Photonics in Particle Physics

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What is “Photonics”

- “The technology of generating and harnessing light and other forms of radiant energy whose quantum unit is the photon” (from Photonics Spectra magazine)
- In our context it is
  - The detection of light generated by some process related to the measurement of some property of particles (e.g. Energy or velocity).
  - The transmission and reception of analogue & digital information connected with the electrical signals from particle detectors.

What systems are used in HEP?

- Calorimeters (which measure energy and position)
  - Scintillation light detected by a photodetector
  - Cherenkov light detection
- Time-of-flight
  - Fast scintillators used to determine the speed of a particle
- Readout of electronics in large *hermetic* detectors.
- Fibre backbone for Local and Wide Area Networks

First use of photonics

- Detection of α particles (He nuclei)
  - Historic experiments of Geiger & Marsden (1909) using ZnS(Ag) scintillator screens
  - Visual detection of scintillation light
  - Rate limited to about 60 s^{-1}
  - Each detected flash contained around 300 photons entering the observer's eye
- Last important visual experiment was the disintegration of Li neuclei by protons (Cockcroft & Walton (1932)
  - Used a human coincidence counter technique

Photodetectors –solid state

- These use the *internal photoelectric effect*
- A photon with energy larger than the bandgap of the material generates an electron-hole pair (eh-pair) *with some probability < 100%*
- The eh-pair is separated by an internal field (e.g. a junction inside a diode)
- The current pulse is externally amplified and digitised.

Photodetectors –solid state

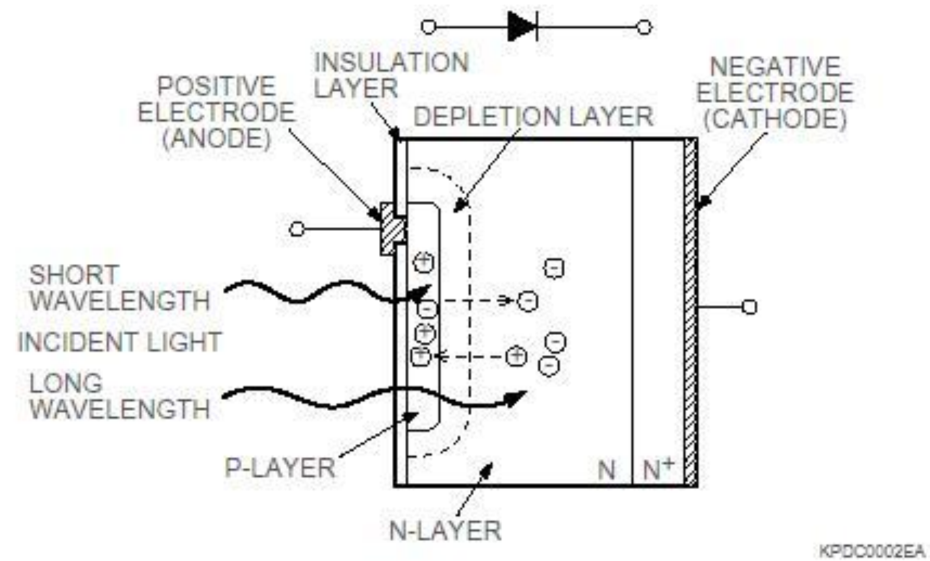


Figure 1-2 Photodiode P-N junction state

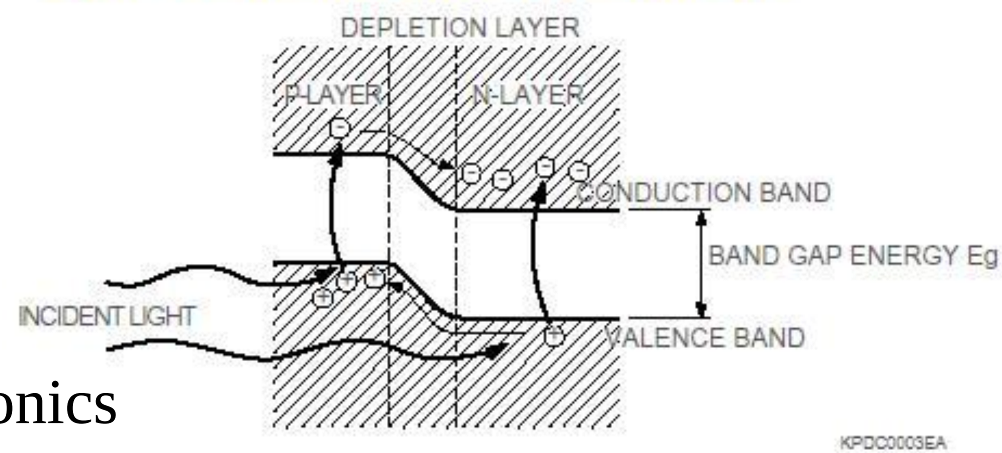
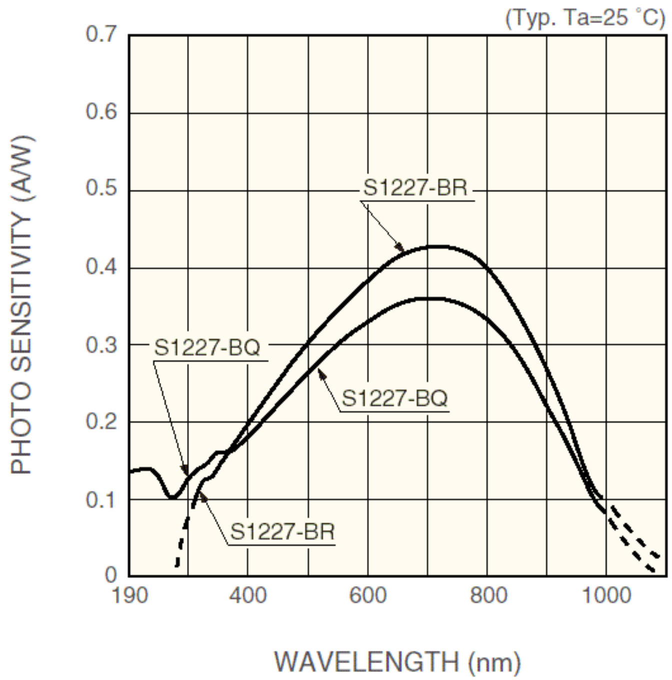


Figure from Hamamatsu Photonics

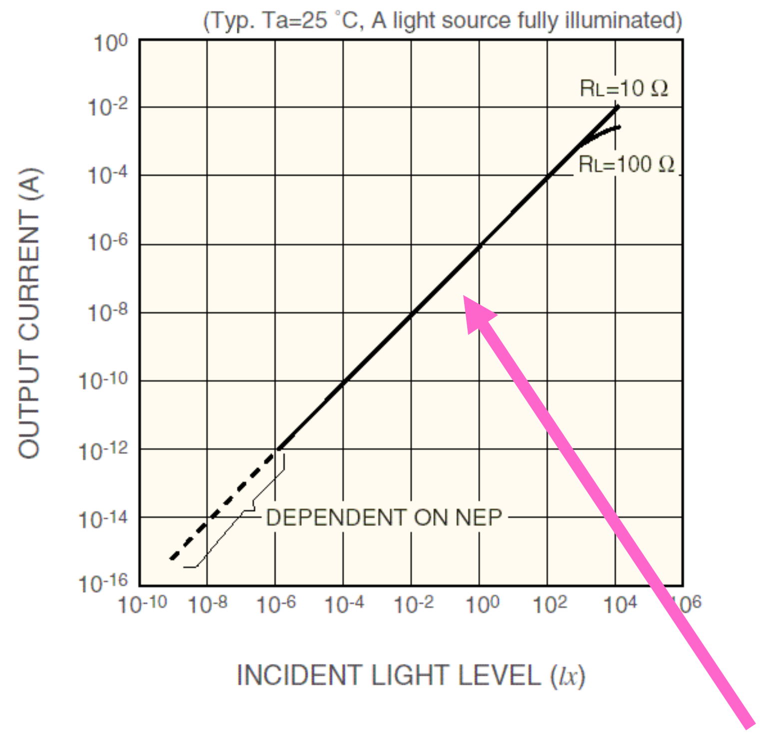
Photodetectors –solid state

- Silicon is the primary material since in general we are detecting fast scintillation or Cherenkov light (near UV to visible)
- Silicon diode technology is well advanced and the quantum efficiency (QE) is high (around 80% peak)
- Silicon devices are tolerant to quite high radiation levels, although there are problems with hadrons.
- Silicon photodiodes are linear over many orders of magnitude
- The *Avalanche Photodiode* has internal gain of about 30 (optimum value).
- See http://www.hamamatsu.com/resources/pdf/ssd/e02_handbook_si_photodiode.pdf

A large area silicon PIN diode



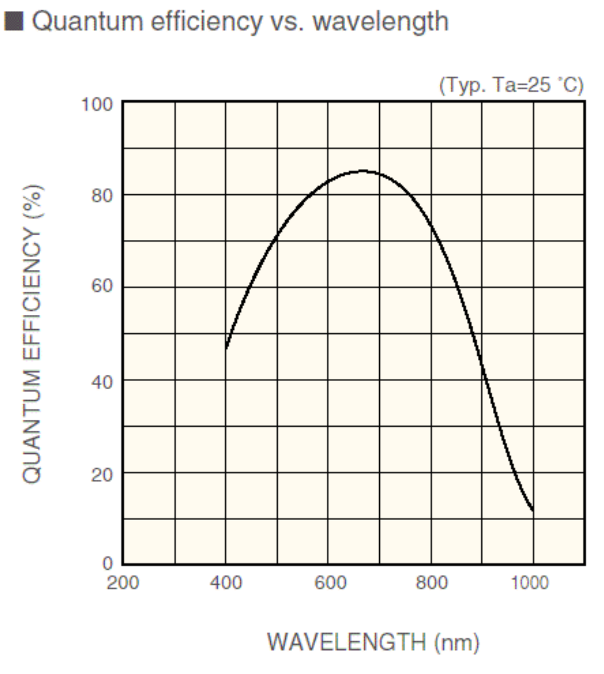
■ Photo sensitivity linearity (S1227-1010BQ/-1010BR)

