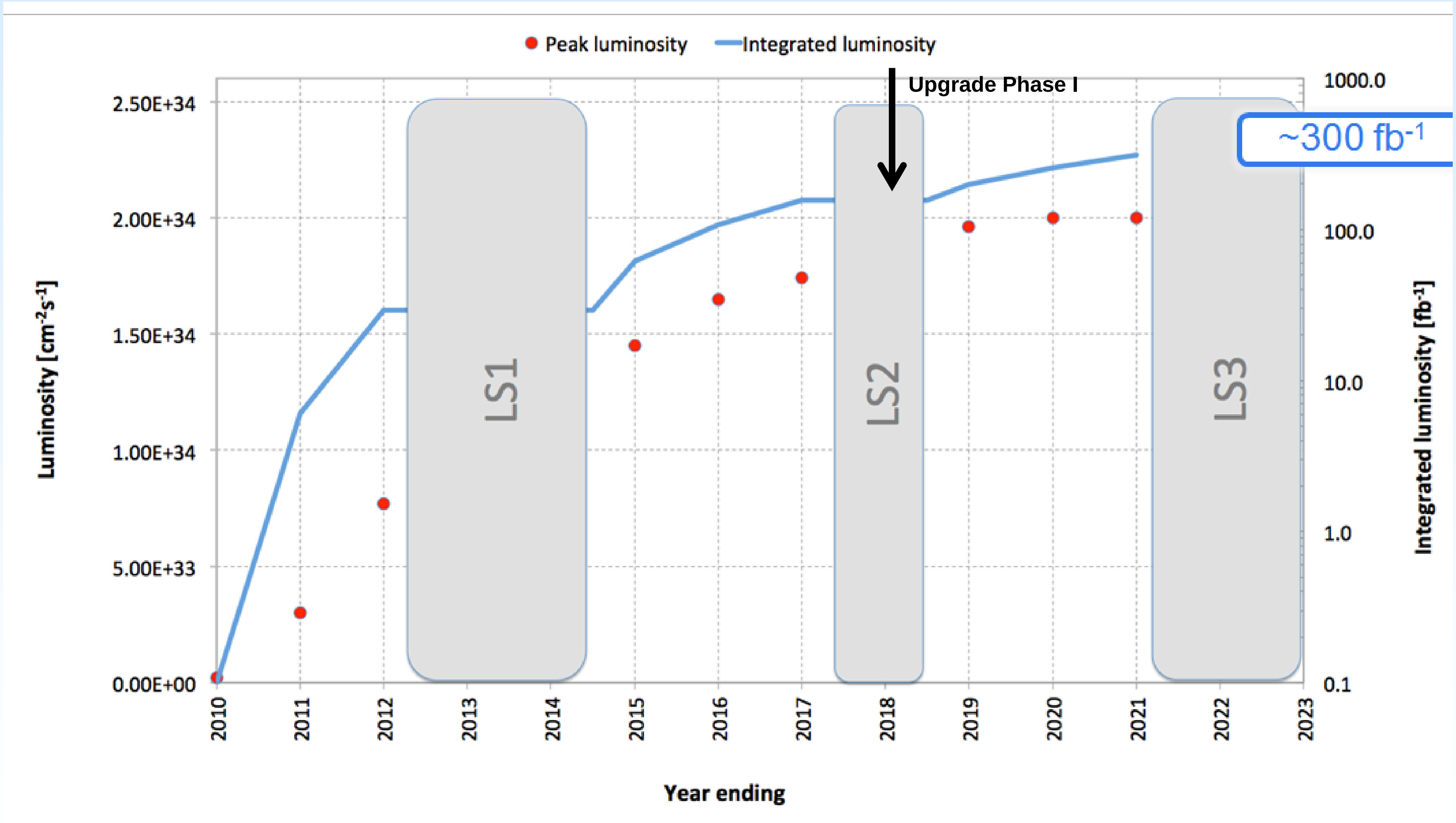
LHC Schedule Drives Experiments Upgrades

Versatile Link



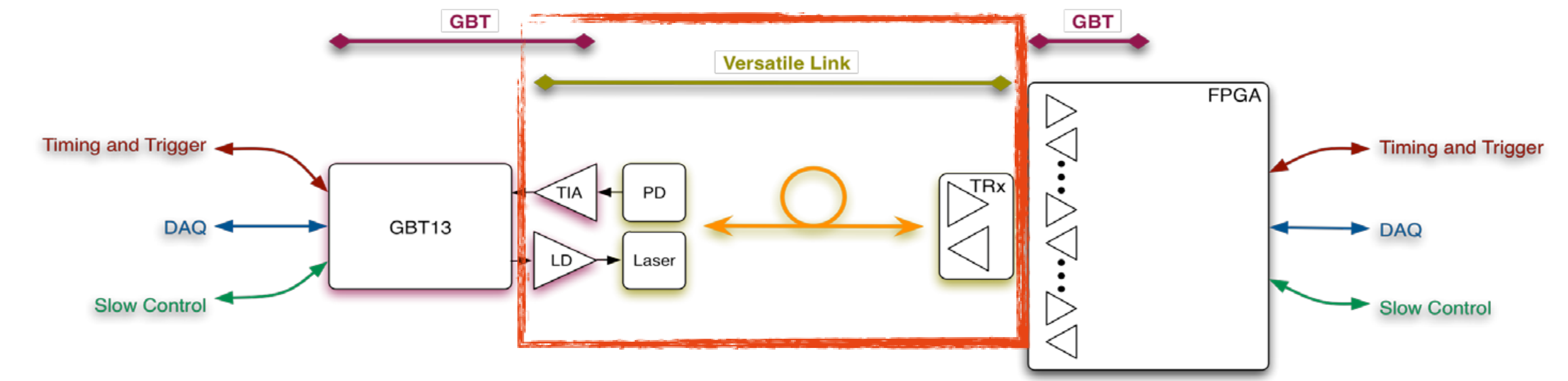
LHC schedule approved by CERN management and LHC experiments spokespersons and technical coordinators
Monday 2nd December 2013

LHC Shutdowns and Upgrades



Phase I Upgrade: Versatile Link

- Optical Physical layer linking front- to back-end
- Bidirectional, ~5Gbps
- Versatile
  - Multimode (850nm) and Singlemode (1310nm) versions
  - Point to Point and Point to Multipoint architectures
- Hostile environment

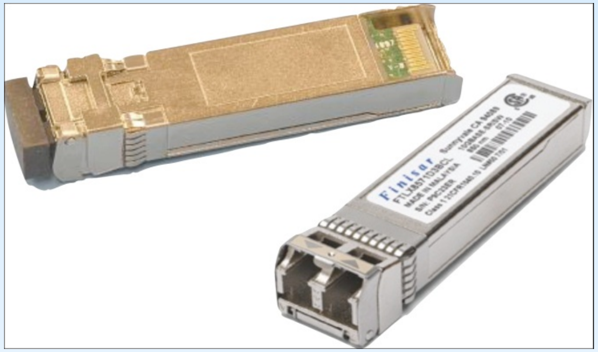


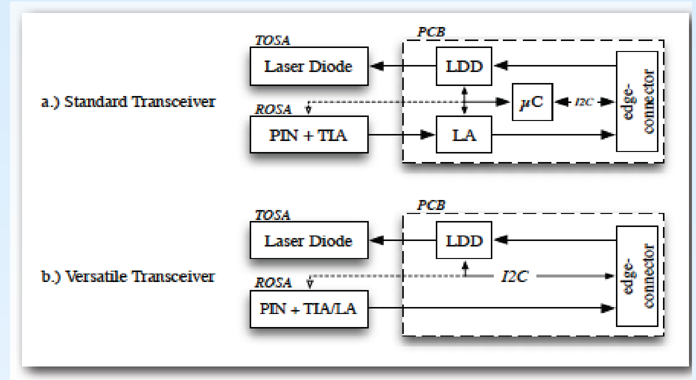
On-Detector
Custom Electronics & Packaging
Radiation Hard

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

Front End Versatile-TRx

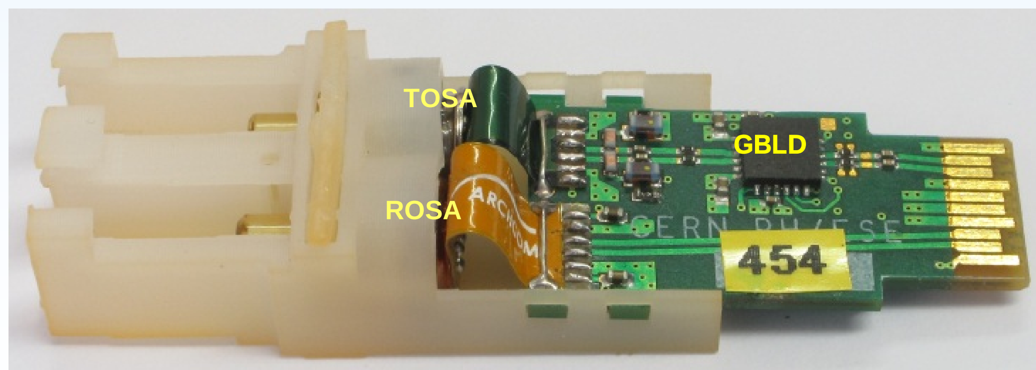
Versatile Link



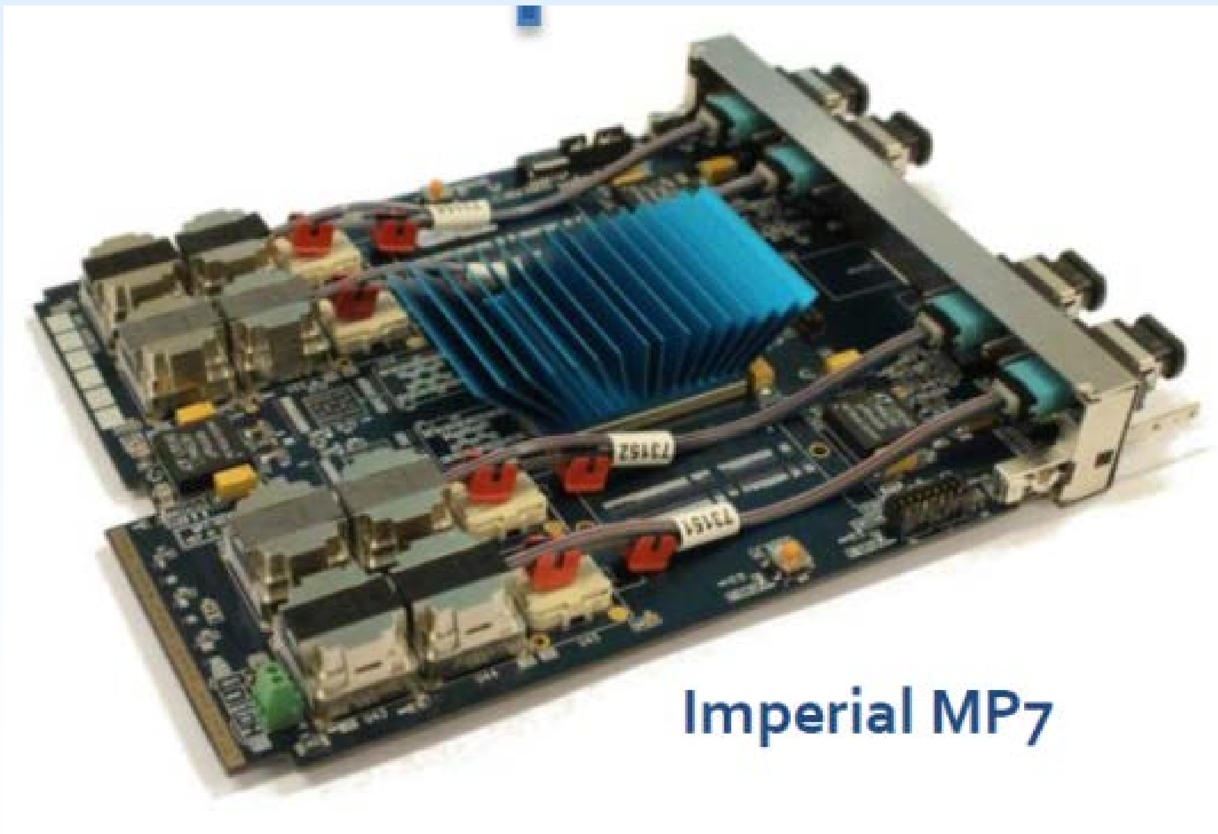


VTRx

- Low Mass & Volume
  - Minimize material, avoid metals
- Non-magnetic, capable of operating in a magnetic field
  - Requires replacement of ferrite bead used in laser bias network
- Bitrate determined by ASICs: 5 – 10 Gbps
  - Custom ASICs
- 850nm and 1310nm flavours
  - COTS Opto
- Radiation hard

