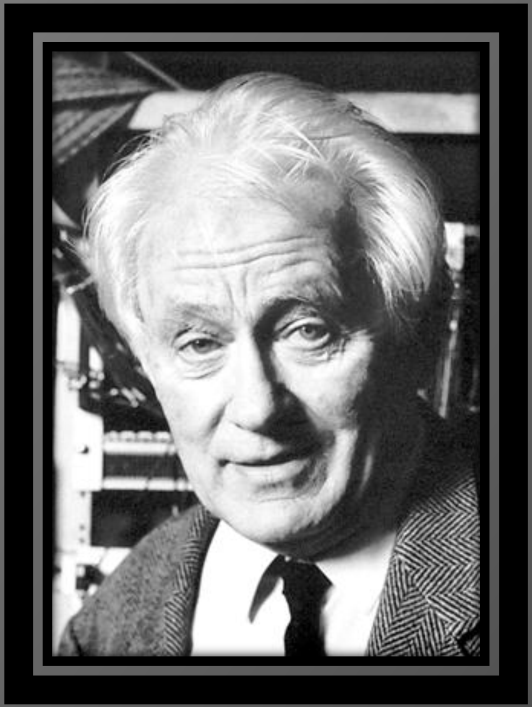
B.Satyanarayana, Tata Institute of Fundamental Research, Mumbai

Detector Development for the Upcoming Experiments



Georges Charpak (1924–2010)

The Nobel Prize in Physics 1992 was awarded to Georges Charpak "for his invention and development of particle detectors, in particular the multi-wire proportional chamber".

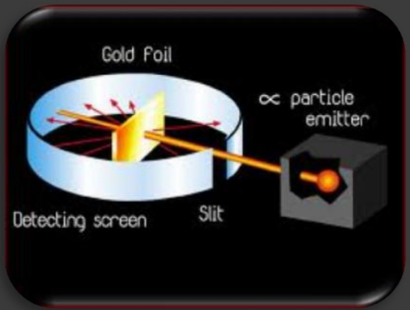
“The discoveries of the W and Z bosons at CERN, the charm quark at SLAC and Brookhaven and the top quark at Fermilab would not have been possible without this type of detector, and current research in high energy physics continues to depend on these devices”.

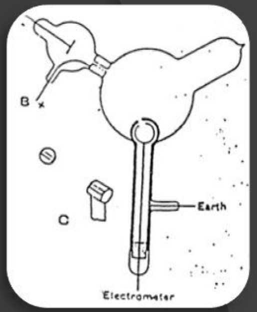
B.Satyanarayana, Tata Institute of Fundamental Research, Mumbai