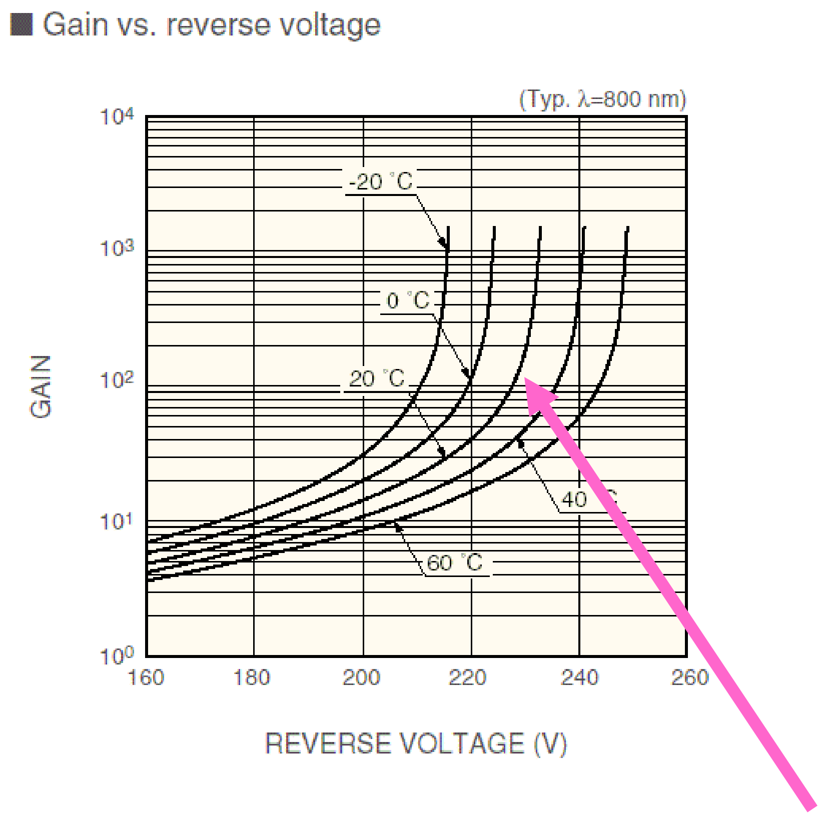


Note 8 to 10 decades of linear response

Data from Hamamatsu Photonics

A large area silicon APD





Note sensitivity to voltage and temperature

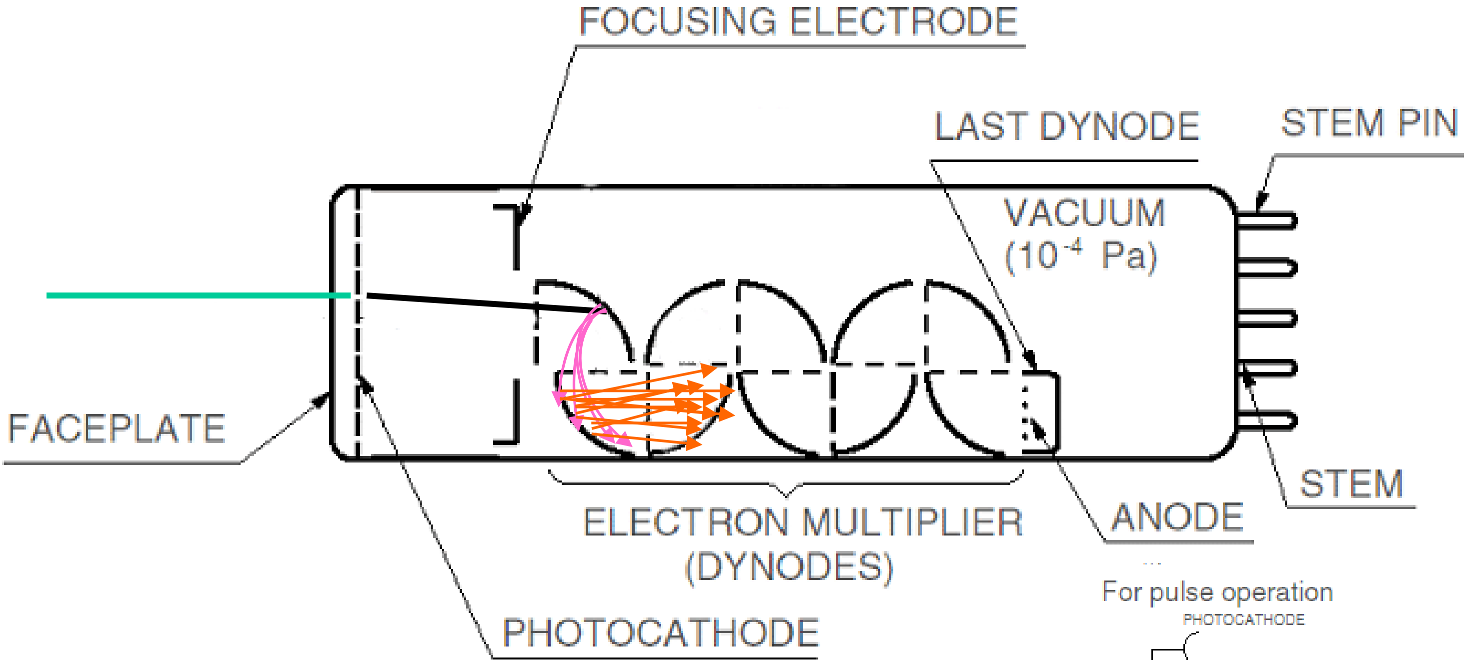
Data from Hamamatsu Photonics

Photodetectors – solid state

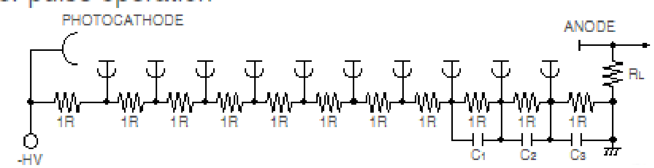
- Silicon is *not* cheaper per unit area than vacuum photodetectors (for areas greater than a few mm^2)
- Really large devices cannot be made (200 mm^2 is the upper limit)
- Problem of damage from high neutron flux in hadron collider experiments such as those at the LHC.
- Need low noise (= expensive) pre-amplifiers
- Hard to do *photon counting* *(but see the hybrid photomultiplier tube later in this lecture).*

Photodetectors –vacuum

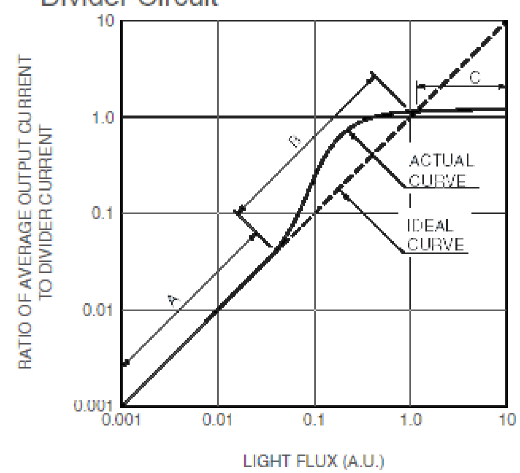
- A *free* electron is liberated from a *photocathode* (photoelectric effect) into a vacuum under an electric field
  - The free electron is accelerated to a few hundred volts and hits a *dynode*
  - Low energy *secondary electrons* are liberated from the dynode (4 to 10 dependent on voltage and material of dynode)
  - Each secondary electron is accelerated and hits the next dynode
  - And so on …
- A typical tube used in HEP has 10 to 14 dynodes
- Thus a high gain is achieved (10^6 to 10^7)
- Large areas (hundreds of cm^2) are possible, but low QE compared to silicon devices
- Most PMT are very sensitive to magnetic fields



For pulse operation



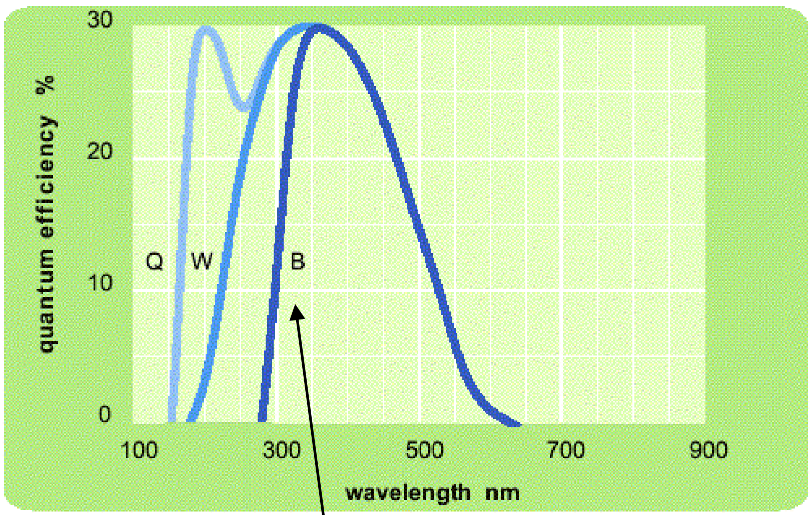
Output Characteristics of PMT Using Voltage-Divider Circuit



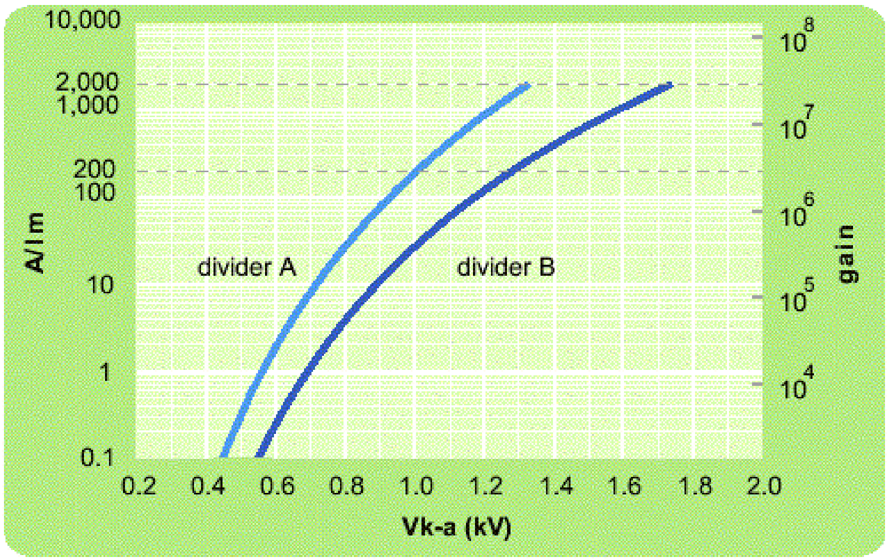
Typical dynode gain is about 5 and a typical PMT has 12 dynodes. Gain is therefore of order $12^5 \sim 250000$.