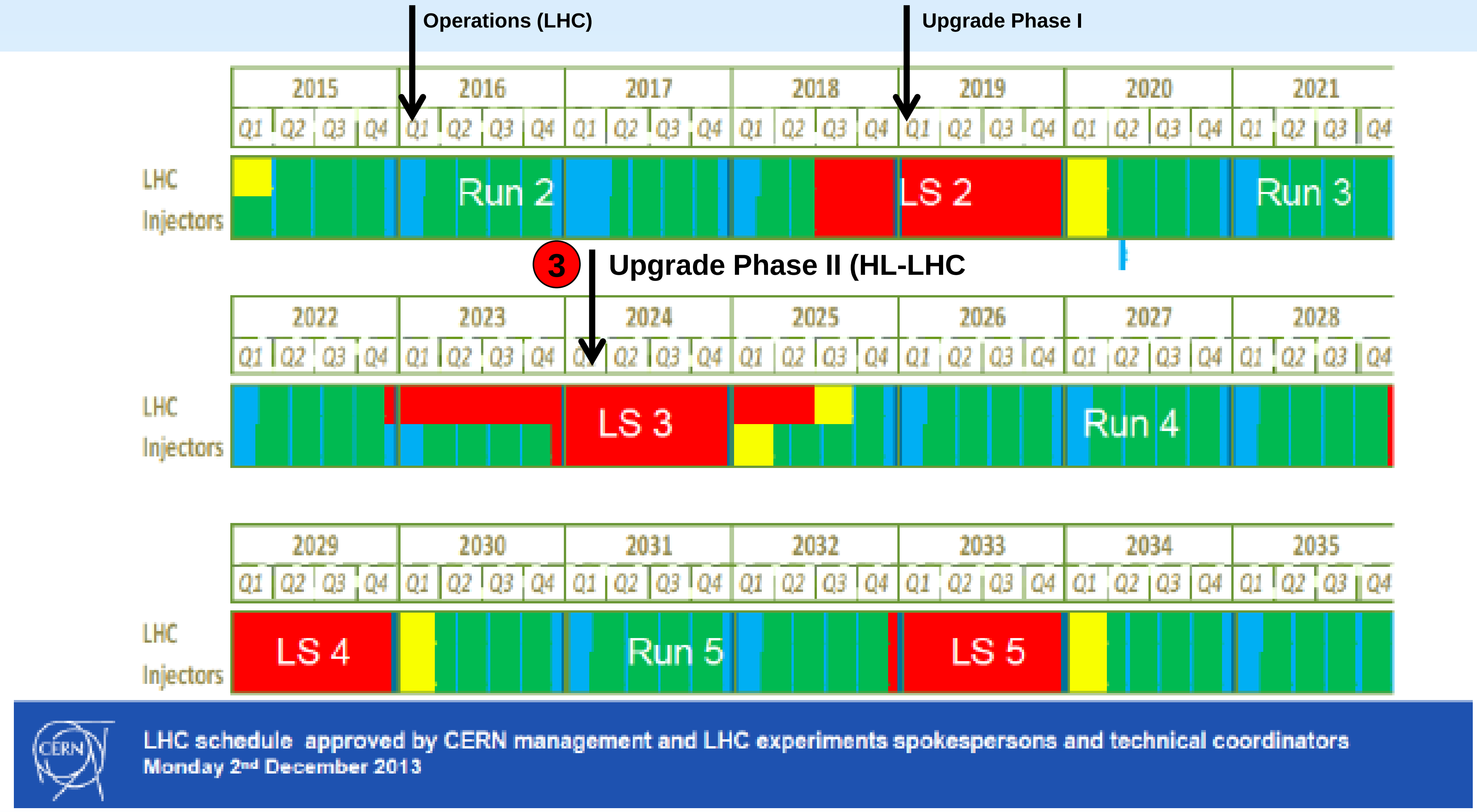


Back-End: mid-board optics

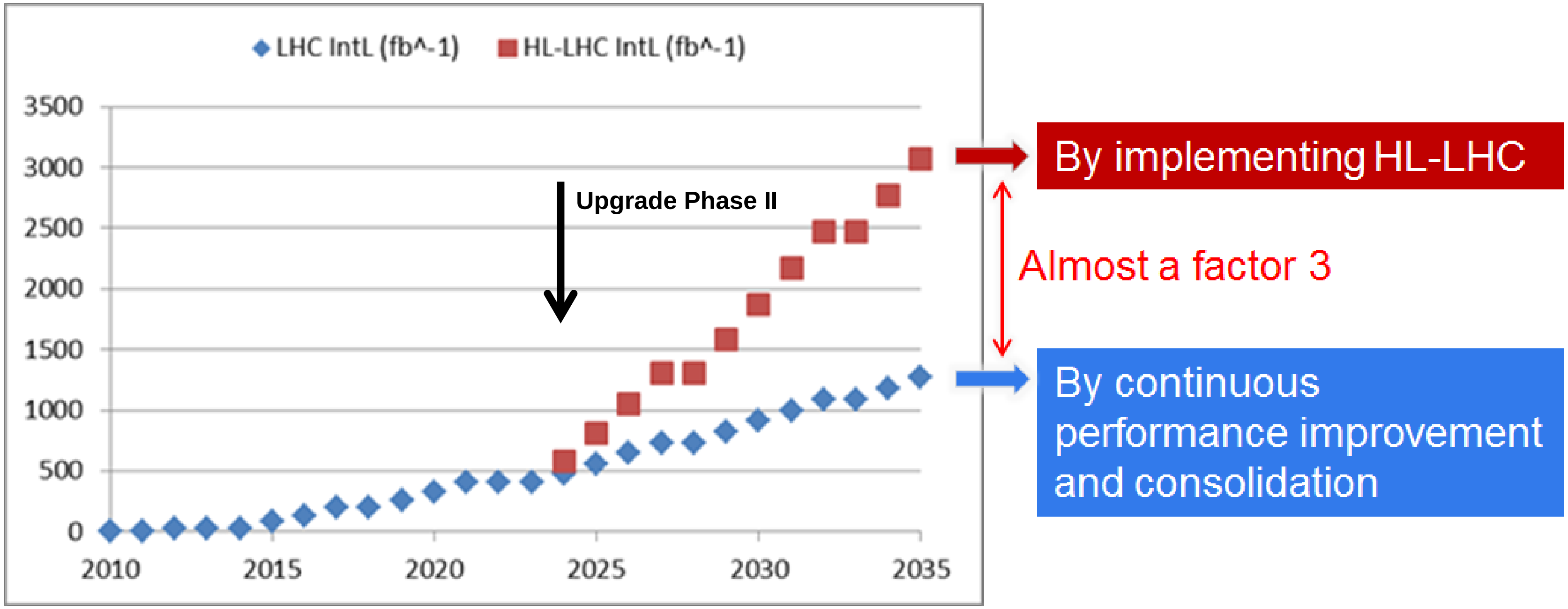


LHC Schedule Drives Experiments Upgrades

Versatile Link



High Luminosity LHC



Goal of HL-LHC project:

- 250 – 300 fb^{-1} per year
- 3000 fb^{-1} in about 10 years

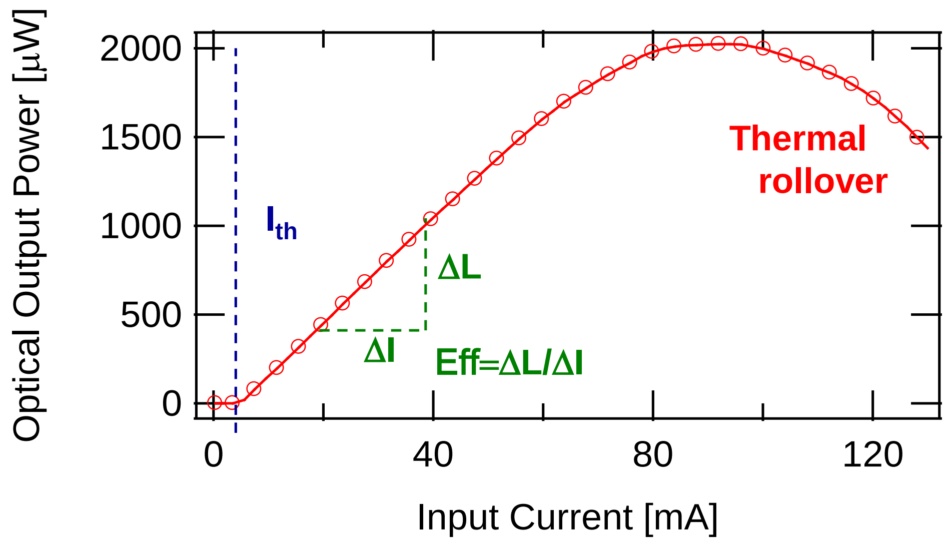
High Luminosity LHC

Environmental Constraints

- Strong Magnetic field (4T)
  - Non-magnetic components
- Compact experiment
  - Reduced footprint, low-mass
- High particle Energy 7+7TeV and High rate
  - Large radiation field (mainly pions and neutrons)
  - Radiation tolerant components
    - Total dose and fluence
    - Single Event Effects
- Limited access
  - High reliability

Laser L-I Characteristic vs Irradiation

Light-Current (L-I) characteristic of a non-irradiated laser at T_{amb}=20°C

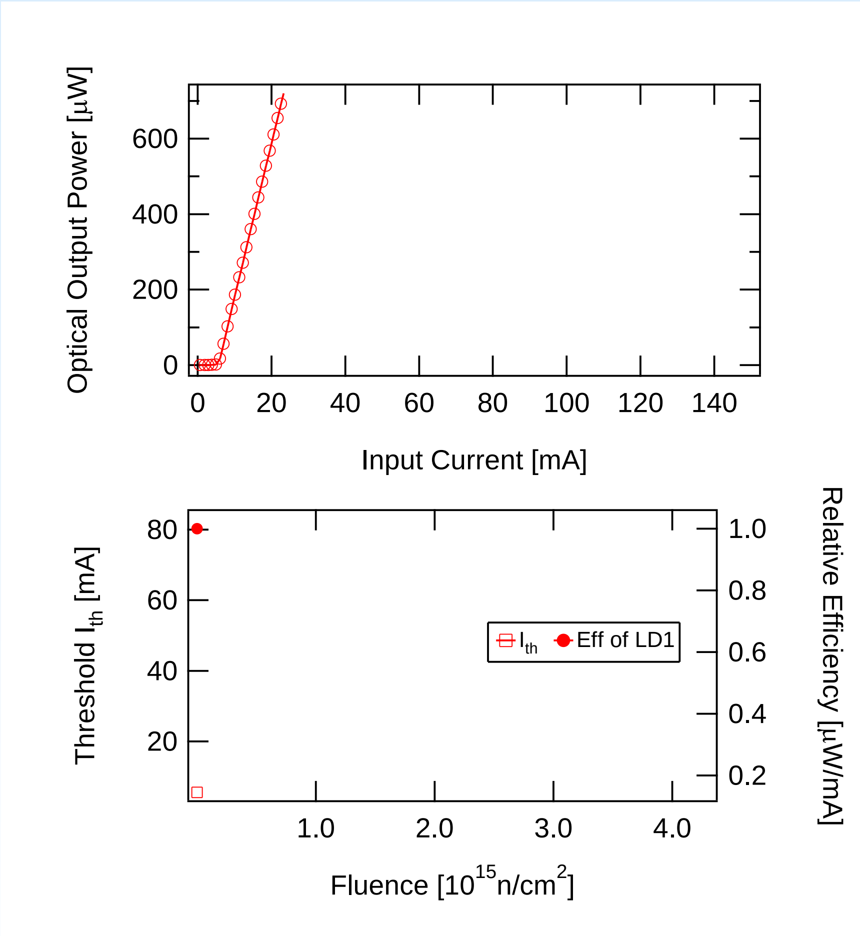


- **Threshold current I_{th}**
  laser starts to emit coherent light

- **Efficiency Eff**
  slope of L-I curve in linear part

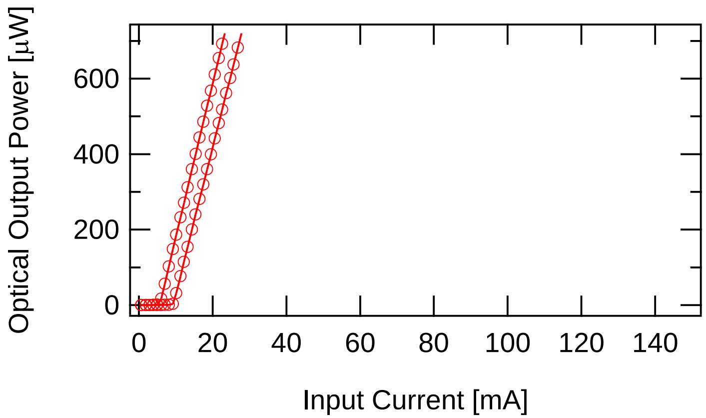
- **Thermal rollover**
  non-linear part of L-I curve where non-radiative recombination mechanisms (Auger) become dominant due to internal temperature

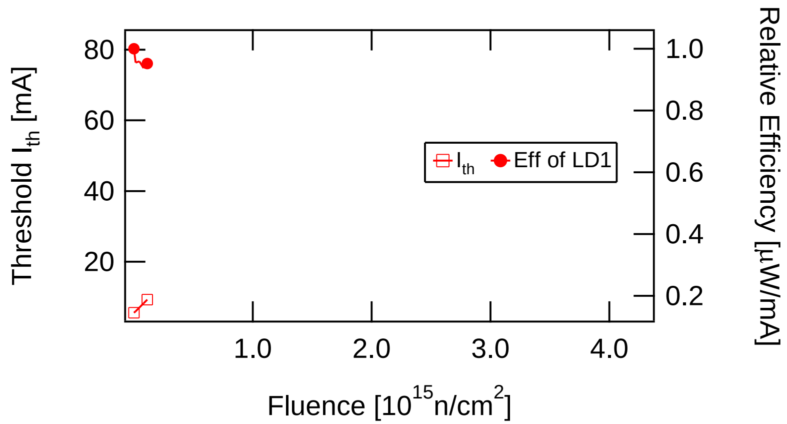
Radiation Damage (1)



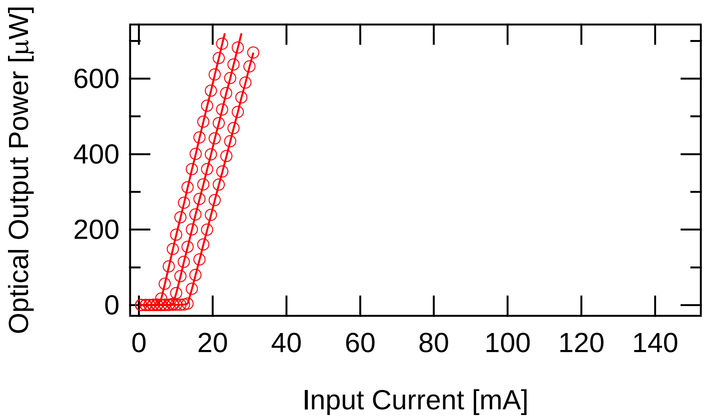
- **Before irradiation**

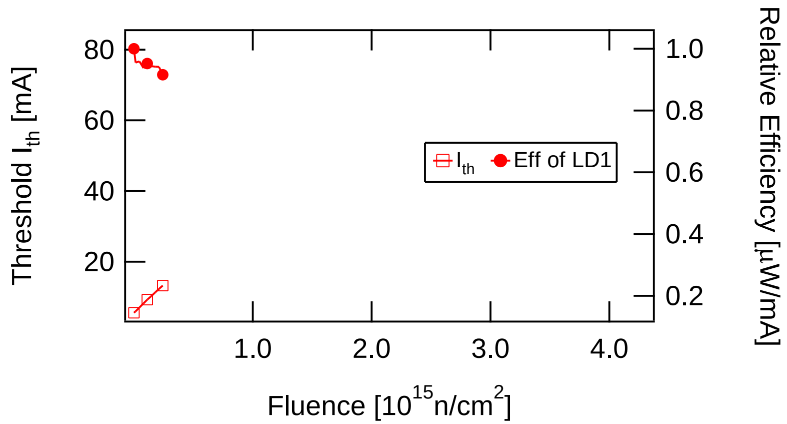
Radiation Damage (2)