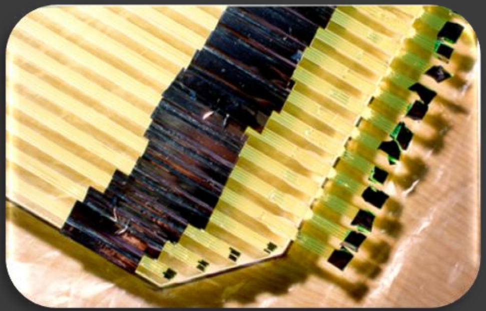
DETECTOR DEVELOPMENT FOR THE UPCOMING EXPERIMENTS

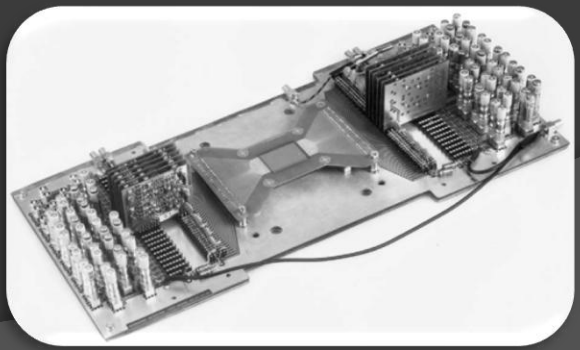
Detectors aided major discoveries

- Crookes Tubes: Sir William Crookes (1869-75)
- Cloud chamber: Charles Thomas Rees Wilson (1894), Nobel Prize in Physics (1927)
- Electron: J.J.Thomson (1897) using Crookes Tubes
- “Gold foil apparatus”: Hans Geiger & Ernest Marsden (1909)
- Proton: E.Rutherford (1911) using “Gold foil apparatus”
- Photon: A.Compton (1923)
- Neutron: J.Chadwick (1932)
- Positron: C.Anderson (1932)
- Muon: C.Anderson & S.Neddermeyer (1937)
- Neutral Kaon: G.Rochester & C.Butler (1947) using cloud chamber triggered by Geiger counters
- Charged Pion: C.Powell (1947) using photographic emulsions carried aloft by balloons
- Lambda: (1947)
- Neutral Pion: R.Bjorkland (1949)
- Bubble chamber : D.Glaser (1952), Nobel Prize in Physics (1960)
- Synchrotron: (1952)
- Xi minus: R.Armenteros (1952)
- Sigma plus: G.Tomasini (1953) using emulsion technique
- Sigma minus: W.Fowler (1953)
- Antiproton: W.Segrè (1955)
- Antineutron: B.Cork (1956)
- MOS transistors: Kahng & Atalla (1960), electronic counters
- Multi-Wire Proportional Counter: G.Charpak (1968), Nobel Prize in Physics (1992)
- Time Projection Chamber: D.R.Nygren (1974)
- Charm quark: SLAC & BNL collaborations (1974)
- Super Proton Synchrotron: John Adams *et al* (1976)
- Stochastic cooling: Van der Meer, Nobel Prize in Physics (1984)
- Large area (20”) PMT: Hamamatsu (1980)
- Resistive Plate Chamber: R.Santonico (1981)
- W & Z bosons: UA1 and UA2 collaborations (1983)
- Micro Strip Gas Chamber: A.Oed (1988)
- Top quark: D0 & CDF collaborations (1995)
- Gas Electron Multiplier: F.B.Sauli (1996)
- Neutrino oscillation: Super-Kamiokande Collaboration (1998)







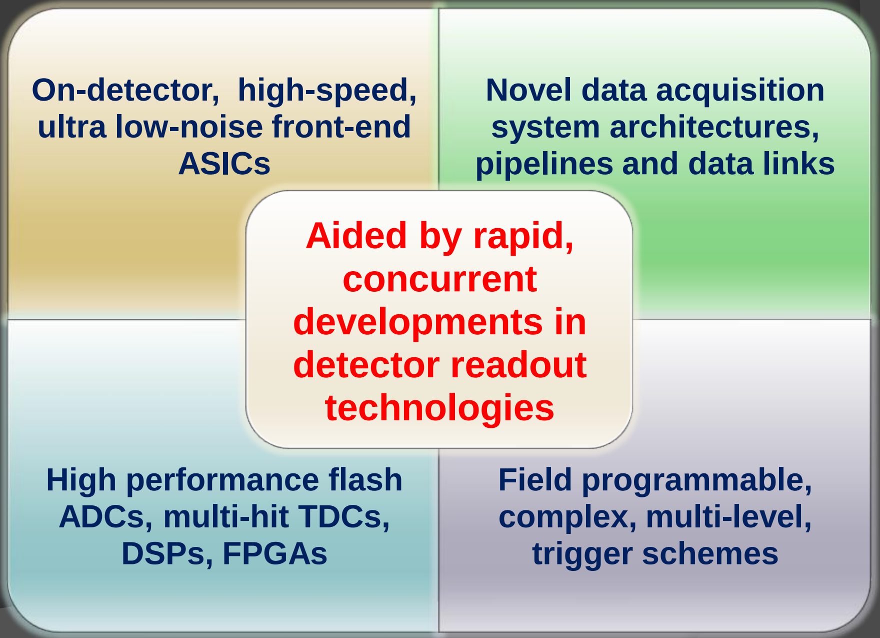


Tasks of HEP detectors

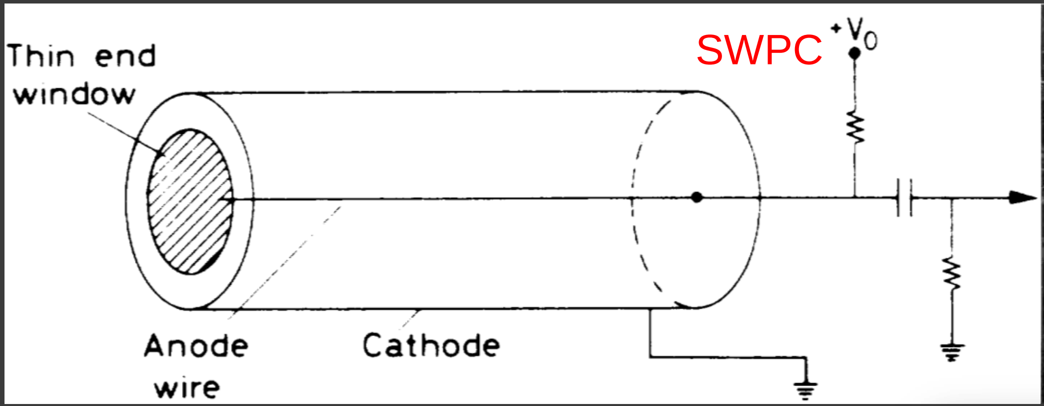
- Tracking detector: Direction, sign and momenta of the particles. Often aided by magnetic field.
- Electromagnetic calorimeter: Energy carried by electrons and photons. Signals proportional to the energy of the incident particles.
- Hadronic calorimeter: Energy carried by hadrons (protons, pions and neutrons).
- Muon system: Muons are charged particles that penetrate large amounts of matter, loosing little of their energy. Essentially made of tracking detectors.
- Particle identification: Identification of charged and neutral particles. Charged particles are identified by combining momentum information with Time-Of-Flight, energy loss *dE/dx*, Čherenkov or transition radiation.
- Displaced vertex: B-, D- or τ-tagging achieved with high spatial resolution detectors.
- RICH detector: Determines the velocity of a charged particle
- Transition radiation detector: Uses the γ-dependent threshold of transition radiation in a stratified material
- Time of flight detector: Discriminates between a lighter and a heavier particle of the same momentum using their time of flight between two detector planes.
- Neutrinos: Detected through inferred momentum conservation.
- Dark matter: Principle of nuclear recoil by candidate particles (mainly WIMPs)