Data from Hamamatsu Photonics and see http://www.hamamatsu.com/resources/pdf/etd/PMT_handbook_v3aE-Chapter1.pdf

Photomultipliers



Effect of different windows



Total supply voltage

A typical 2” tube designed for high blue-green response

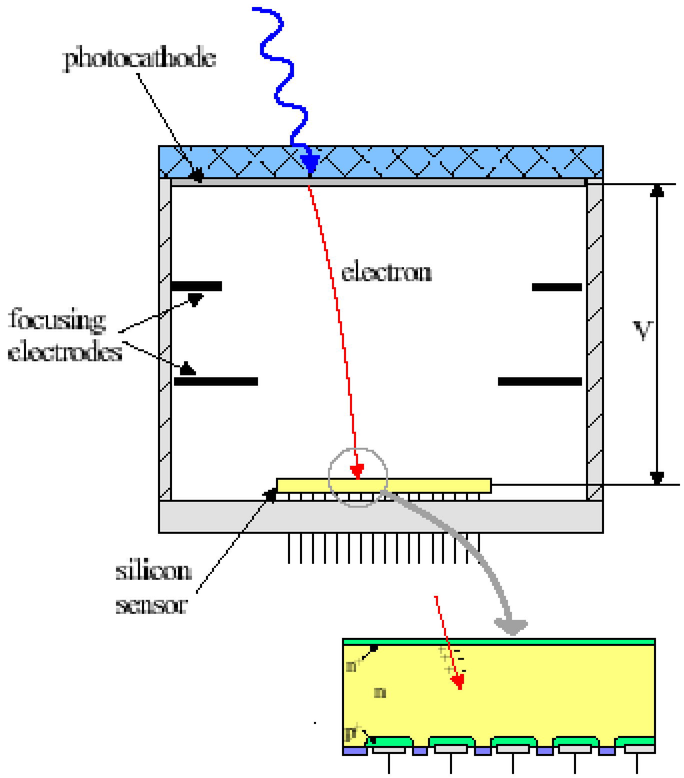
Data from ET Enterprises, UK

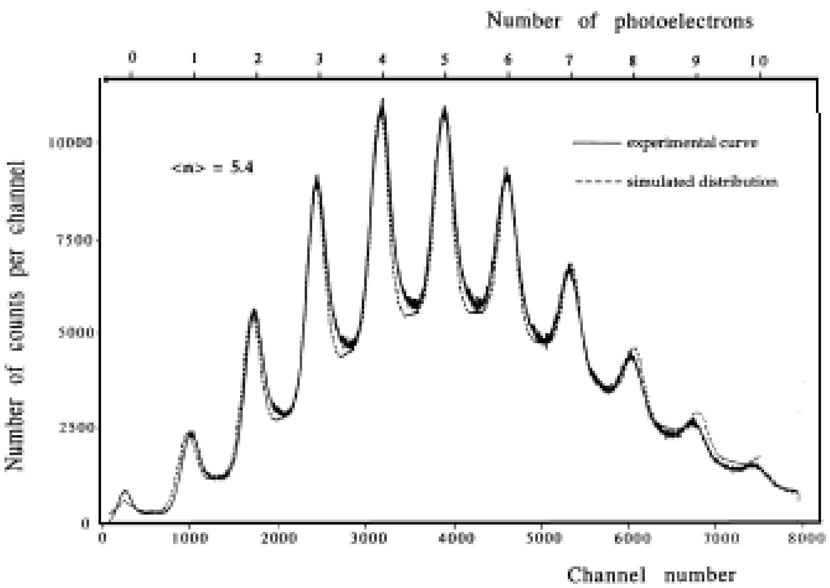
See http://www.et-enterprises.com/files/file/Understanding-photomultipliers.pdf

Photodetectors – hybrid

- Generate free photoelectrons in a vacuum (like a photomultiplier tube)
- Accelerate photoelectrons to a high (10 to 20 kV) energy
- Use a silicon diode as a *particle (electron) detector*. Get approximately 2500 eh-pairs for each photoelectron at 10 kV
- *Large* photocathode plus *small* area diode

Hybrid detector





Note the excellent resolution of 1,2,3,… photons <n> = 5.4

C. Joram, CERN, *Large Area Hybrid Photodiodes*
6th International conference on advanced technology and particle physics, Como, Italy, October 5-9, 1998

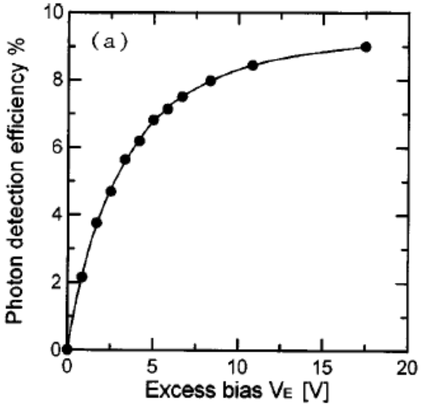
See lhcb-doc.web.cern.ch/lhcb-doc/presentations/conferencetalks/postscript/1998presentations/como.pdf

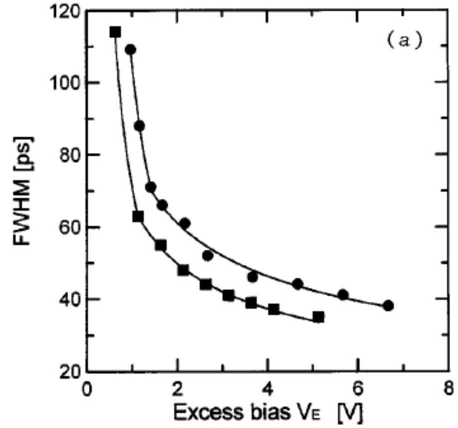
Also see http://www.photonis.com/en/ism/64-hybrid-photo-diodes.html

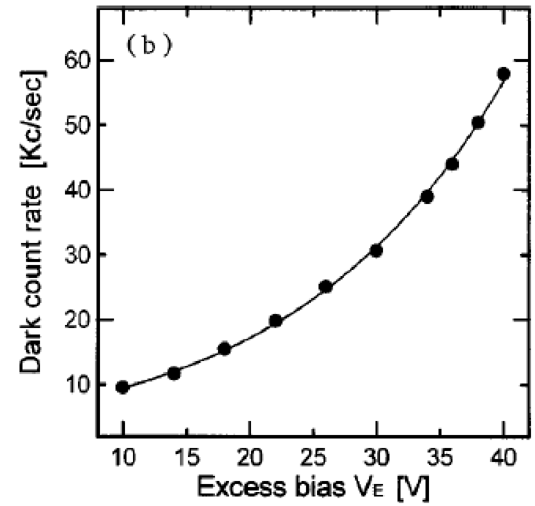
SPAD and Geiger-mode arrays

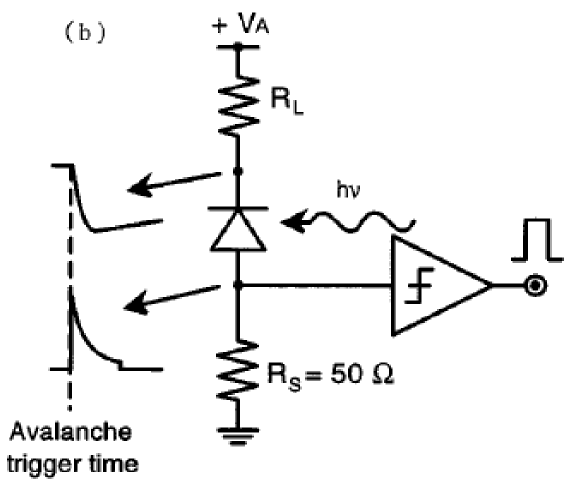
- Operate an avalanche photodiode at a potential just above the breakdown voltage.
- A single e/h pair will trigger breakdown with a *self-sustaining* avalanche.
- Rapidly quench this via an external resistor to avoid destructive heating effects.
- The basis of an important set of very fast photon detectors with large signal amplitude.
- Similar in some ways to a Geiger counter

SPAD









Passive quenching in "current mode"

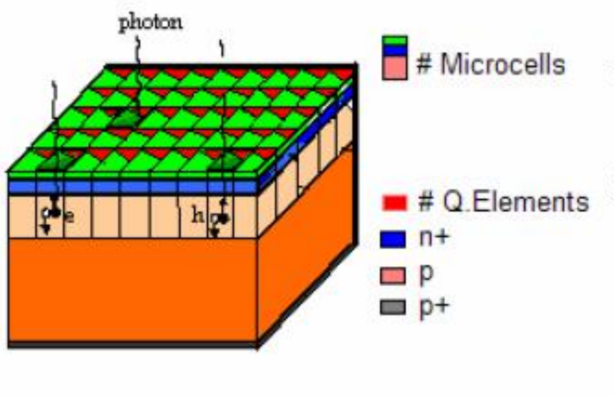
Note the high dark count rate

"Avalanche photodiodes and quenching circuits for single-photon detection", S. Cova et al, *Applied Optics*, Vol. **35**, pp. 1956-1976 (1996)

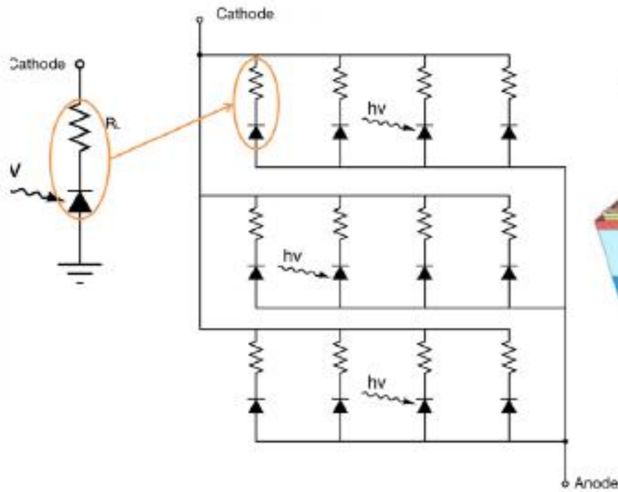
See also http://www.picoquant.com/products/category/photon-counting-detectors