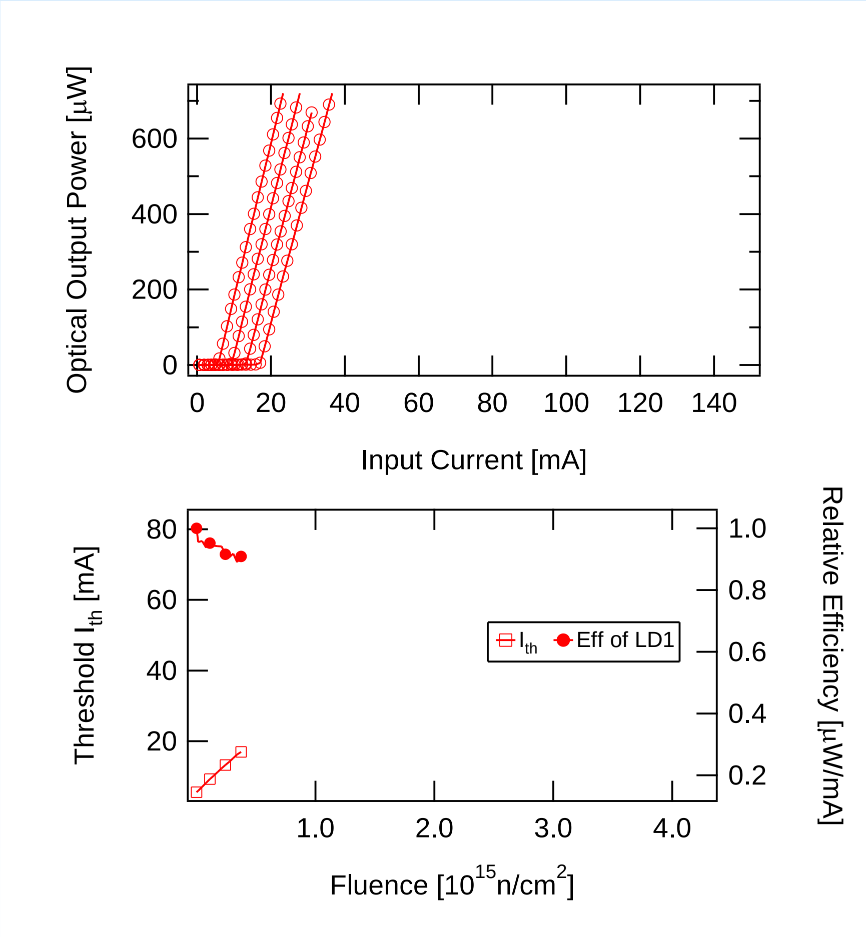


Radiation Damage (3)



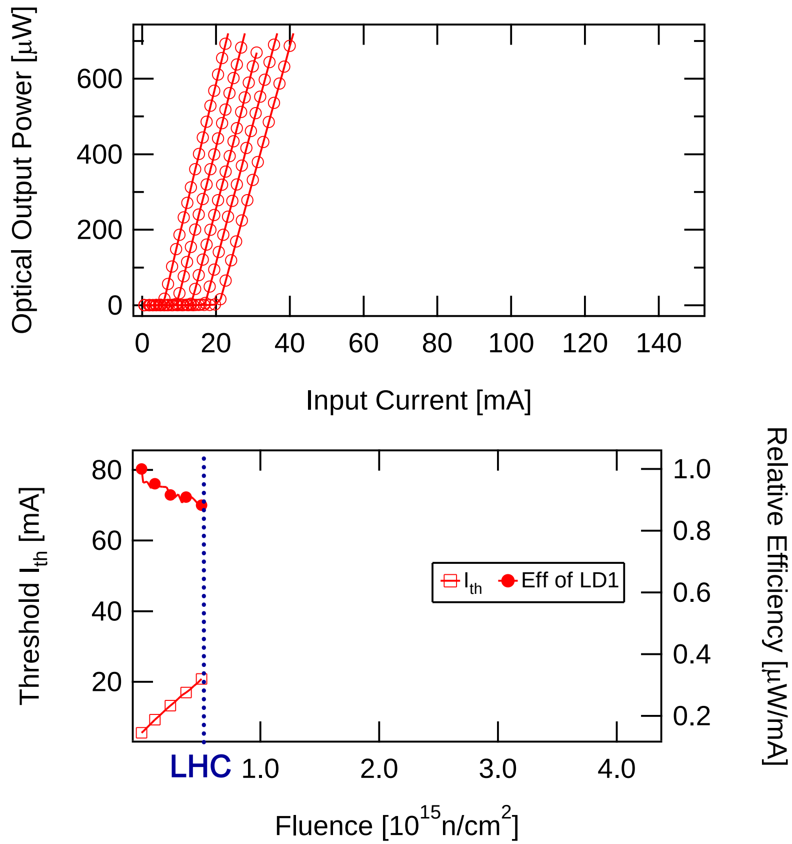


Radiation Damage (4)



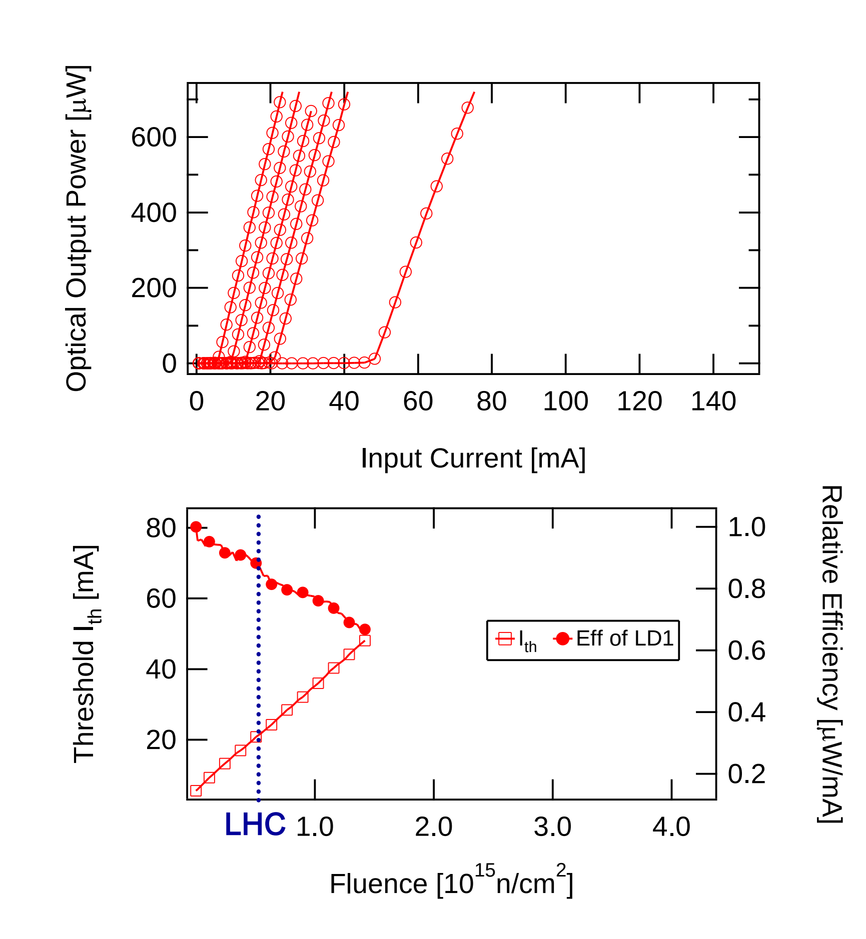
Radiation Damage (5)

Versatile Link



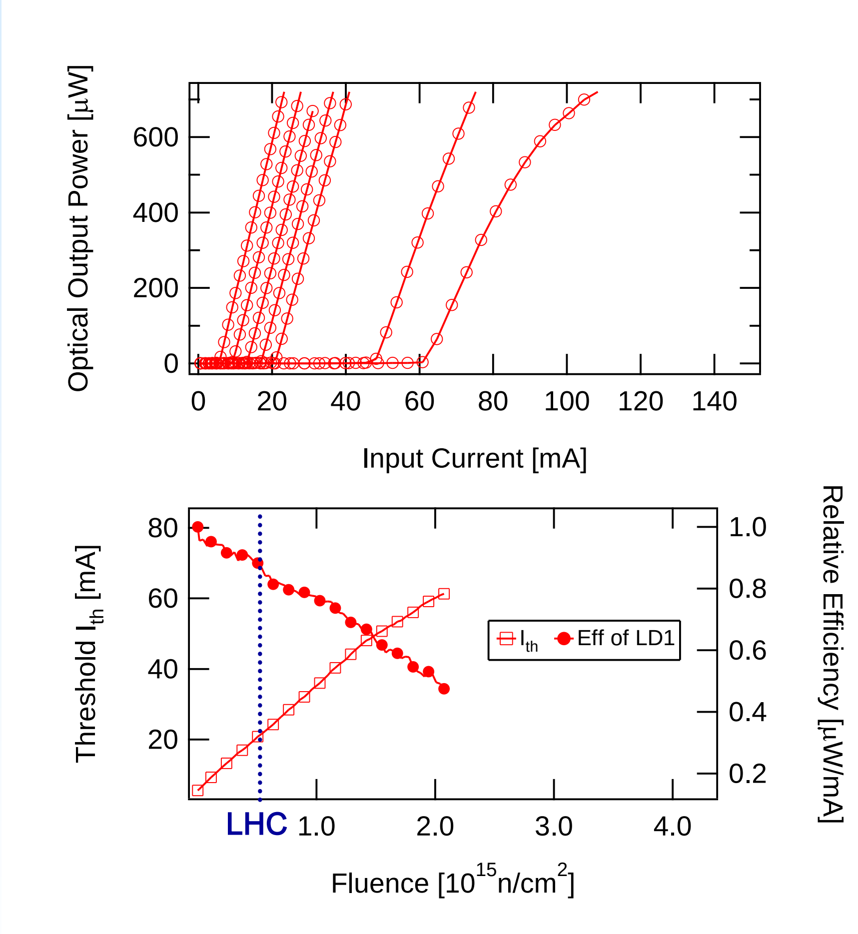
- After ~2.5 hrs of irradiation a fluence of $4x10^{14}$ n/cm^2 (20MeV) reached ('LHC fluence')
- Radiation damage in terms of threshold or efficiency is proportional to neutron fluence
  - Threshold increase
  - Efficiency loss
- ~70% of damage will eventually anneal
- Driving electronics designed accordingly

Radiation Damage (6)



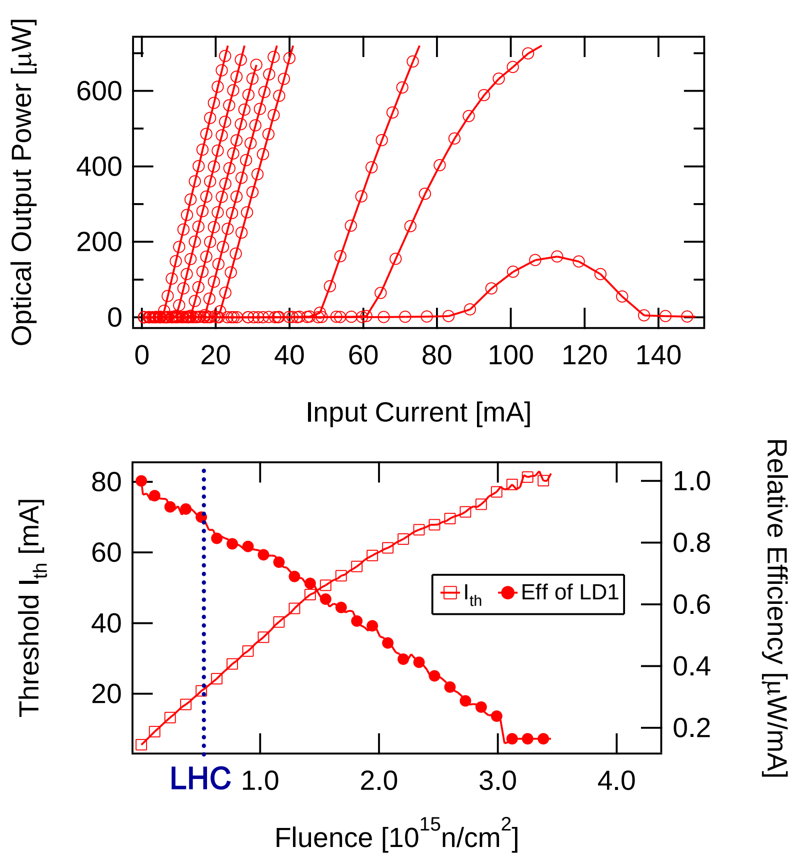
- Beyond a **fluence of $4x10^{14}$ n/cm^2** (‘LHC fluence‘)
- Radiation damage in terms of threshold or efficiency is still proportional to neutron fluence

Radiation Damage (7)

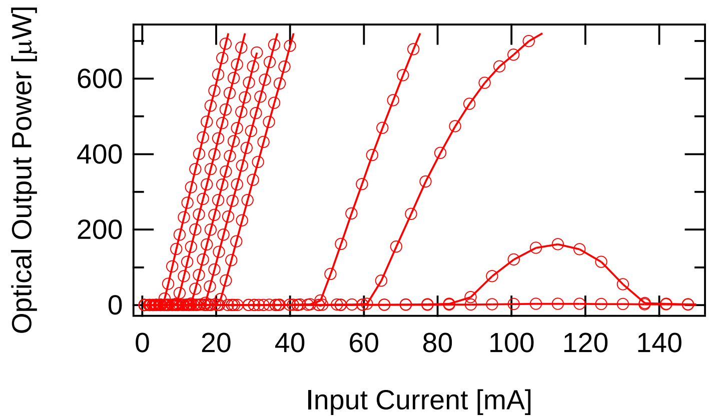


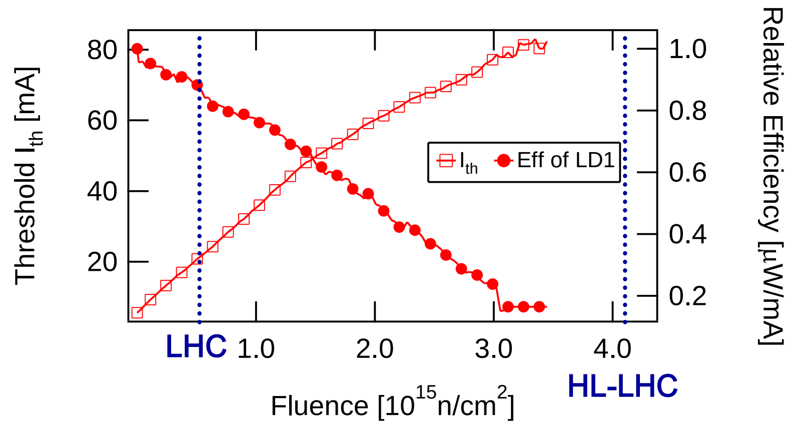
- **Thermal rollover becomes visible**

Radiation Damage (8)