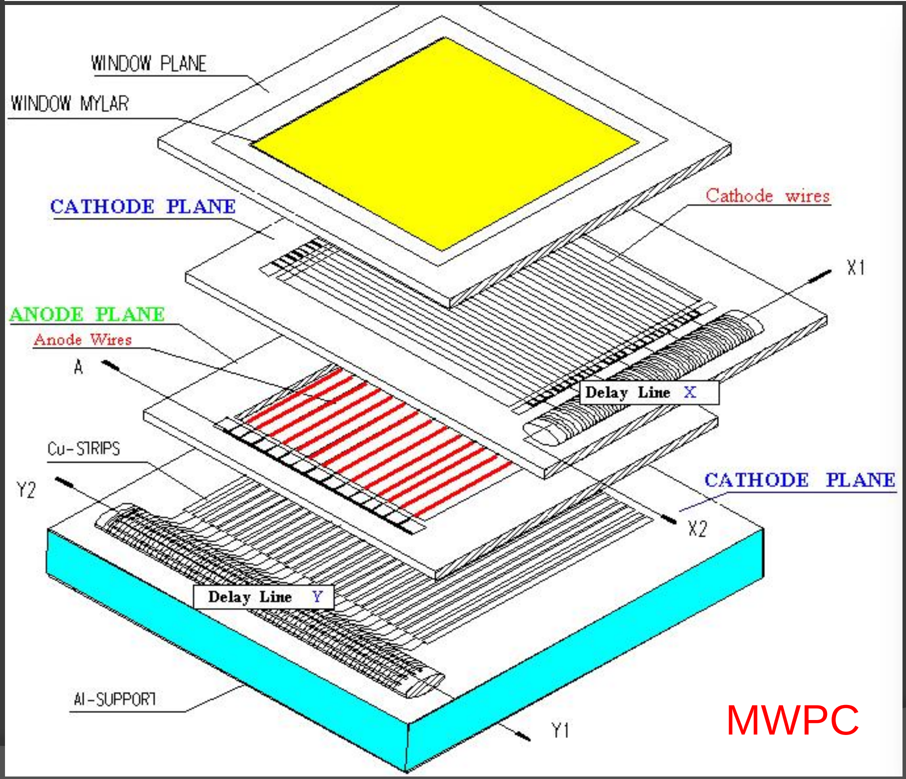
Classification of HEP detectors

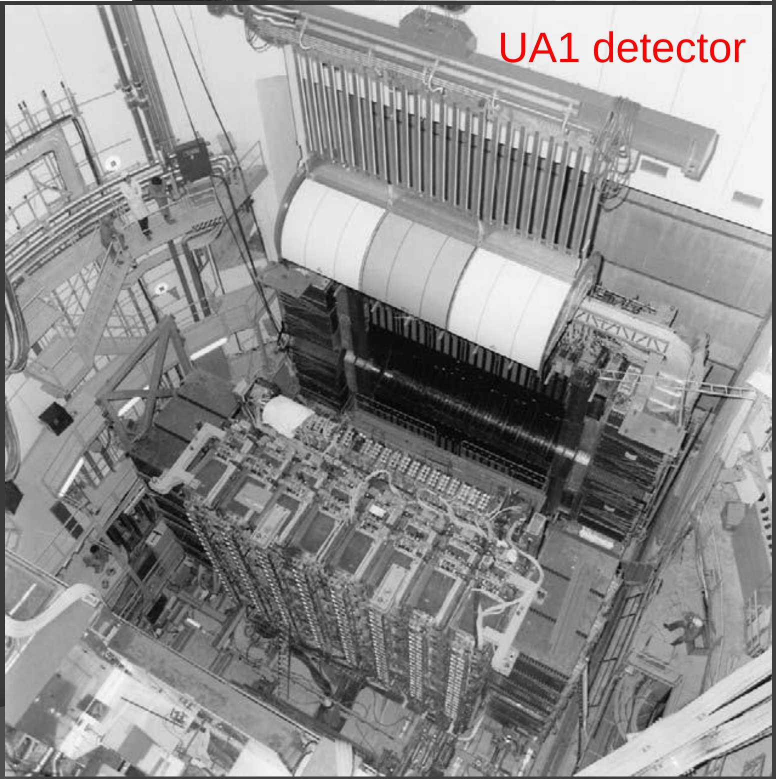
- *Non-electronic* detectors
  - Emulsions, cloud chamber, bubble chamber
- Gaseous detectors
  - GM, SWPC, MWPC, PMD, drift chamber, TPC, MSGC, GEMs, streamer tube, spark chamber, PPAC, RPC, CSC (Types: wired, micro-pattern, wire-less)
- Scintillation detectors
  - Organic (crystals, liquids, plastics, *extruded*), inorganic crystals, gas, glass
- Silicon detectors
  - Strip, pixel, *readout integrated*
- Photo detectors
  - PMT, PD, APD, VLPC, SiPM
- Liquid ionisation detectors
  - Scintillator, Argon, Xenon
- Hybrid detectors
  - HPD, LArTPC