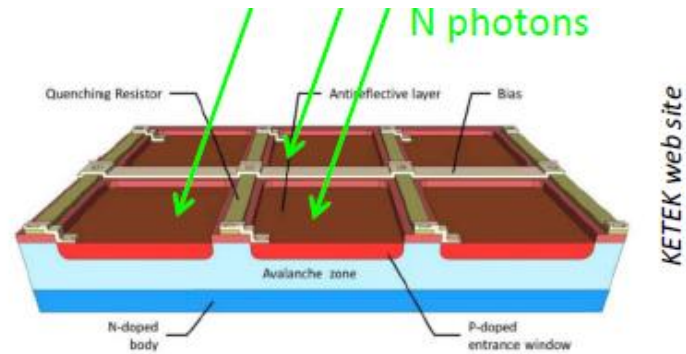
The Silicon Photomultiplier

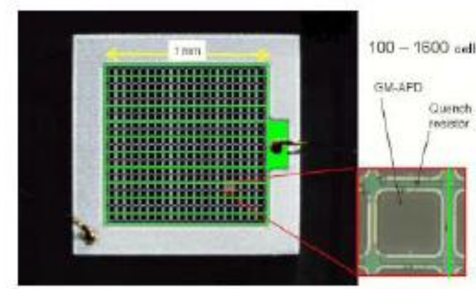
From V Puill, NDIP 2014



Valeri Saveliev, ISBN 978-953-7619-76-3





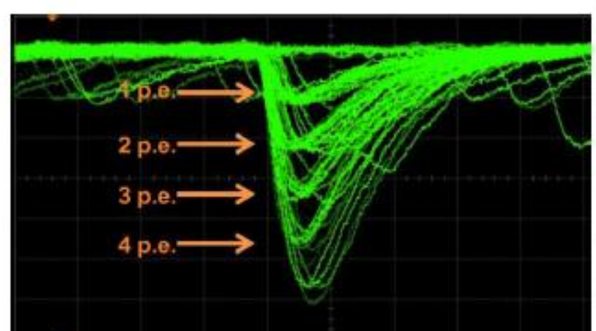


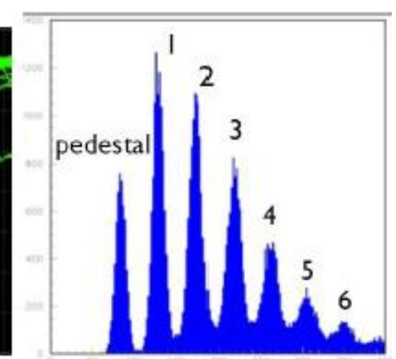
- ✓ GM-APDs (cell) connected in parallel (few hundreds/mm²)
- ✓ Each cell is reverse biased above breakdown
- ✓ Self quenching of the Geiger breakdown by individual serial resistors

Each element is independent and gives the same signal when fired by a photon

⇩

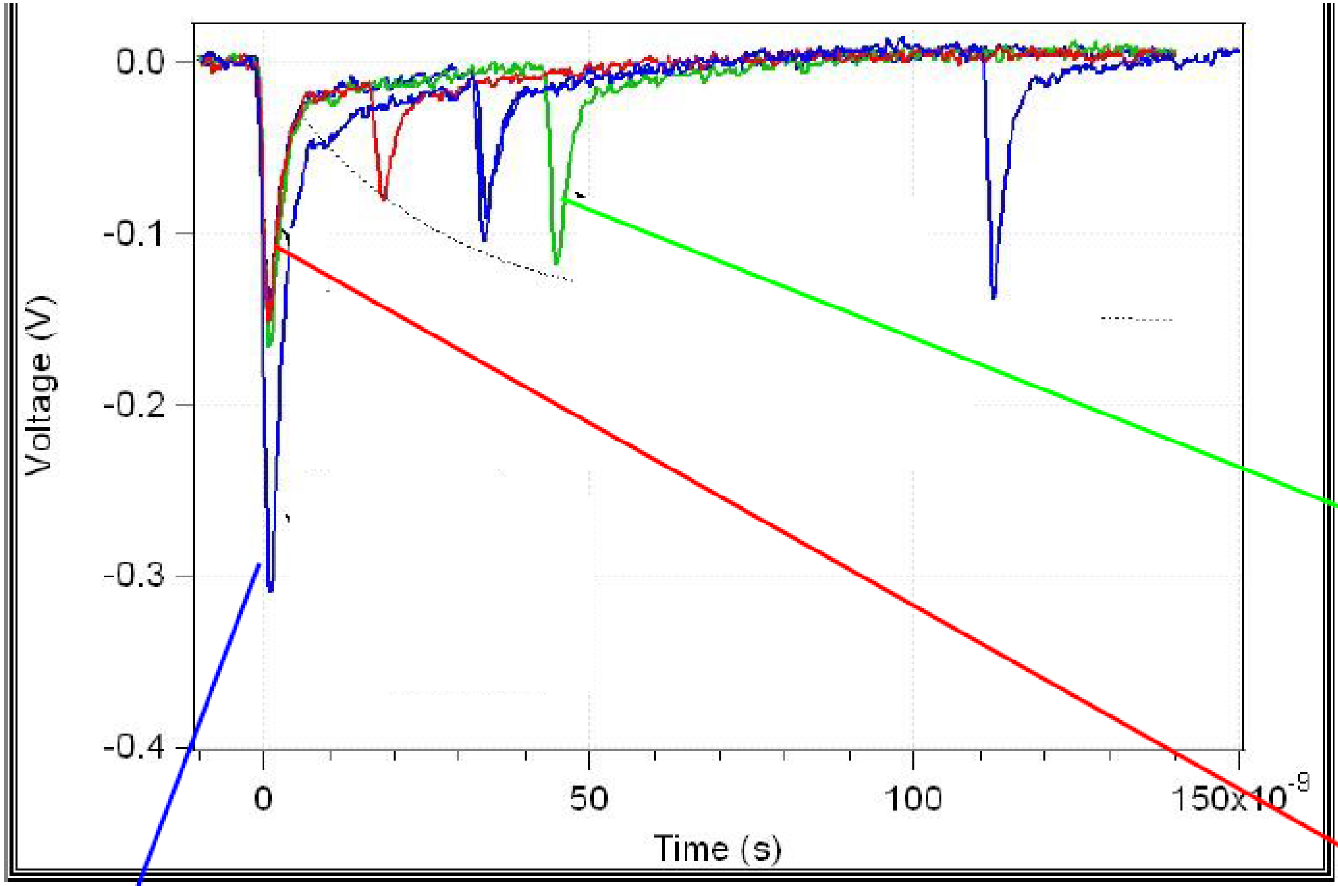
output charge is proportional to the number of of incident photons





From V Puill, NDIP 2014

Noise in SiPM



After-pulses

carriers trapped during the avalanche can produce delayed secondary pulses

Dark counts

pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

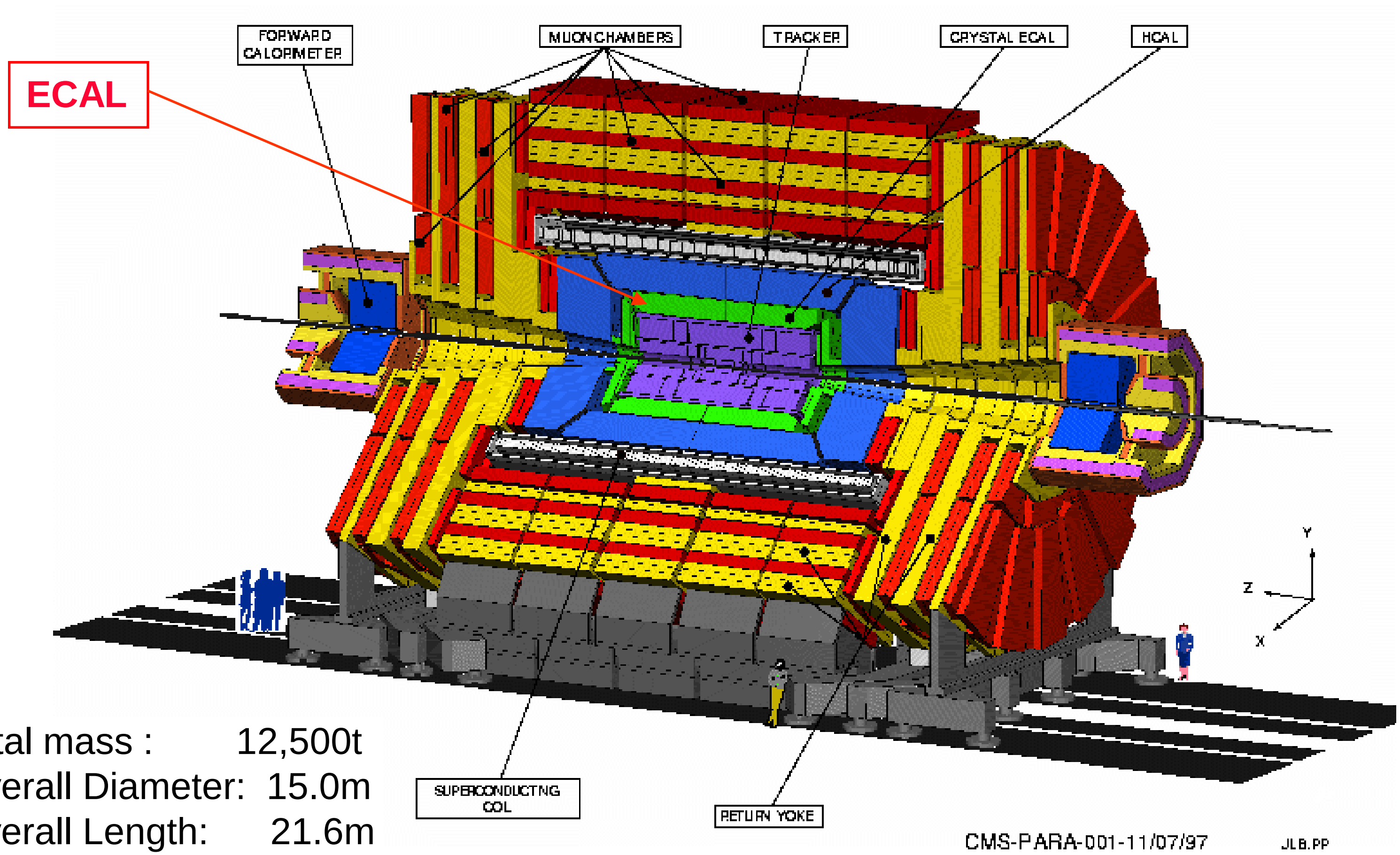
Cross-talk : amplitude = 2 p.e

avalanche in one cell → proba that a photon triggers another avalanche in a neighboring cell without delay

Application - Calorimetry

- Conversion of particle Energy into light by either the *scintillation* process or by the *Cherenkov* effect.
- Number of UV/visible photons is proportional to energy deposited $\Rightarrow$ measure the light with a fast and linear photodetector.