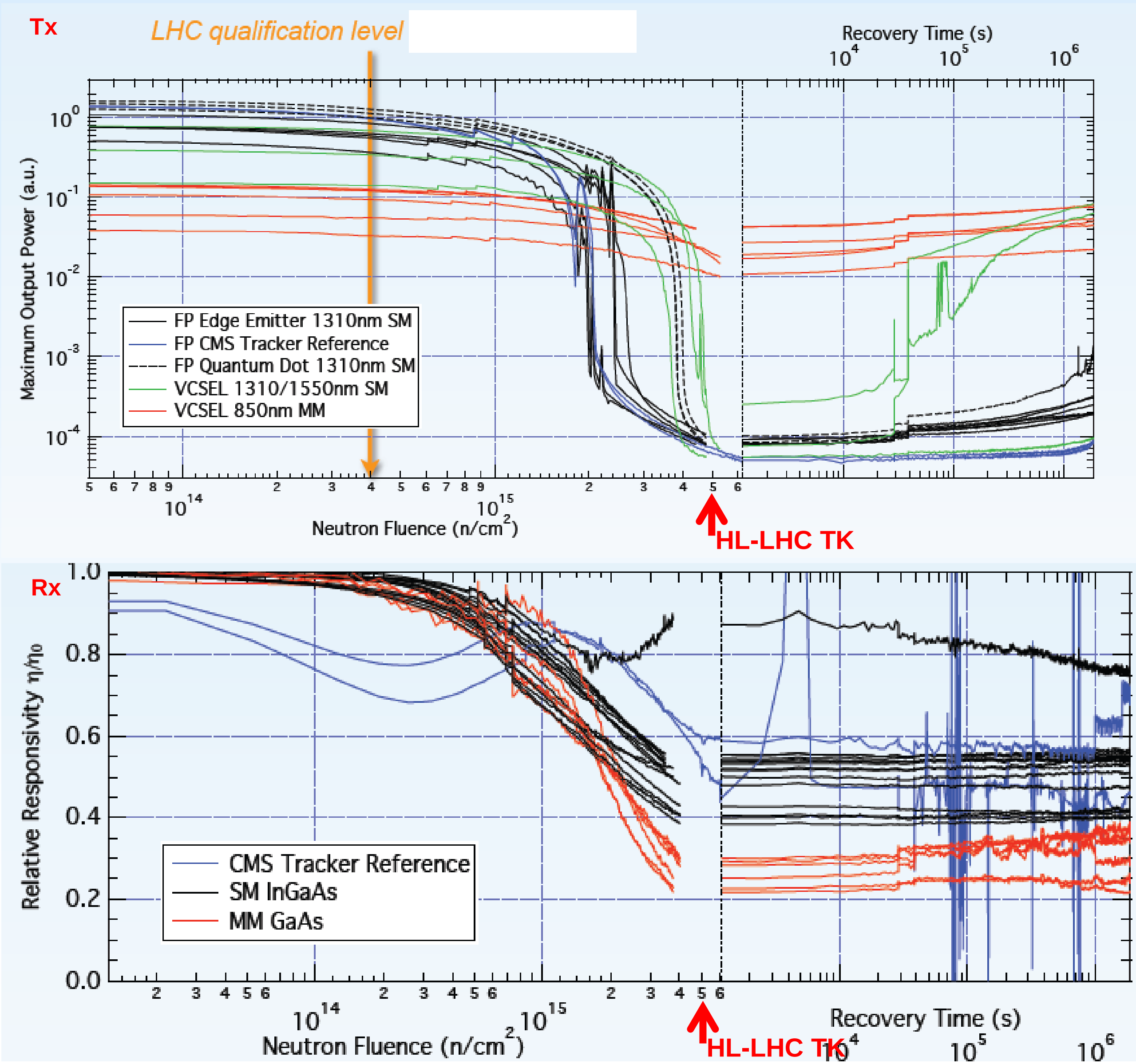
Radiation Damage (9)





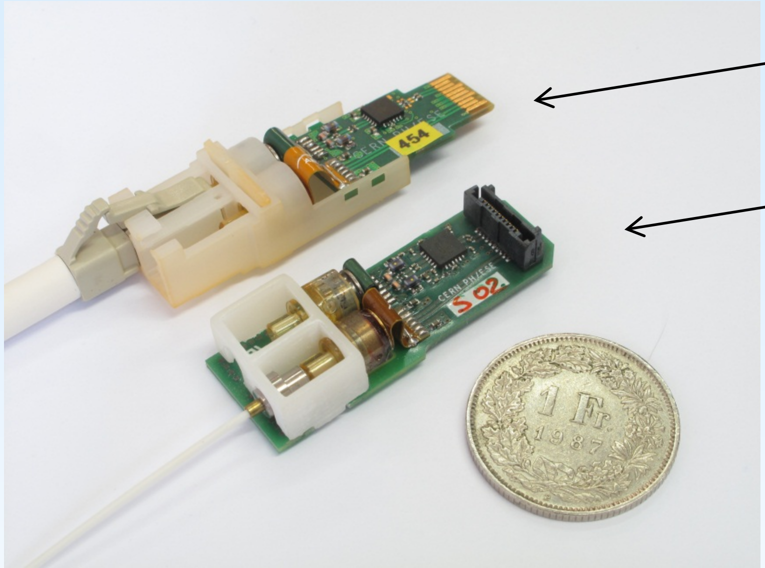
- **Thermal rollover**
- **In excess of 3x10^{15} n/cm^2 the efficiency approaches zero**

Radiation Resistance Summary



- ASICs OK
- Active opto devices OK except for pixels
  - Tight margins
  - Are there alternatives for fluences beyond 10^{16} cm^{-2} ?
- Reconsider Passives?
  - modulators

Towards HL-LHC



SF-VTRx versus Multi-mode VTRx

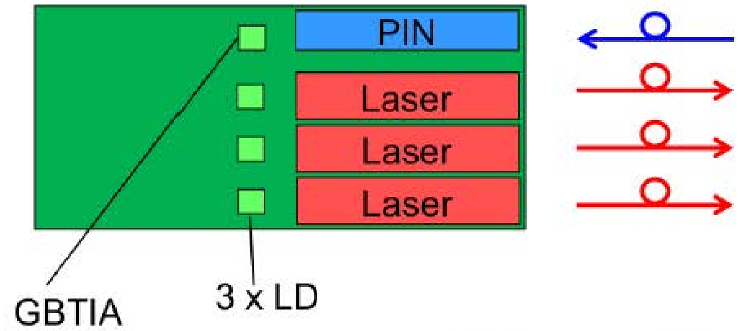
Phase I upgrade, now in production

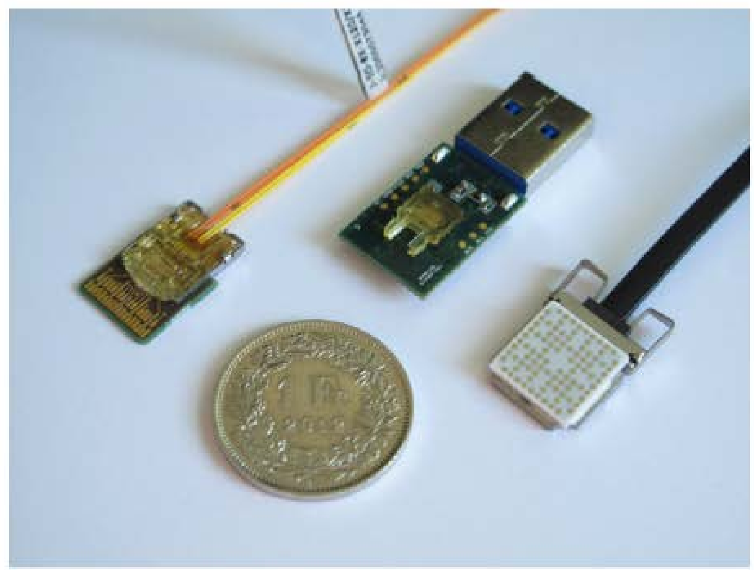
Phase 1.5

Phase II upgrade ???

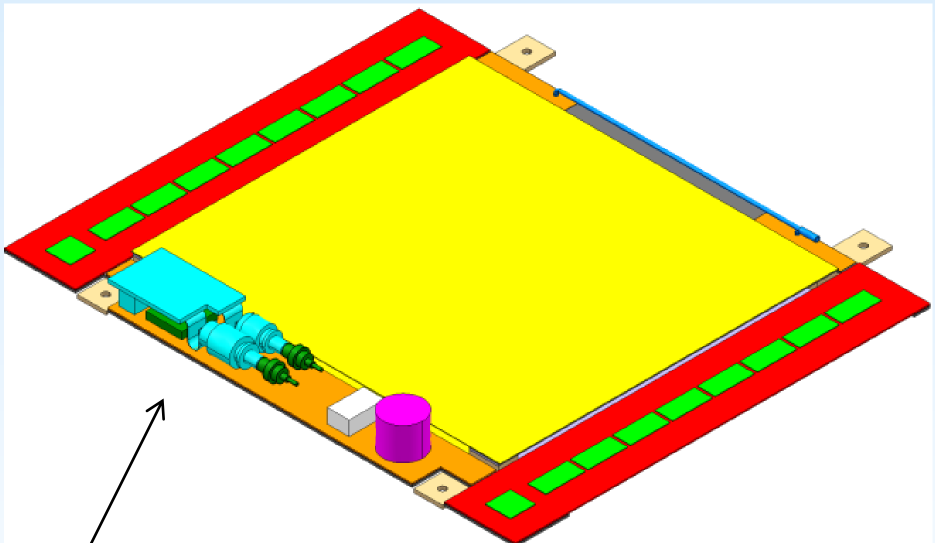
The Versatile Link +

- Small form factor, high speed optical modules needed for:
  - CMS tracker modules
  - ATLAS EoS
- 5G downstream, 10G upstream:
  - Driven by GBTX evolution path
  - 10G laser driver ASIC
- Smaller
  - Revised optical interface
  - MM only
- Denser
  - Up to 4 channels
- Versatile
  - Common package
  - Number of up/down links
  - Configurable at assembly time or by turning off unused channels
- On-going work
  - 10 Gb/s tiny single/quad LD
  - Package, fibres, connectors
  - Feasibility study until fall 2015

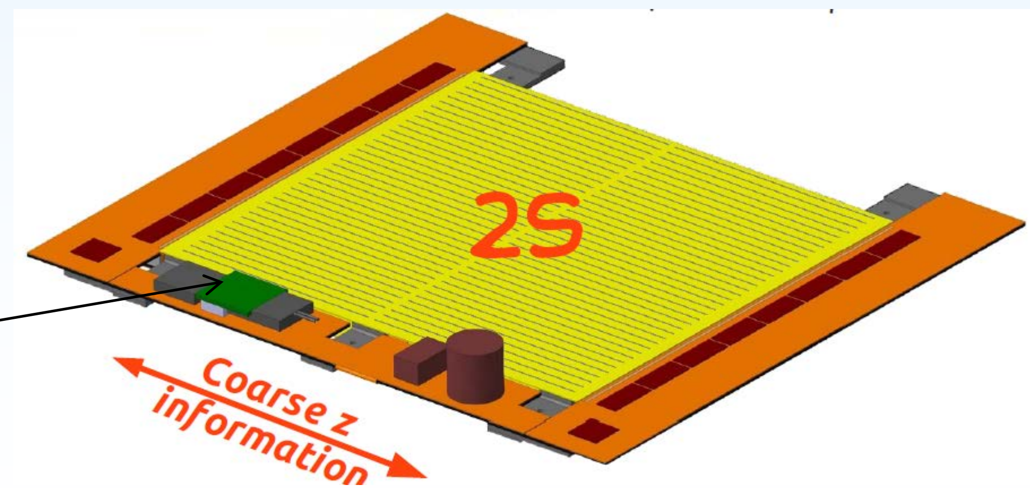




Integration on Phase II Sensor Module

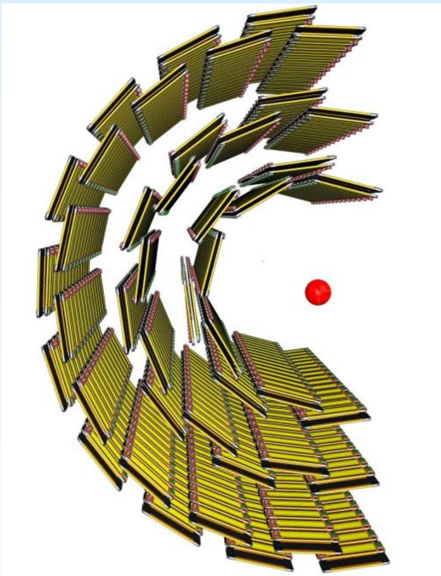


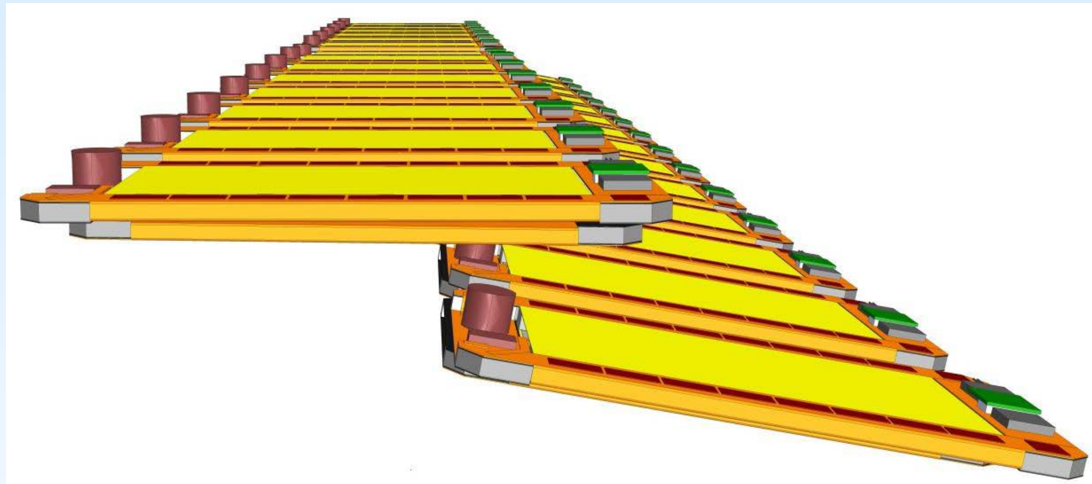
Phase 1.5 SF-VTRx

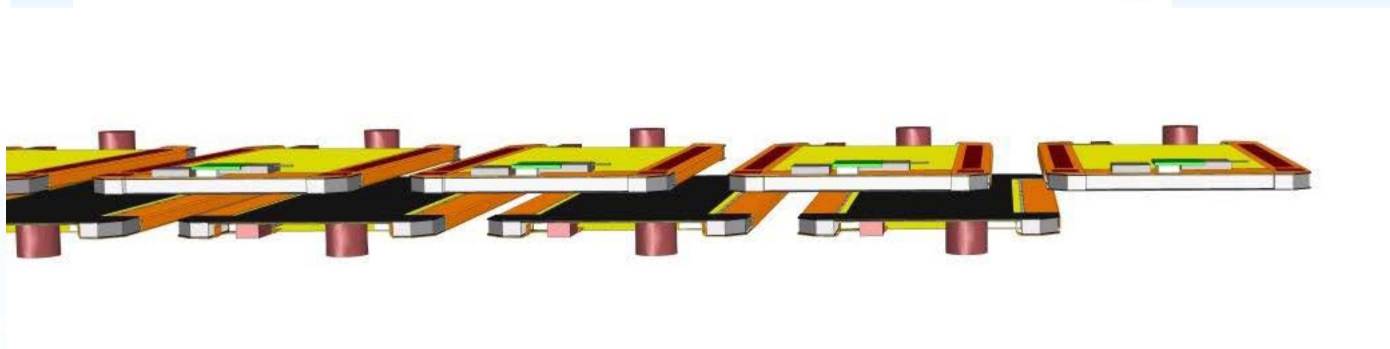


Phase 2 VTRx+

Building Tracker Barrel Rods



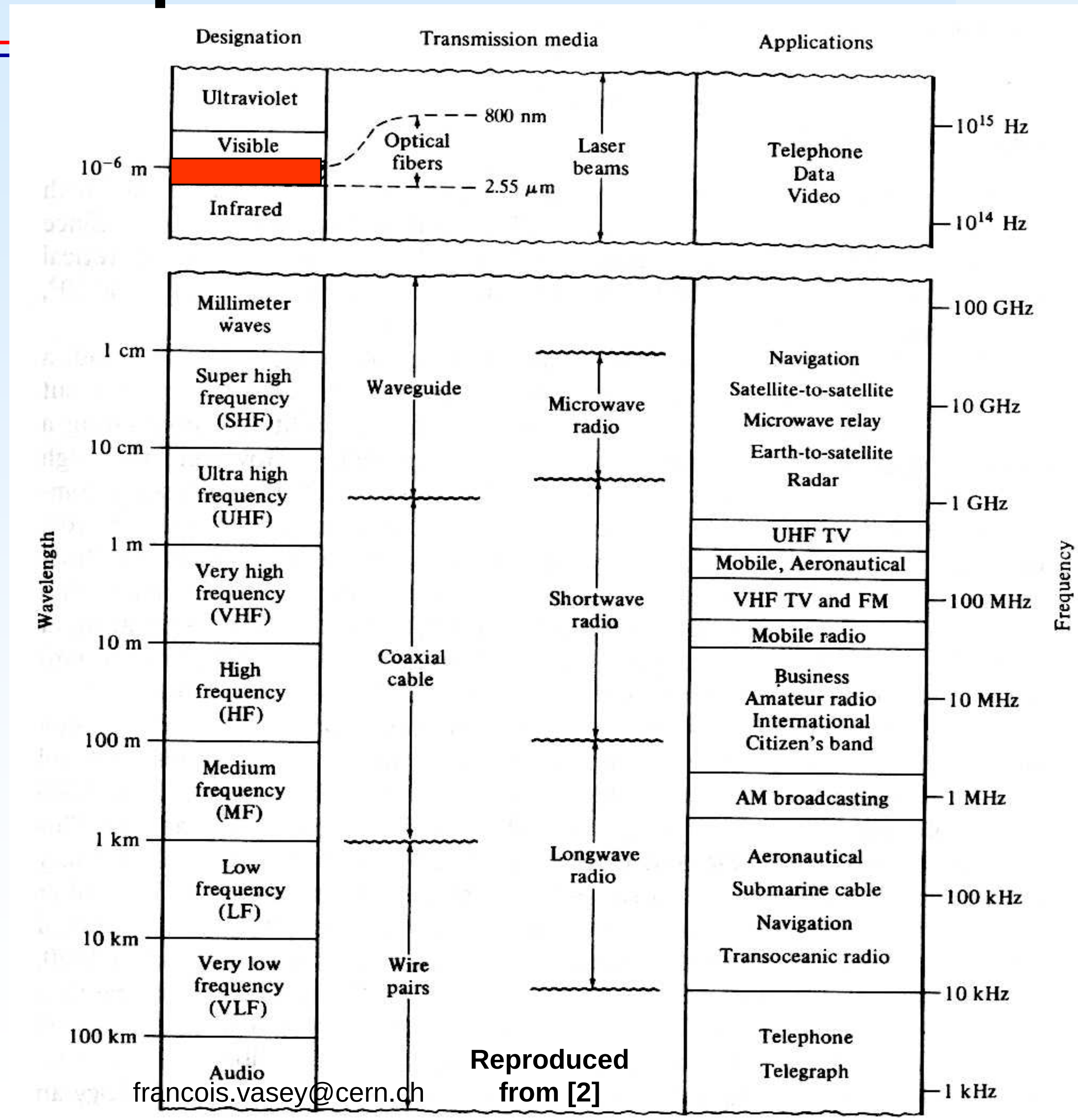




Backups

EM Spectrum

- EM spectrum usage:
- 1840s Telegraph
- 1880s Telephone
- 1890s Radio
- 1940s Microwaves
- 1950s bipolar transistors
- 1960s Lasers
- 1970s Optical fibres
- 1990s Er-doped fibre



Reproduced from [2]

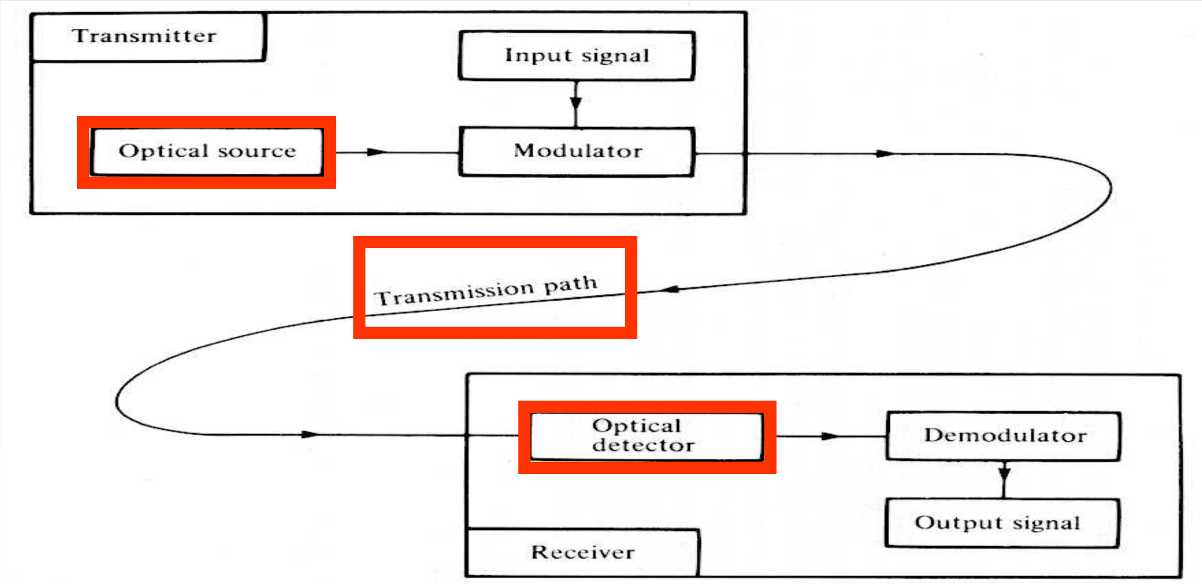
Data Transmission Model

Versatile Link

Emission

Refraction
Attenuation
Dispersion

Absorption

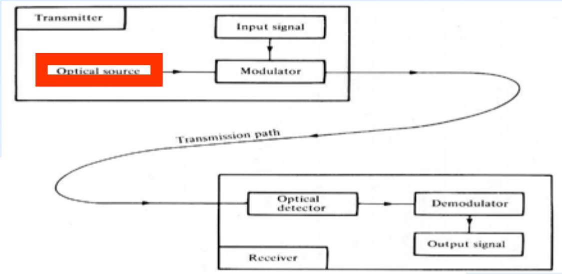


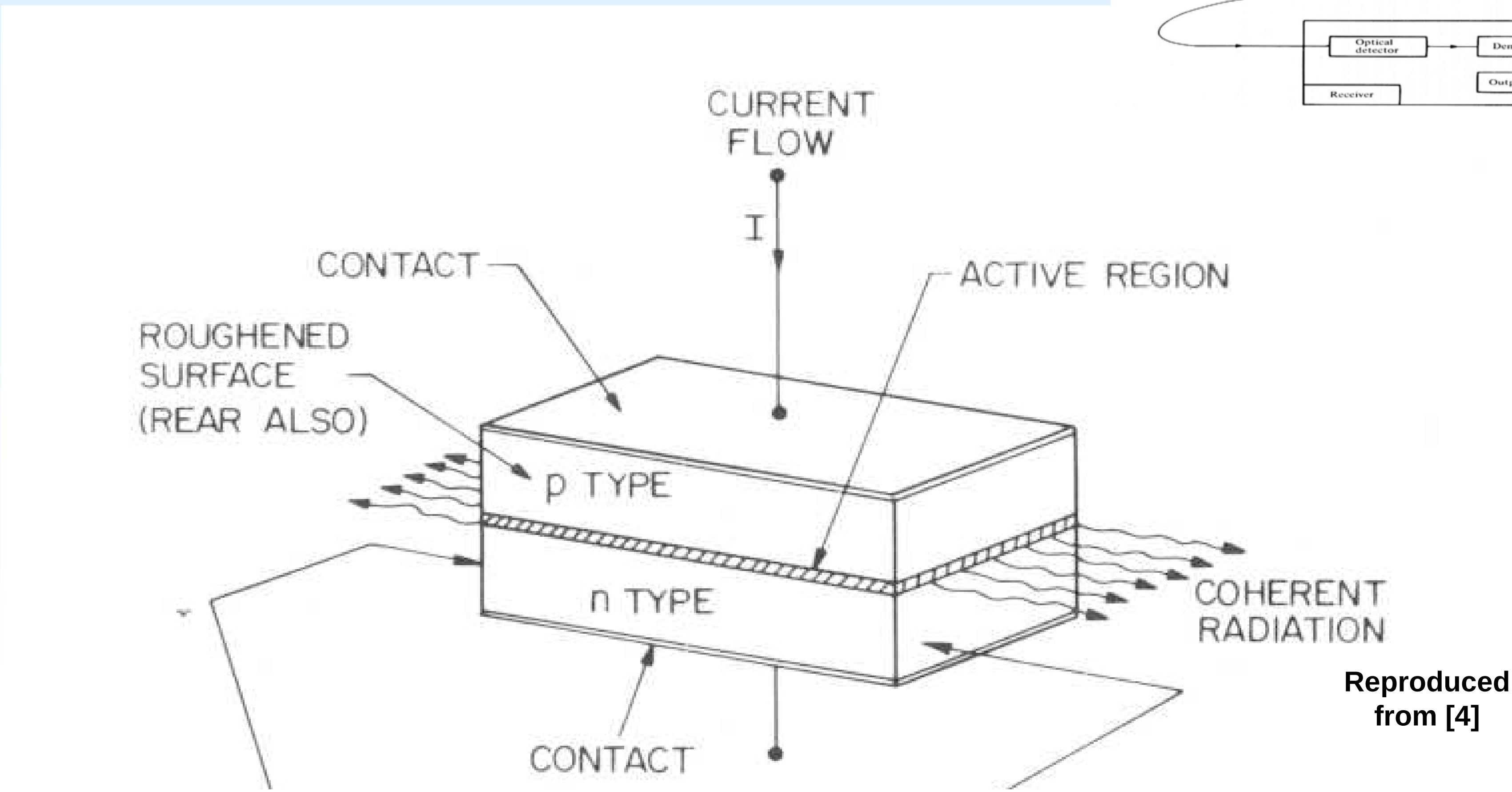
Optical communication systems are not new
Greek fire chains with relay stations existed 1000years BC
Missing for a long time was the perfect match of bandwidth, distance and availability

Emission in semiconductor cristal

Versatile Link

- Injection luminescence
- Competition with non-radiative transitions
- External quantum efficiency must be maximised
- Coupling efficiency problematic: horizontal, vertical