The Compact Muon Solenoid Detector for LHC



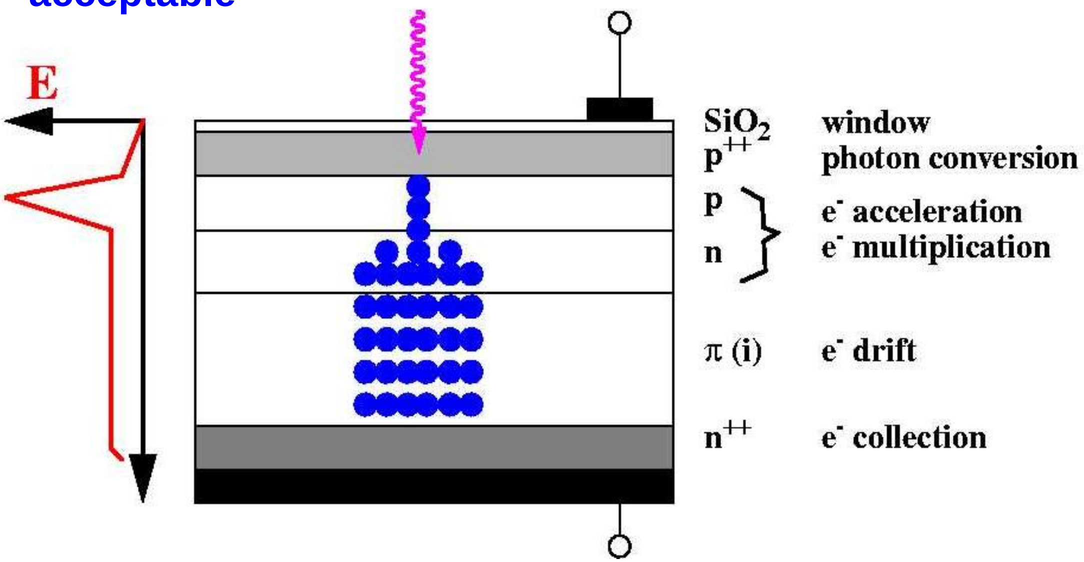
Total mass : 12,500t
Overall Diameter: 15.0m
Overall Length: 21.6m
Magnetic field: 4T

See CMS outreach page: http://cms.web.cern.ch//

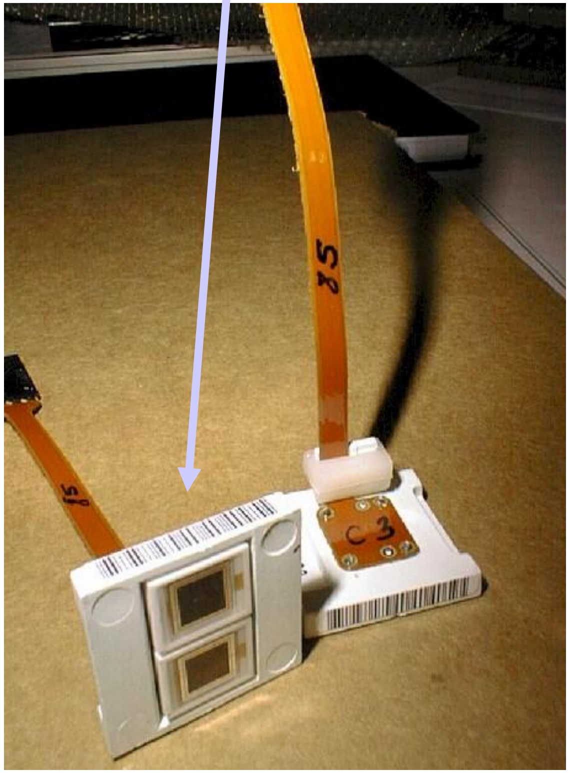
Photodetectors: barrel

Avalanche photodiodes (APD)

- Operated at a gain of 50
- Active area of 2 x 25mm^2/crystal
- Q.E.~80% for $PbWO_4$ emission
- Excess noise factor is F=2.2
- Insensitive to shower leakage particles (d_{eff}~6 μm)
- Irradiation causes bulk leakage current to increase ➔ electronic noise doubles after 10 yrs - **acceptable**



Each crystal has two 5x5 mm^2 APD

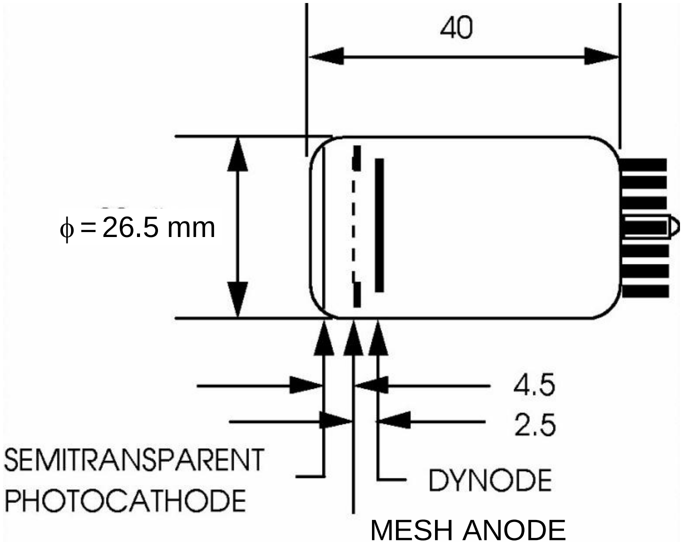


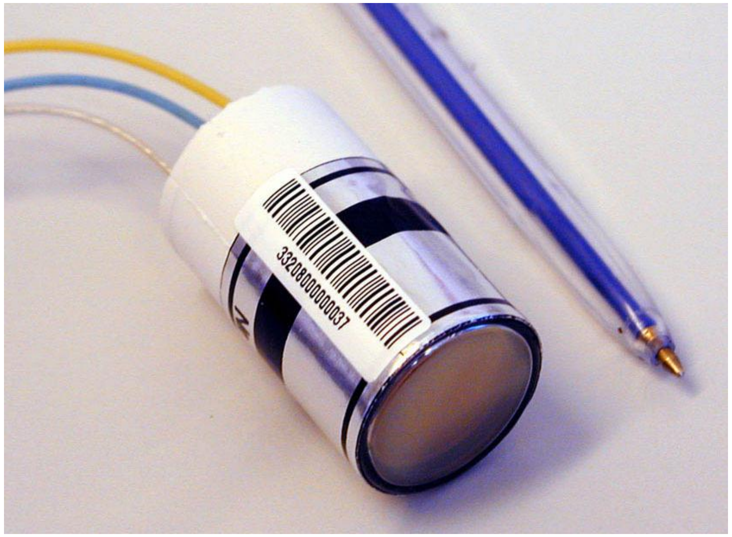
Photodetectors: end caps

Vacuum Phototriodes (VPT)

B-field orientation in end caps favourable for VPTs
(Tube axes $8.5^o < |\theta| < 25.5^o$ with respect to field)
Vacuum devices offer greater radiation hardness than Si diodes

- Gain 8 - 10 at B = 4 T
- Active area of ~ 280 mm^2/crystal
- Q.E. ~ 20% at 420 nm
- Insensitive to shower leakage particles
- UV glass window - less expensive than 'quartz'
 - more radiation resistant than borosilicate glass
- Irradiation causes darkening of window
 ➔ Loss in response < 20% after 10 yrs - **acceptable**





Order placed with RIE (St Petersburg)
> 8000 devices (50%) delivered so far and tested.

Application - Tracking

Can use planes of thin scintillating fibres, readout with a photodtector at one or both ends as a tracking detector. I use here as an example the MICE fibre tracker to which Brunel has contributed.

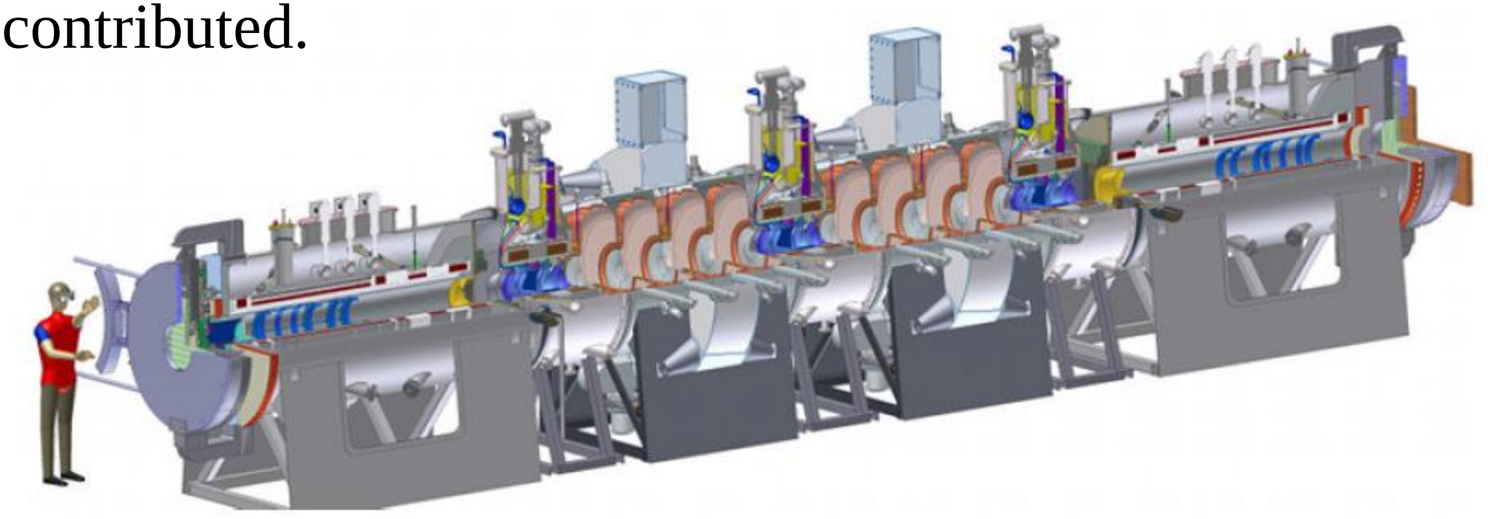


Figure 1: Cutaway 3D rendering of the international Muon Ionisation Cooling Experiment (MICE). The muon beam enters from the bottom left of the figure. The upstream PID instrumentation (not shown) is composed of two time-of-flight hodoscopes (TOF0 and TOF1) and two threshold Cherenkov counters (CKOVa and CKOVb). The upstream spectrometer is followed by the MICE cooling channel, which is composed of three 20 l volumes of liquid hydrogen and two sets of four 201 MHz accelerating cavities embedded in a solenoidal transport channel. This in turn is followed by the downstream spectrometer, a third time-of-flight hodoscope (TOF2), and a calorimeter system (KL and EMR).