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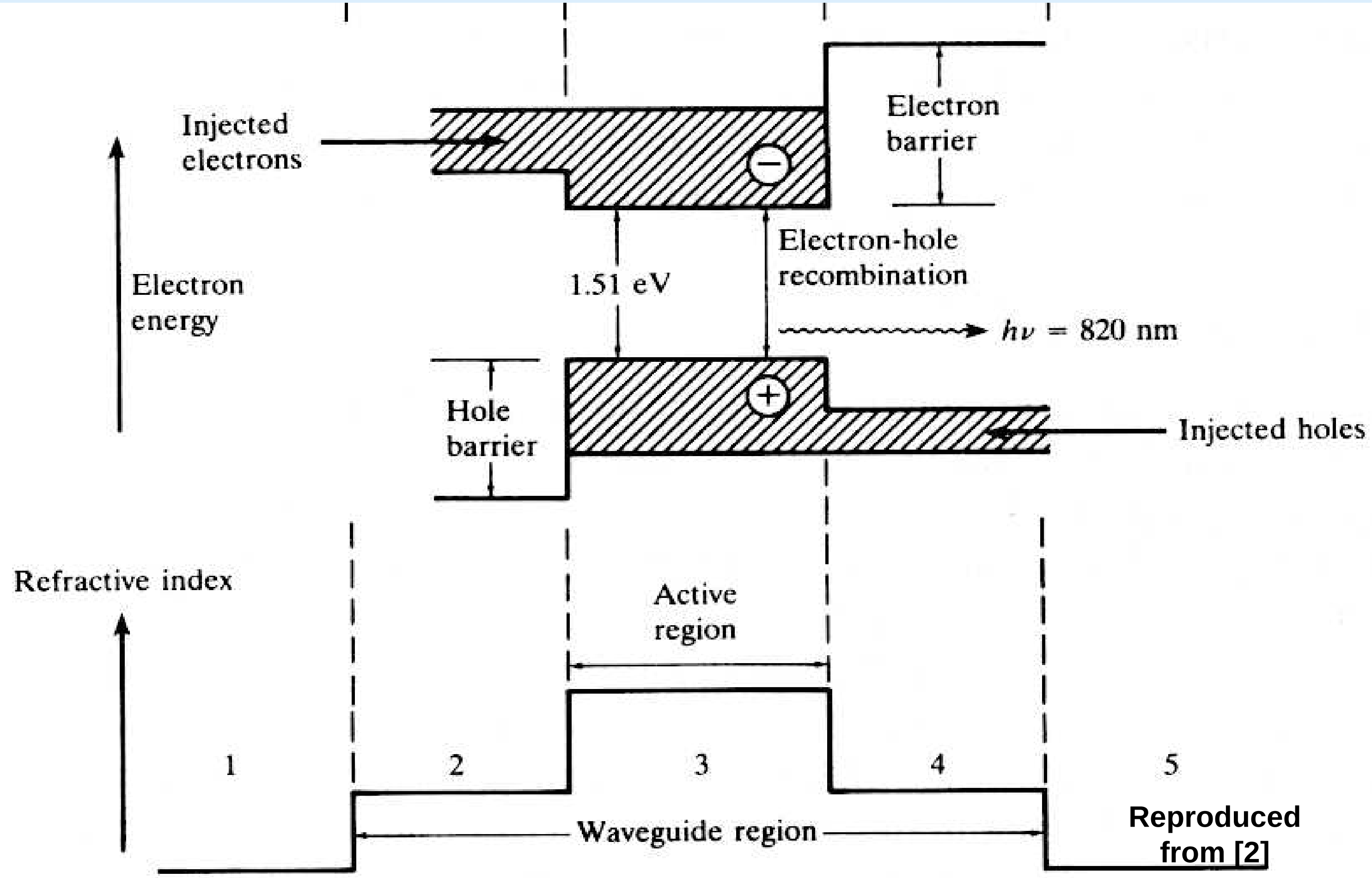
Semiconductor heterostructure

- Modulation by direct injection
- Electrical confinement
- Optical confinement
- Temperature dependence



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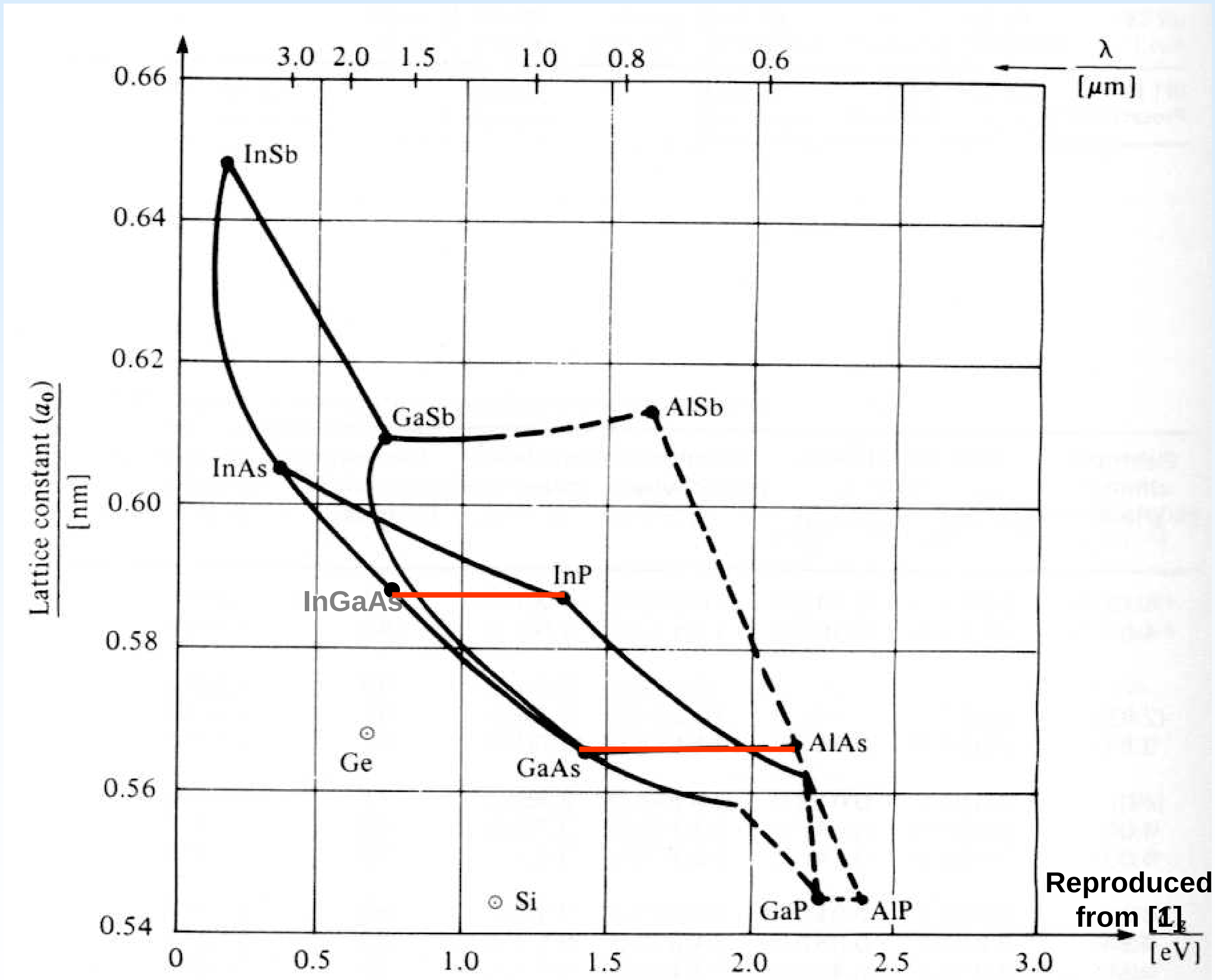
Ternary Material System

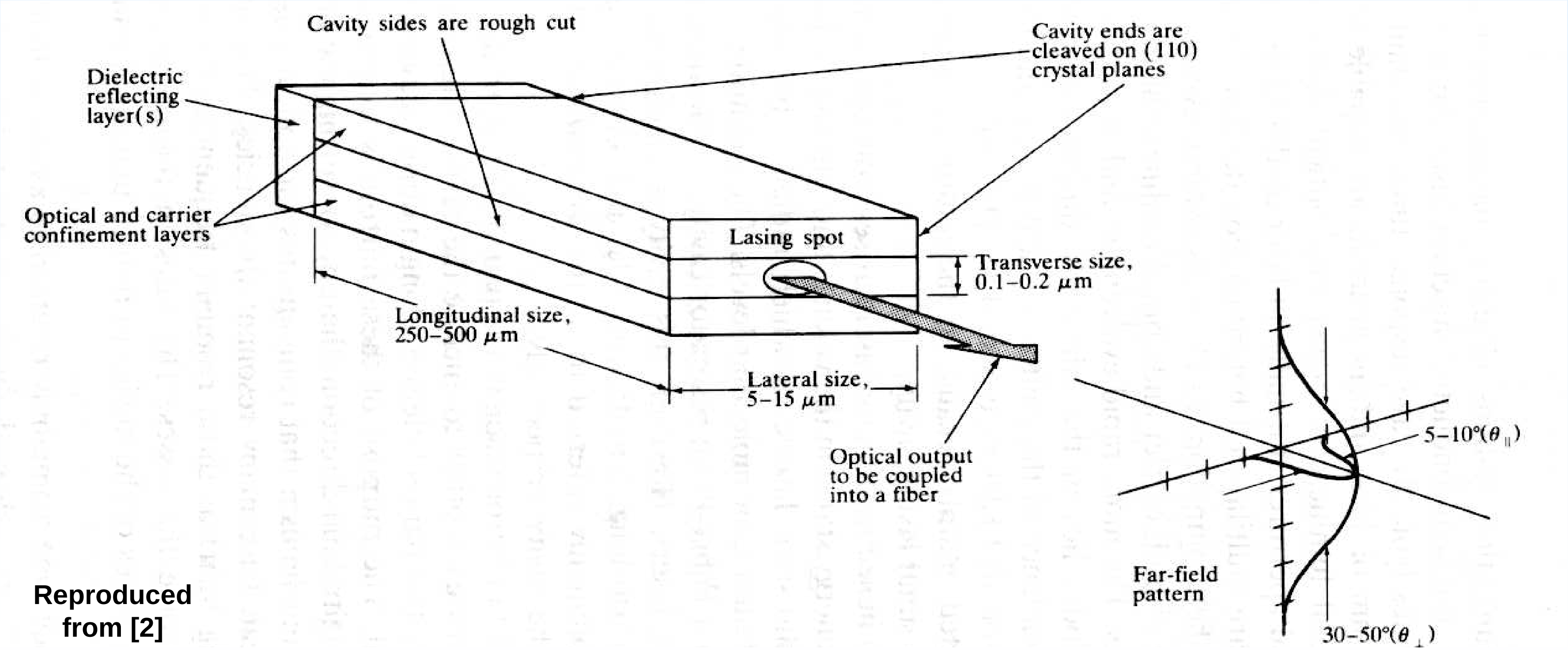
- (quasi) lattice matched structures
- Epitaxial growth
- Tight defect control



Reproduced from [1]

Semiconductor Laser Structure: horizontal cavity

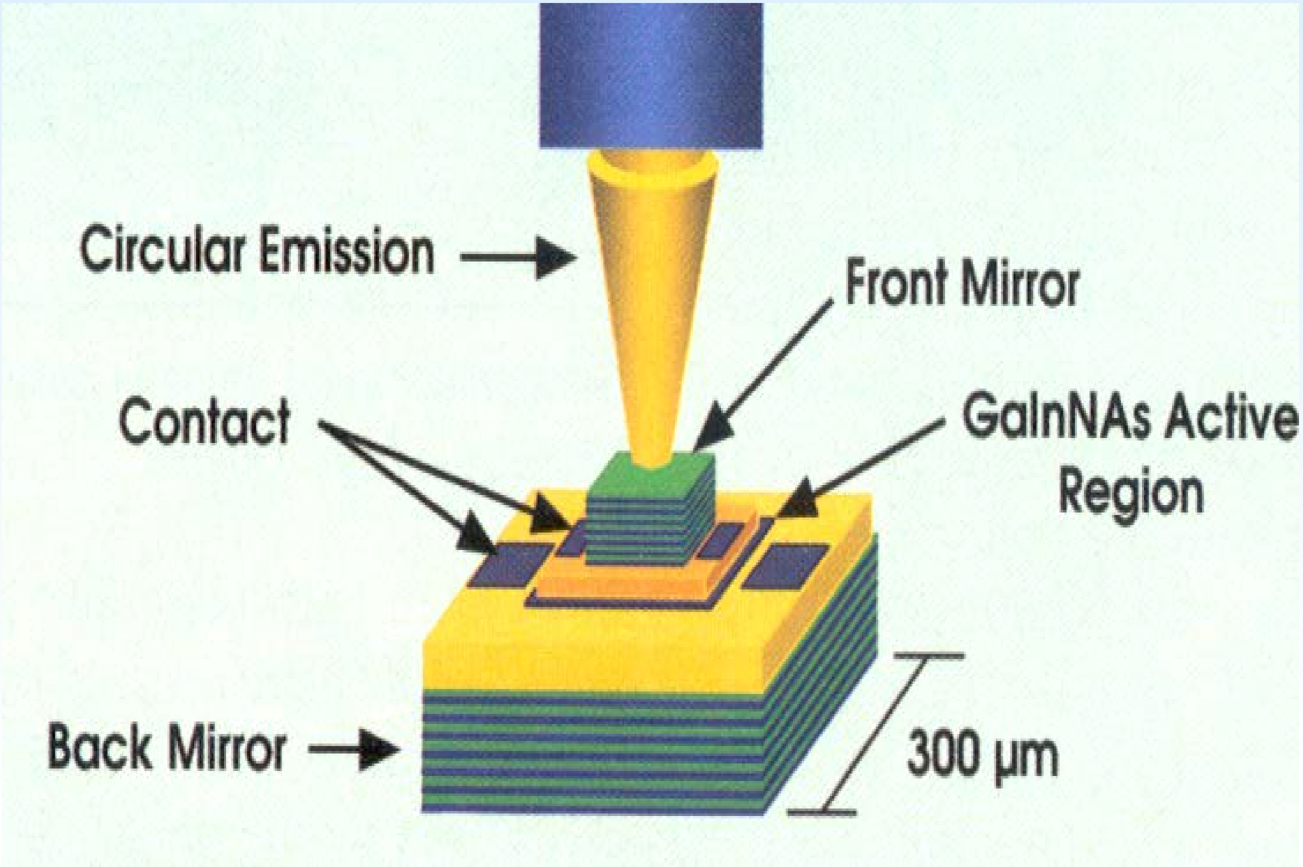
- Narrow Spectrum
- Multiple longitudinal modes
- High modulation bandwidth
- Divergent beam
- Cleaved facets



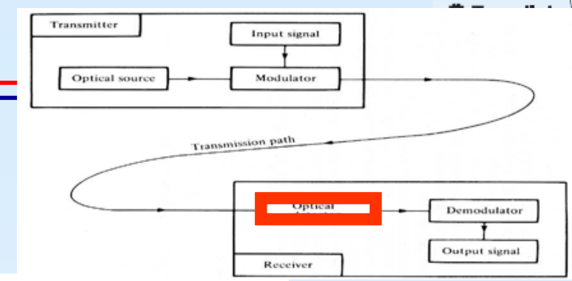
Reproduced from [2]

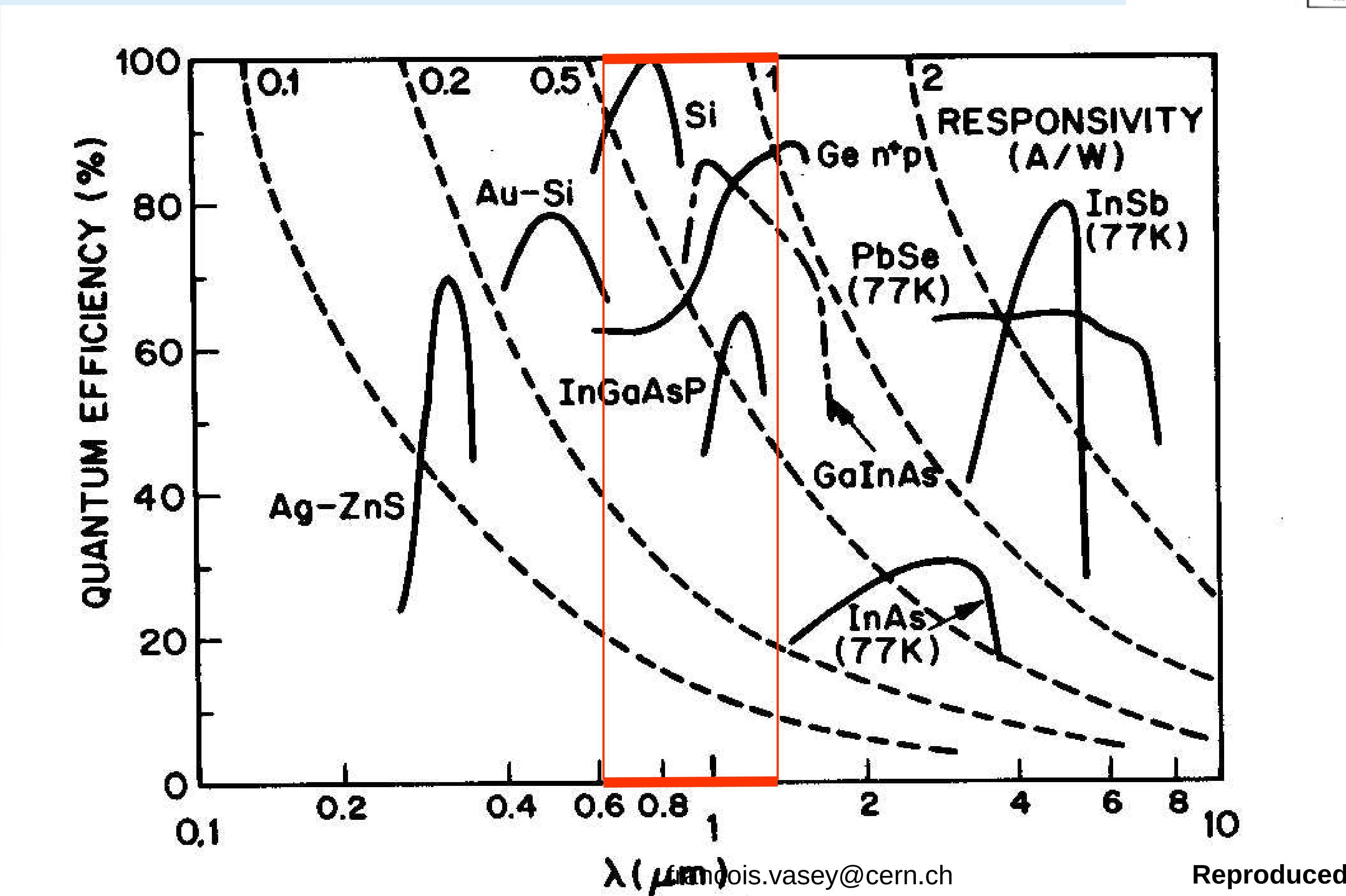
Semiconductor Laser Structure: vertical cavity

- Single longitudinal mode
- On wafer testing
- Complex epi growth
- Difficult to realize in InP material system
- Direct coupling to fibre



Detector Material Responsivities

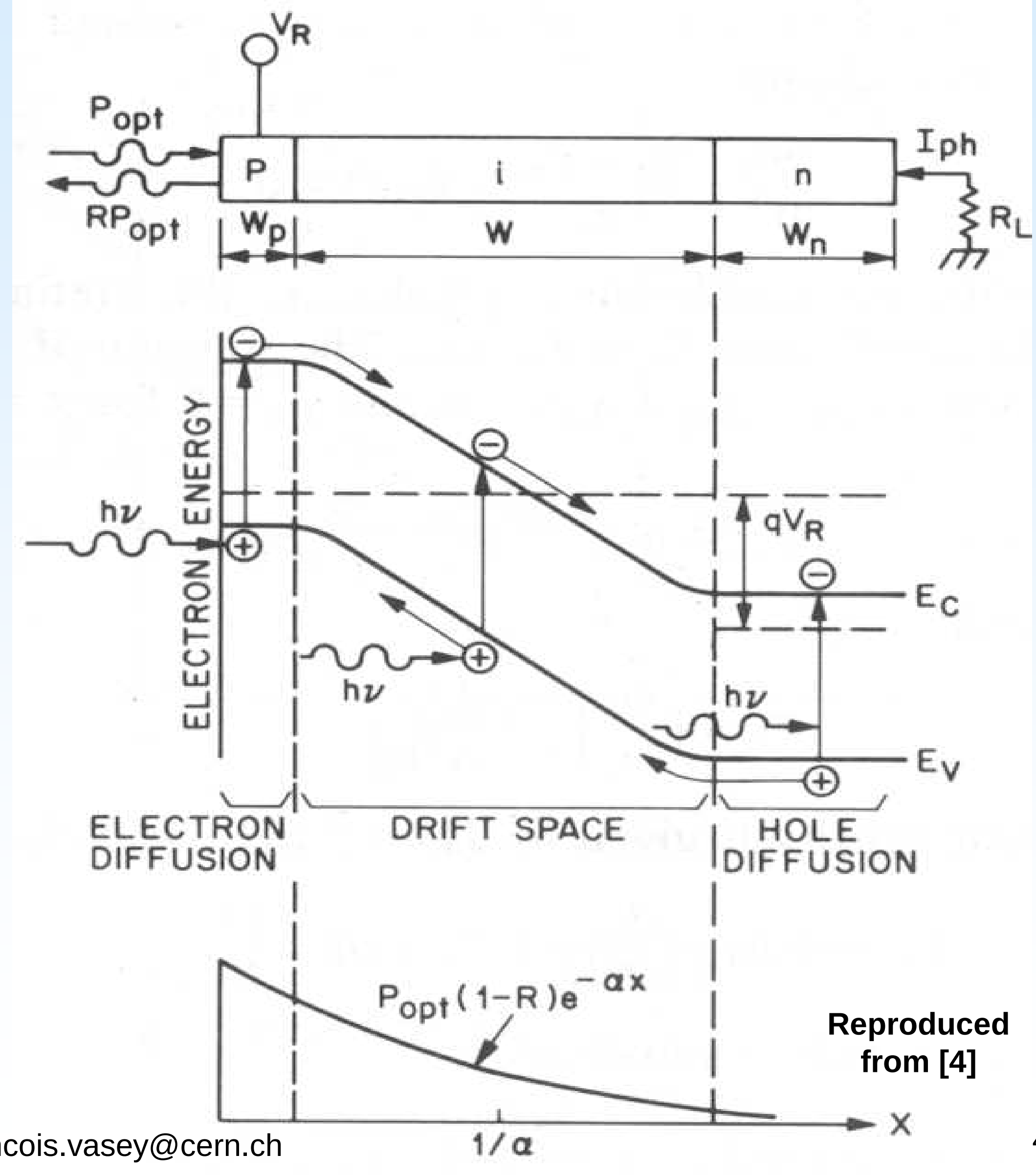




Reproduced from [4]

Detector PIN structure

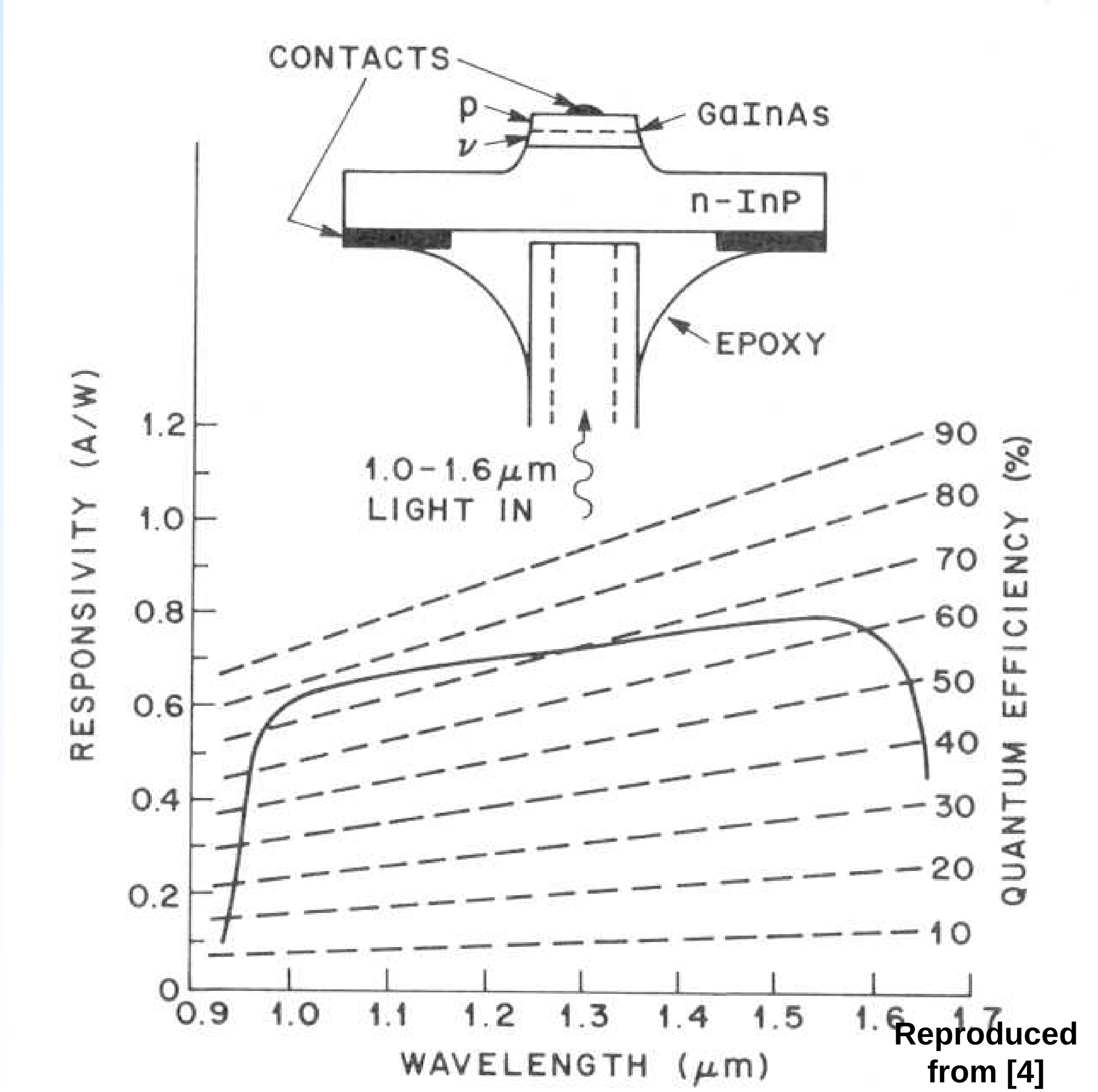
- Electron-holes separated by bias field
- Absorption depth optimised wrt recombination time
- Capacitance wrt light collection efficiency



Reproduced from [4]

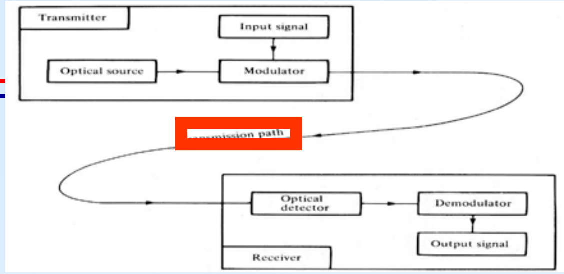
InGaAs pin diode

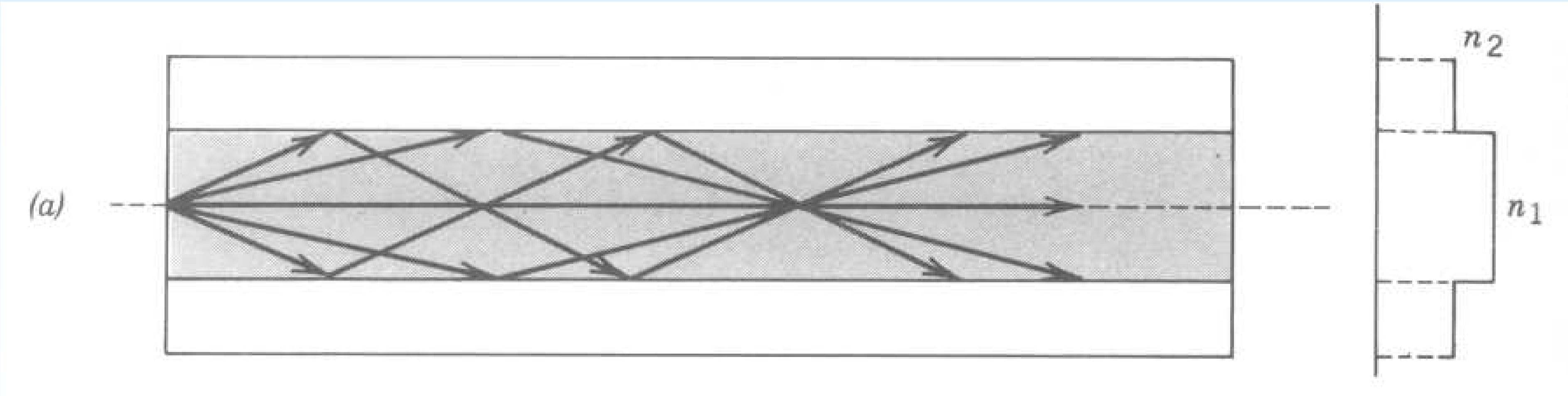
- Vertical access
- Back or front illuminated (transparent substrate)
- Excellent coupling
- Short wavelength response dominated by surface absorption



Reproduced from [4]