http://bura.brunel.ac.uk/handle/2438/6213

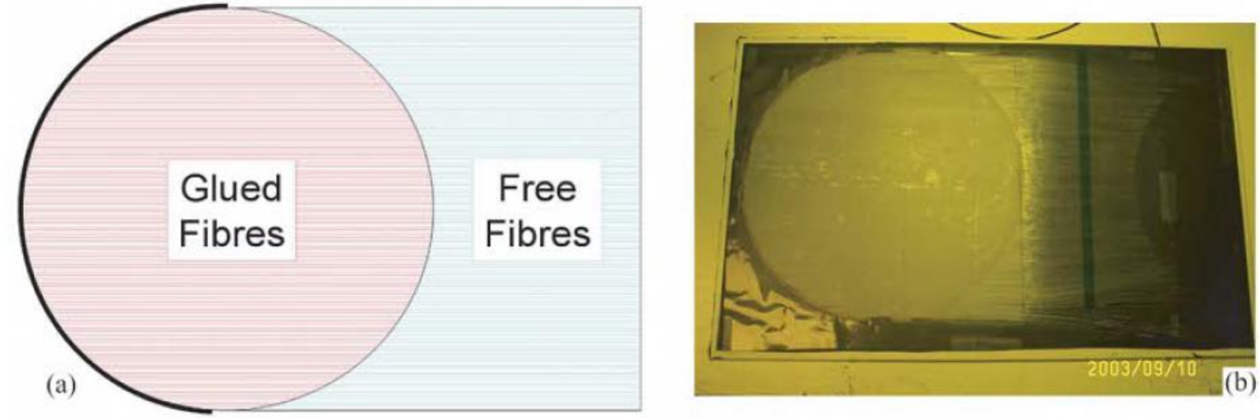
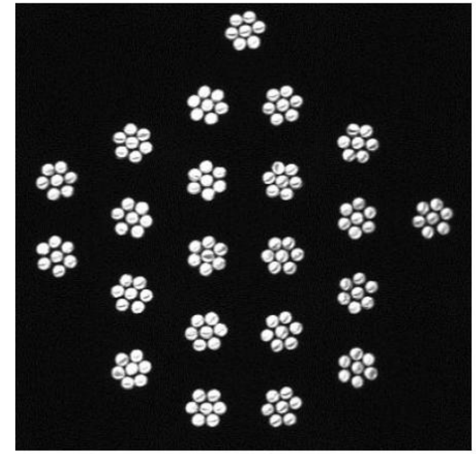


Figure 4: (a) Schematic diagram of the scintillating-fibre ribbon. The circular area of diameter 32 cm that is glued to form the doublet layer is indicated by the red hatching. The mirrored end of the fibre is indicated by the solid black line. (b) A photograph of a completed ribbon on its substrate.



Fibre bundle under UV illumination

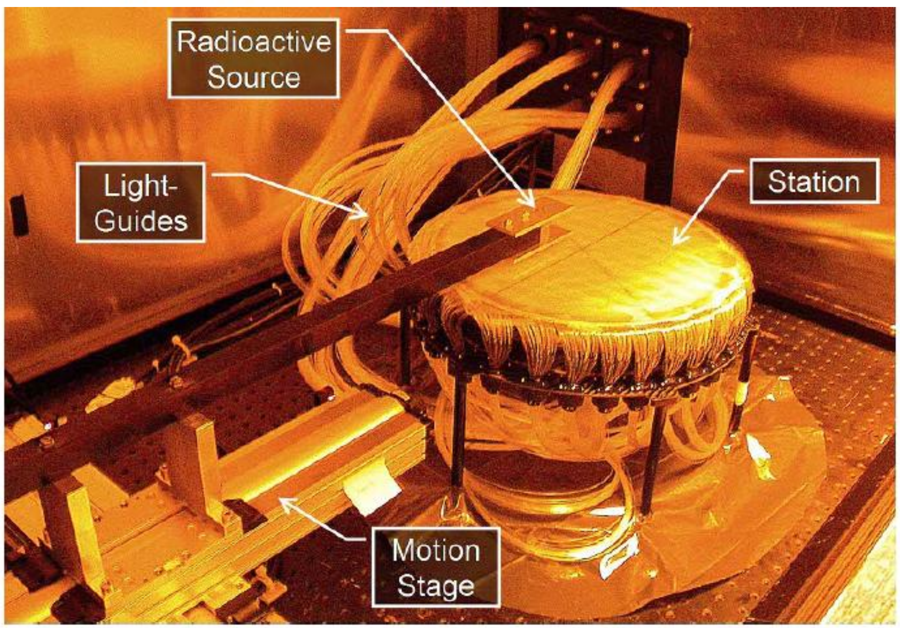


Figure 14: A photograph of a tracker station mounted in the QA test stand. The picture was taken from within the light-tight box which encloses the system. The internal light-guides can be seen connected at the station and the patch panel. The radioactive source was positioned in the holder which was mounted on the motion stage.

VLPC light detector for MICE

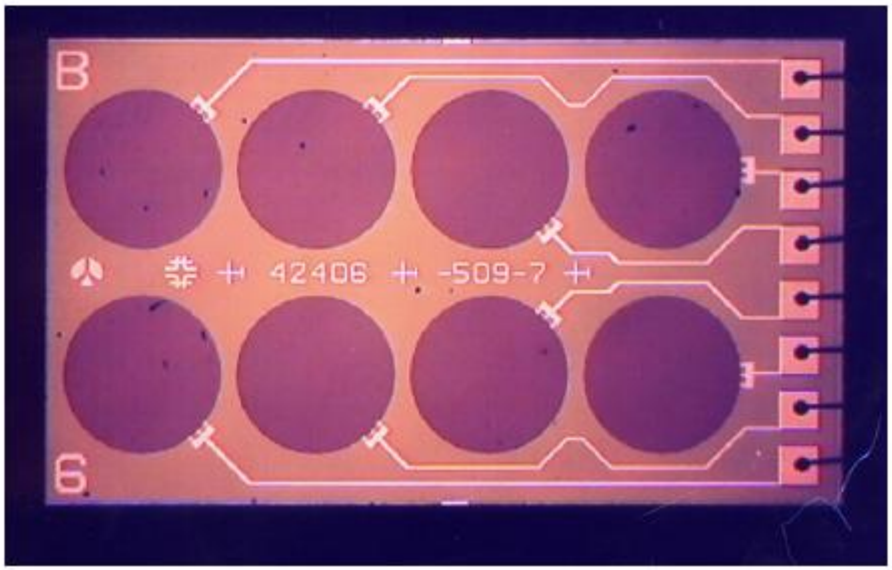
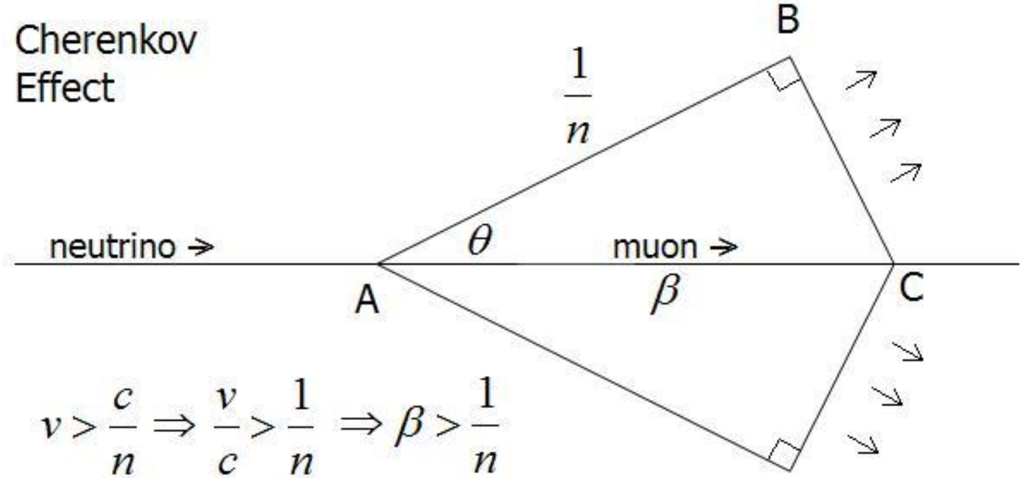


Figure 29: Photograph of the 8-element VLPC array.

Visible Light Photon Counter (VLPC) is a silicon avalanche device operated at cryogenic temperature (9K). QE > 75%, Gain 20 to 60 thousand.

Cherenkov Effect



$$v > \frac{c}{n} \Rightarrow \frac{v}{c} > \frac{1}{n} \Rightarrow \beta > \frac{1}{n}$$

$$\cos\theta = \frac{AB}{AC} = \frac{1/n}{\beta} = \frac{1}{n\beta} = \frac{1}{n}$$

$$\theta_C = \arccos(1/n\beta)$$

$$\approx \sqrt{2(1-1/n\beta)}$$ for small critical angles e.g. in a gas

Number of photons N per unit length x produced by a particle of charge z is given by

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Note the dependence on 1/wavelength^2 . This implies good UV transparent materials and detectors with UV response.