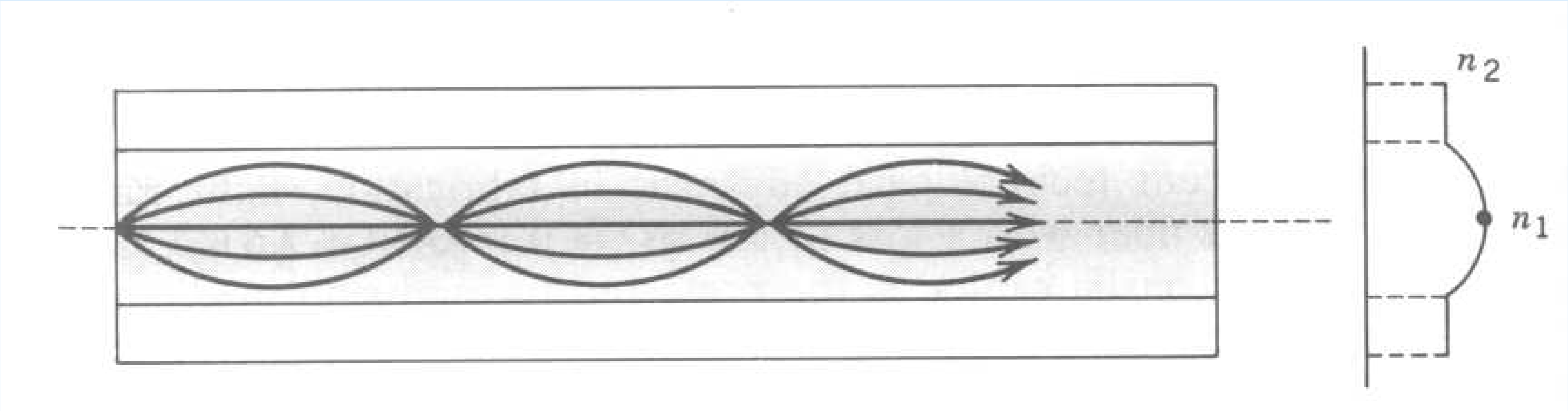
Step Index Optical Fibres





- Only a discrete set of guided modes propagate
- Most energy in core
- Launch from edge only
- Leakage in bends
- Subject to modal dispersion

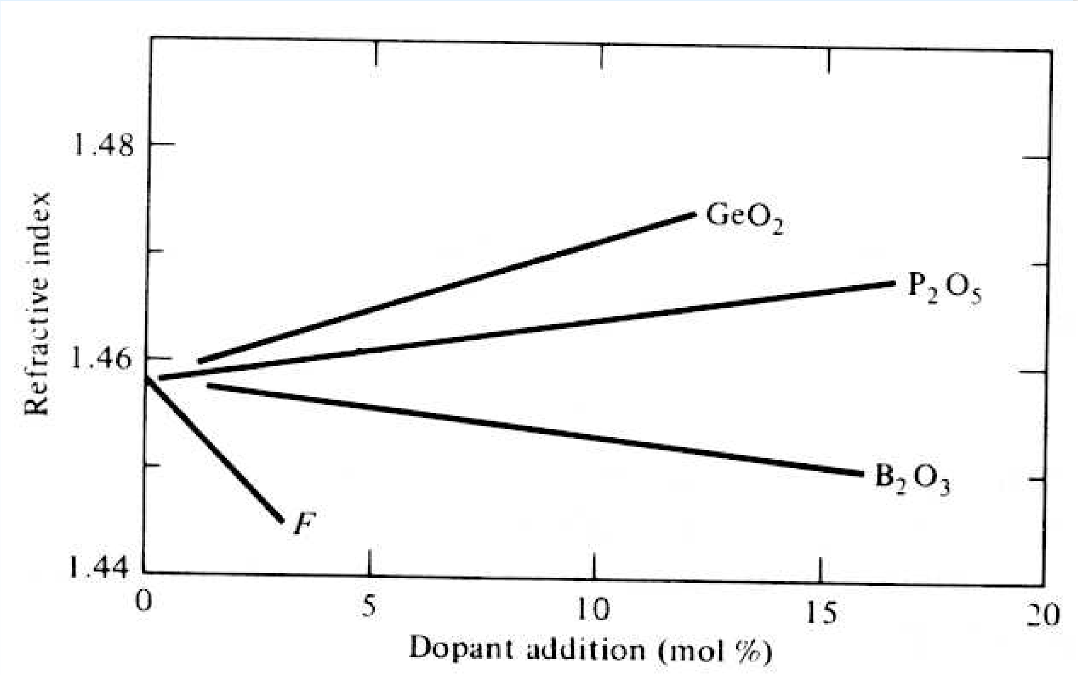
Graded Index Optical Fibres

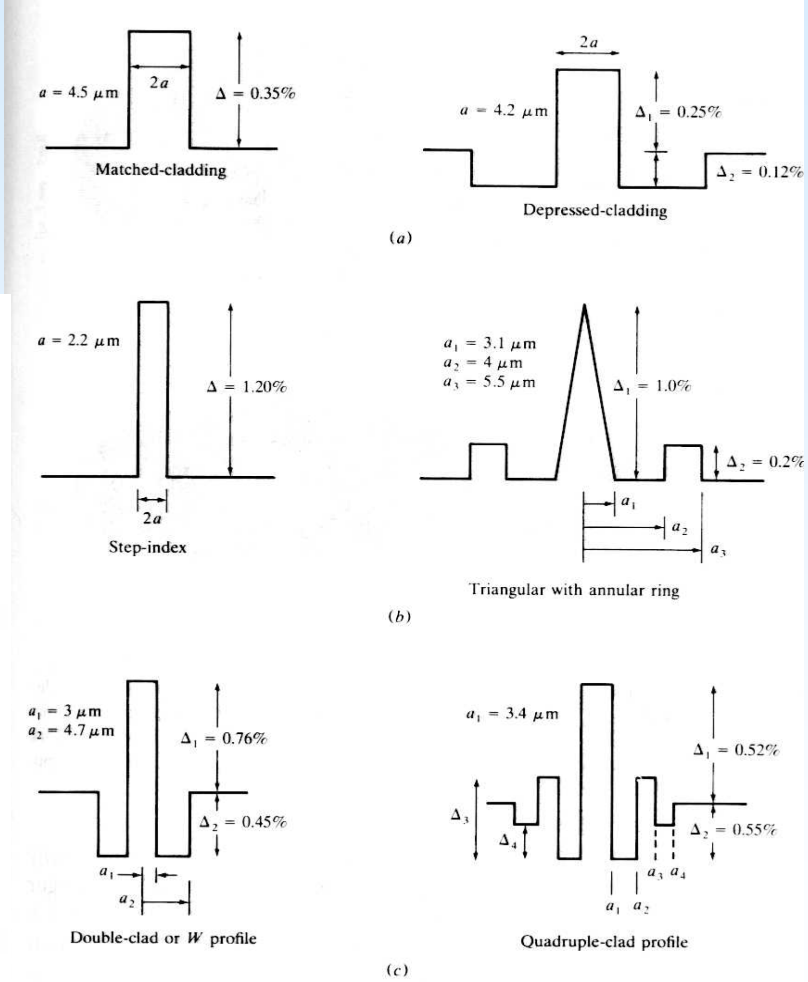


- Multi-mode fibre
- Large core diameter
- Equalized phase velocities
- Difficult index profile realization

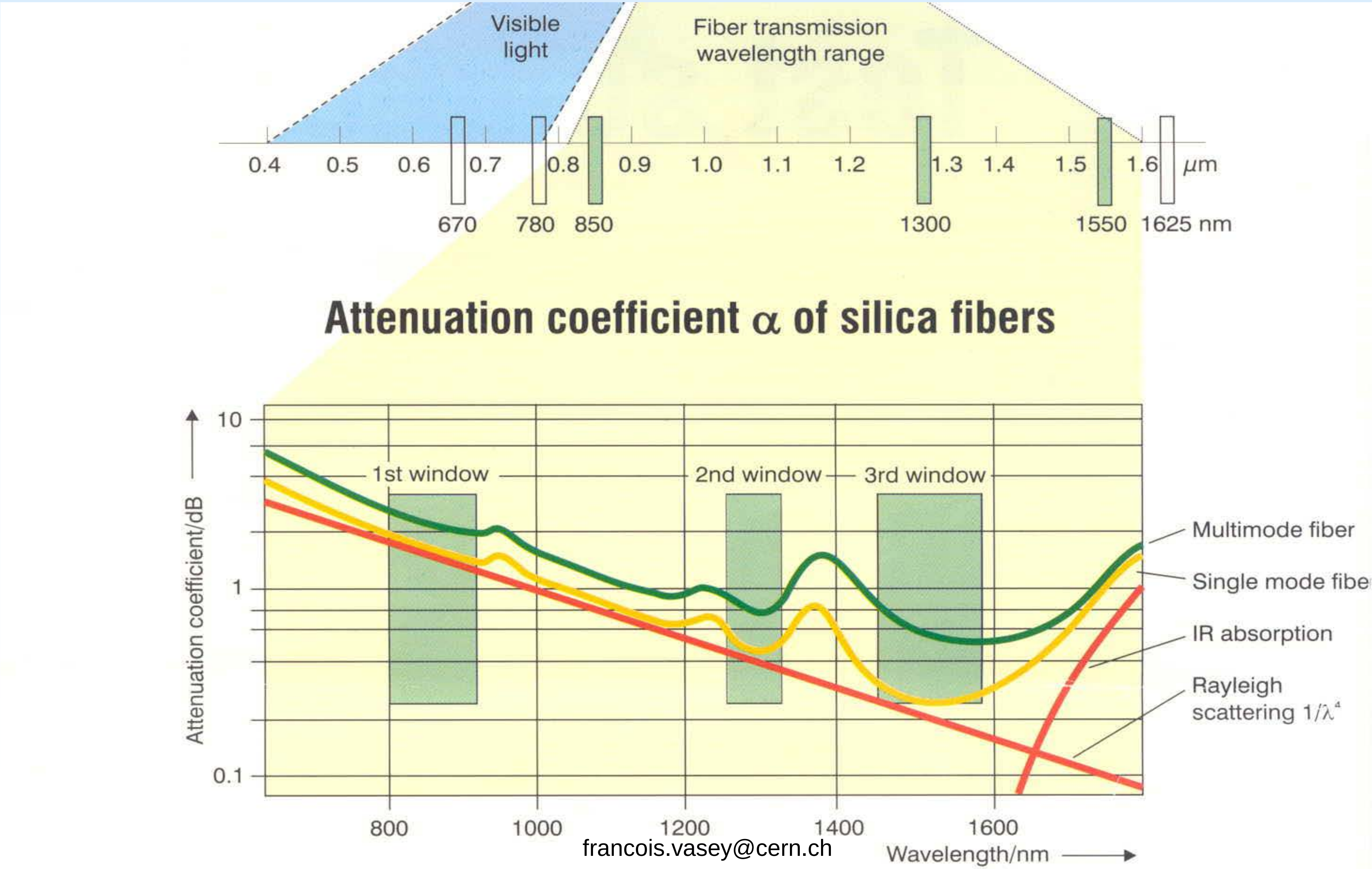
Optical Fibres: material engineering

- Ge-doped core or F-doped cladding
- Waveguide dispersion engineering

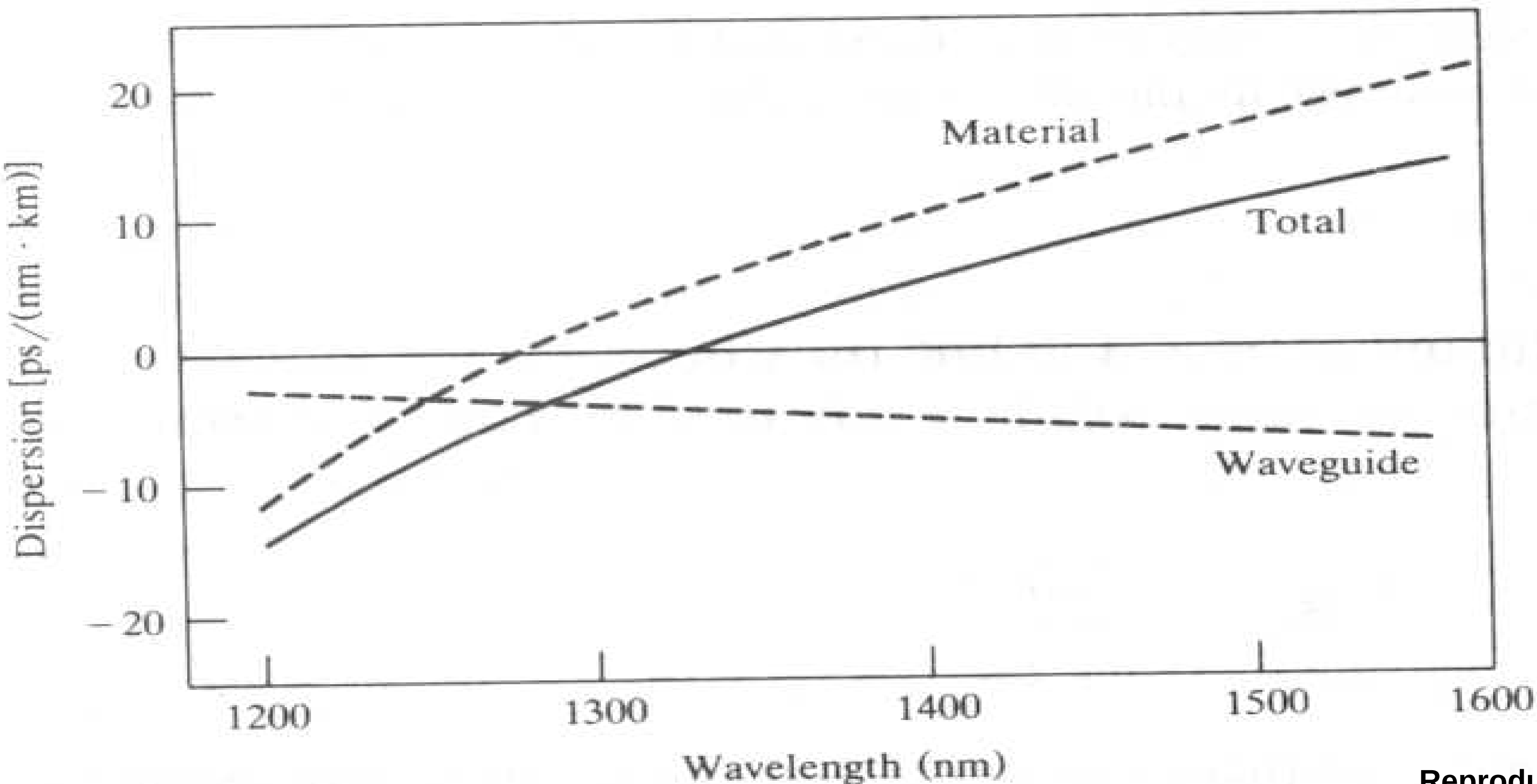




Silica transmission windows



Optical Fibres: Dispersion



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Optical Fibres Application Range