Application - Cherenkov

- Cherenkov effect
  - Analogous to a supersonic missile shock wave
  - When a *charged* particle travels in a dense medium *faster* than the speed of light *in that medium* then Cherenkov light is produced.
  - For a given medium there is a *minimum* velocity below which no light is produced.
  - Light is emitted in a cone around the particle trajectory
  - Light yield is proportional to λ^{-2}

Cherenkov Detector issues

In practice one detects of order 30 to 100 photons per cm.

For highly relativistic particles one needs refractive indices that are close to 1 and also long path lengths.

Use of *silica aerogels* provides materials with refractive indices between that of gases and liquids.

Currently quite a renewed interest in these detector technologies for calorimetery, neutrino and cosmic ray detectors etc.

For example “QUARTIC”:
http://inspirehep.net/record/1124339?ln=en

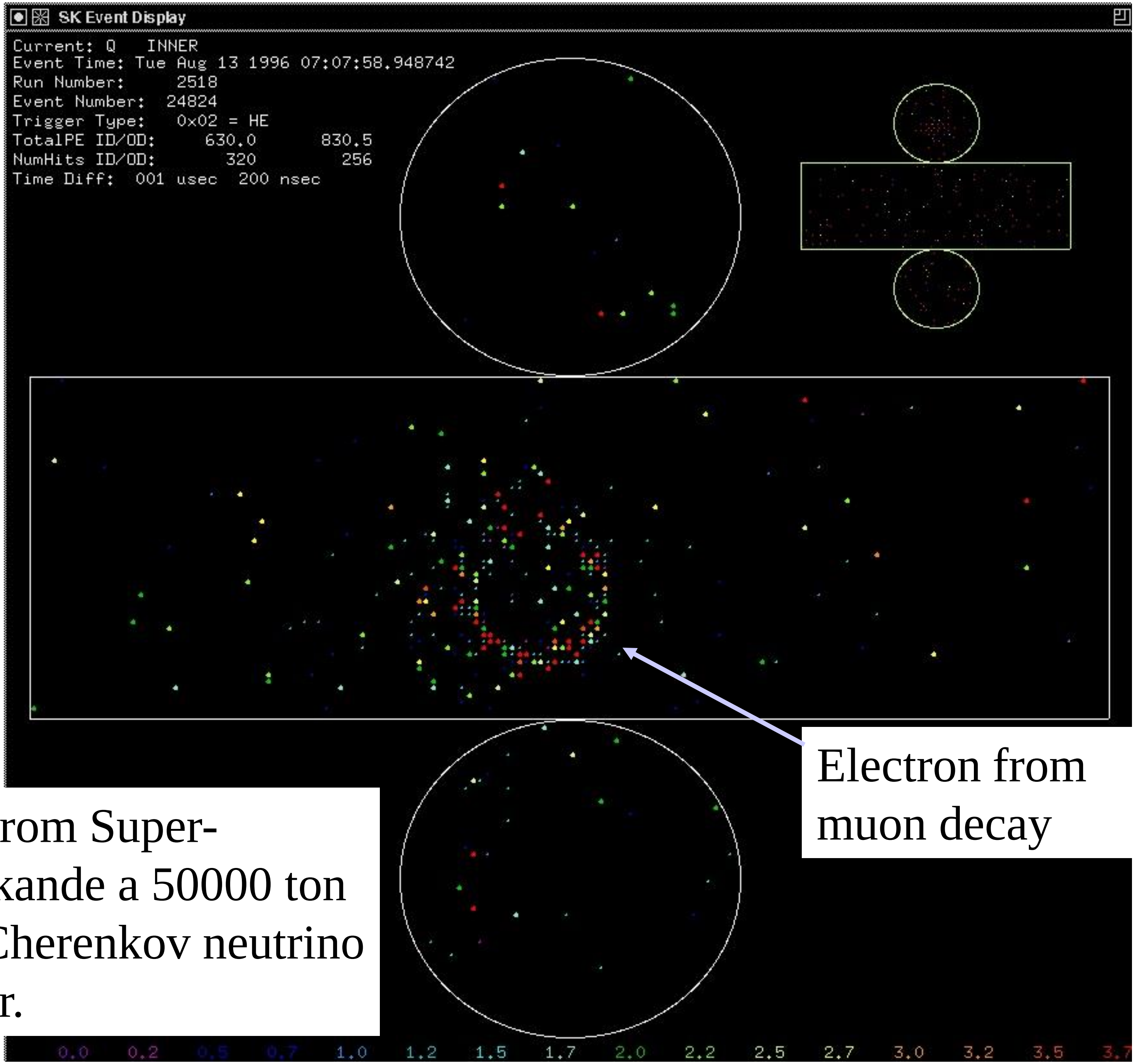
Application - Cherenkov

- Water Cherenkov
  - Pierre Auger Observatory (http://www.auger.org/)
  - Super Kamiokande (http://www-sk.icrr.u-tokyo.ac.jp/sk/index-e.html)
- Air Cherenkov
  - SPASE at South Pole (VULCAN detectors) (http://www.bartol.udel.edu/spase/)

ICECUBE: http://icecube.wisc.edu/l

MAGIC: https://magic.mpp.mpg.de/home/l

HESS: http://www.mpi-hd.mpg.de/hfm/HESS/



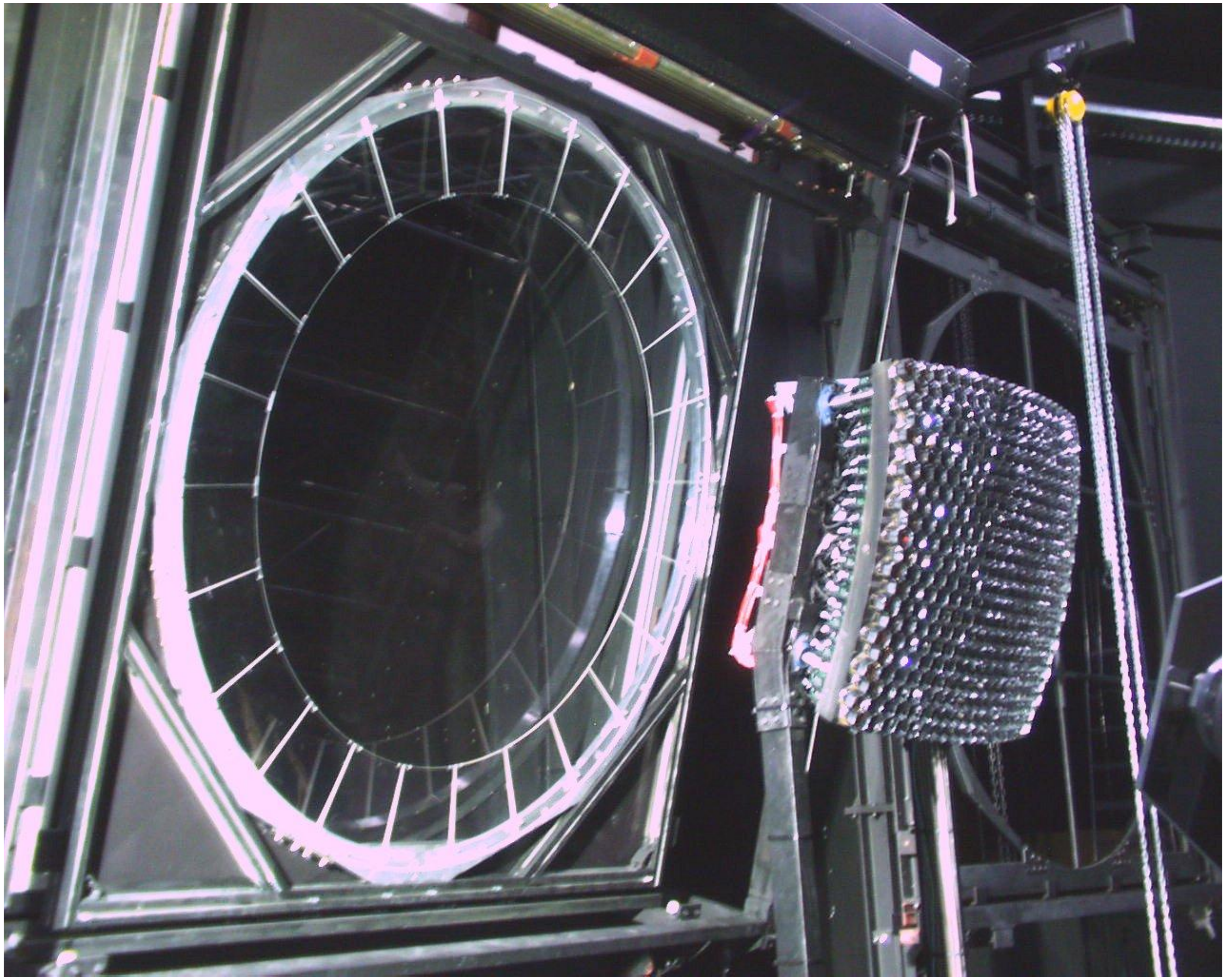
Electron from muon decay

Event from Super-Kamiokande a 50000 ton water Cherenkov neutrino detector.

Pierre Auger Laboratory

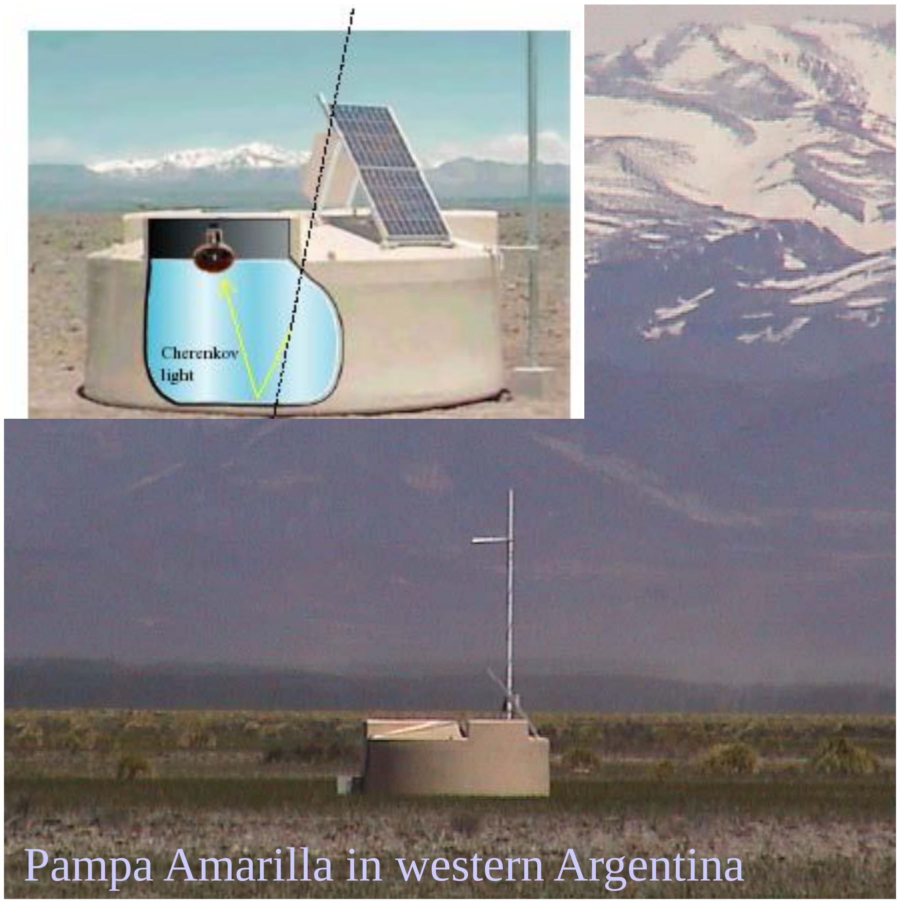
- Goal is to understand the flux of extremely high energy cosmic rays (10^{18} to 10^{20} eV)
- They are very, very rare (about 1 per square kilometre per week to one per century!)
- Detect using air fluorescence (telescopes) and also ground based Cherenkov detectors (water tanks). These detectors use arrays of hexagonal photomultiplier tubes (telescope) or giant photomultiplier tubes (water Cherenkov).

Air fluorescence telescope



Focal plane array of photomultiplier tubes

Water Cherenkov



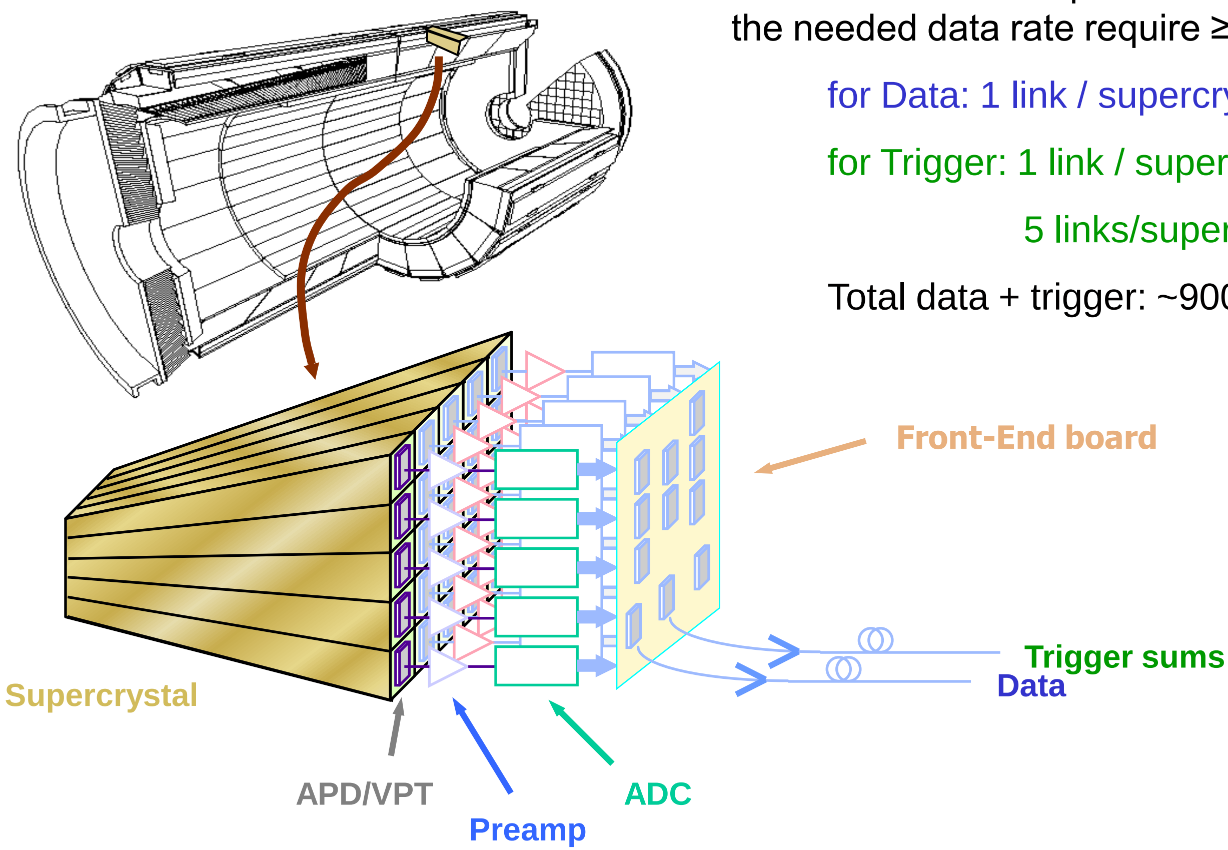
Pampa Amarilla in western Argentina

B. Genolini, et al, *Low power high dynamic range photomultiplier base.* Poster presented at Beaune 2002, France, June 2002

Application – Data transport

- Use of fibres to carry high speed digital (or analogue) data from fast low-noise electronics inside the experiment to the outside world.
- Many conventional co-axial cables can be replaced by a few much smaller fibres
- The dead-volume (i.e. of cables) is greatly reduced $\Rightarrow$ a more *hermetic* detector.

CMS ECAL Front-End architecture



ECAL has ~77,000 lead tungstate crystals arranged in supercrystals or trigger towers of 25.

Front-End electronics of each supercrystal send the data off-detector via the optical links. The architecture and the needed data rate require ≥600 Mb/s with modularity:

for Data: 1 link / supercrystal

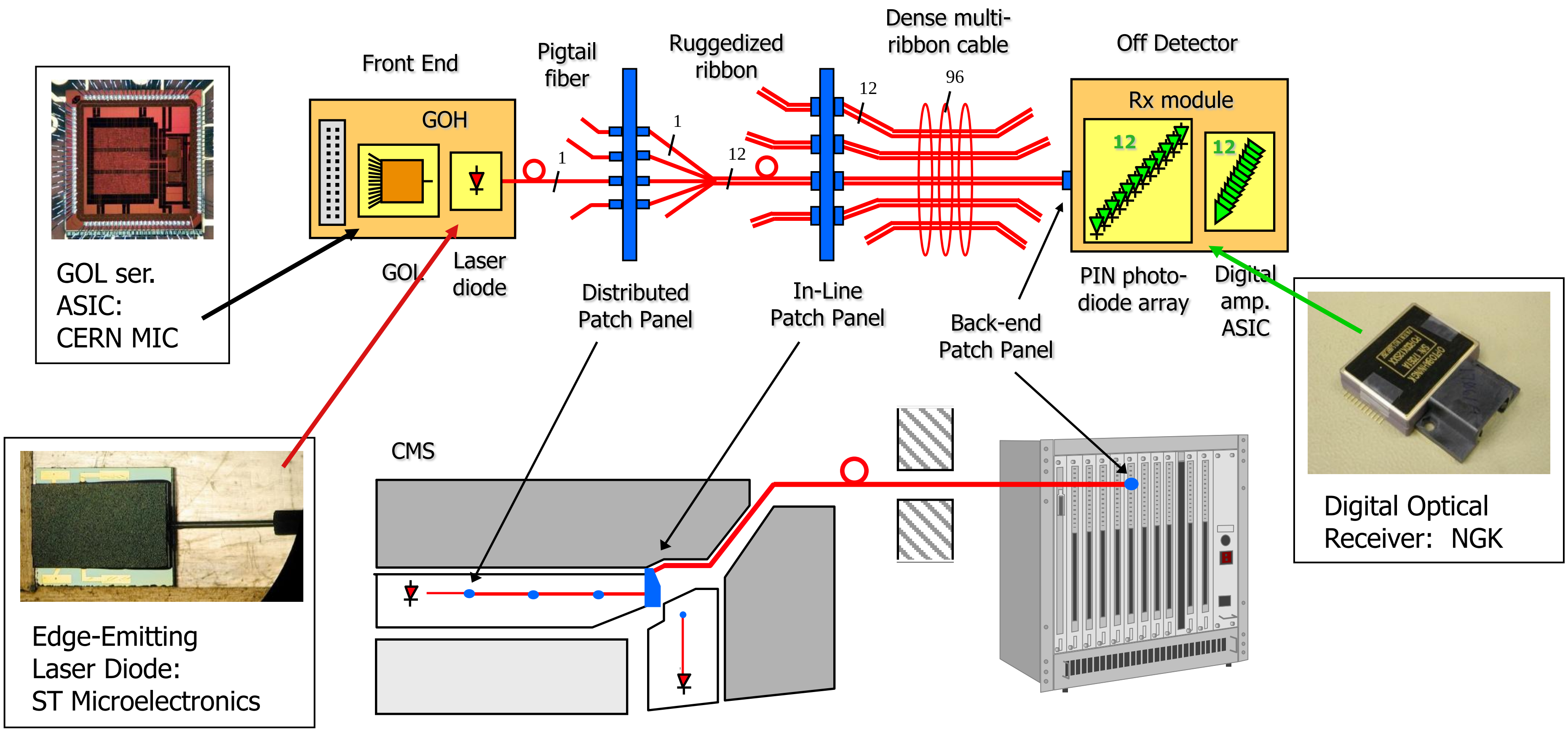
for Trigger: 1 link / supercrystal (barrel)

5 links/supercrystal (endcap)

Total data + trigger: ~9000 links

This and the next slide from J. Grahl, U. Minnesota talk at CALOR 2004, Perugia, March 2004

CMS ECAL Link System



Summary

- Many particle detectors, in particular electromagnetic calorimeters, produce light (*scintillation or Cherenkov)* which is detected.
  - Fast signals
  - Easy to avoid cross-talk
  - Detection of single photons
- Current and planned experiments also use light to transmit the electronic signal from the detector elements to the computers.
  - Conventional cables produce too much dead space in otherwise *hermetic* detector systems
- Everyone uses light to connect computers together in WAN and LAN and data centre networks.
- A good resource on photodetectors are the NDIP series of conferences: http://www.ndip.fr/