Gas proportional counters

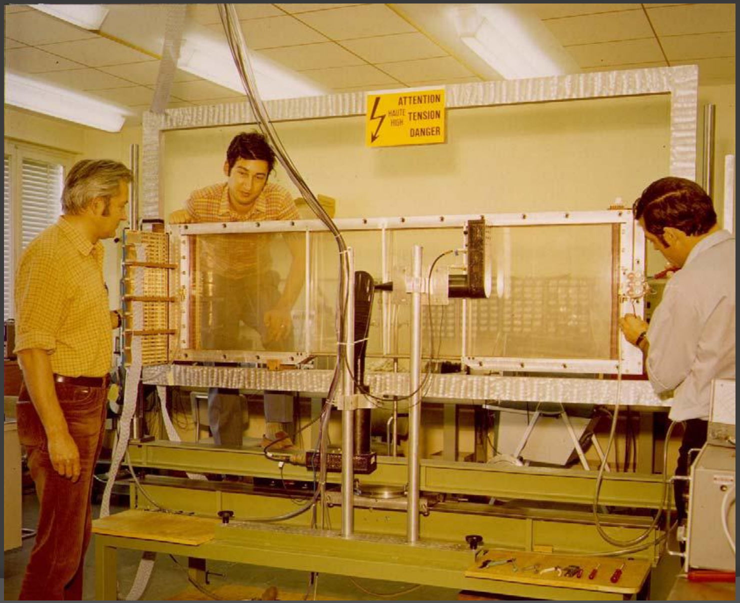


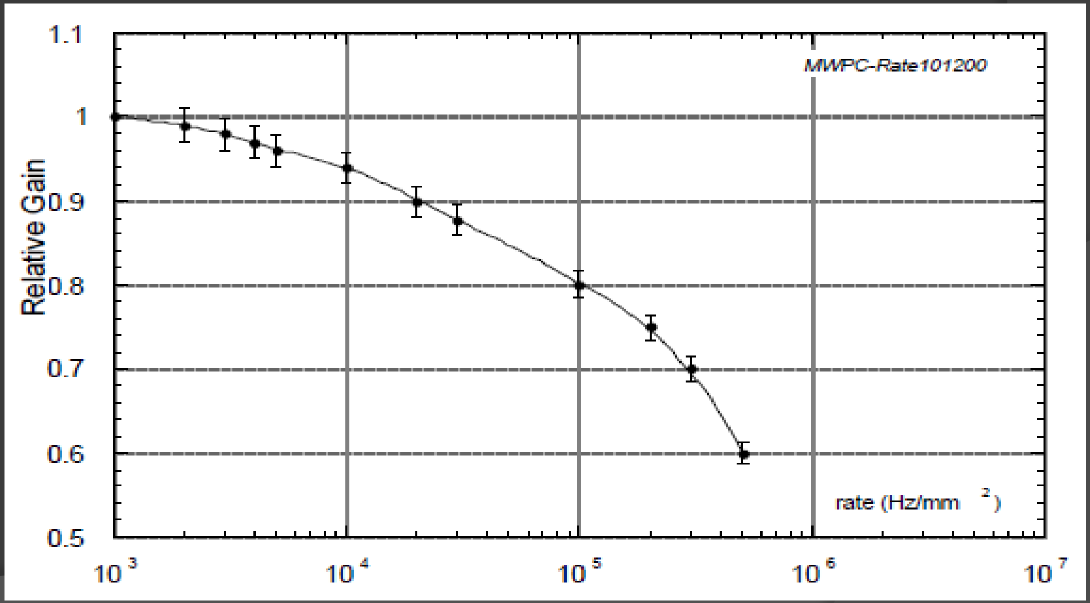




Features of wire chambers

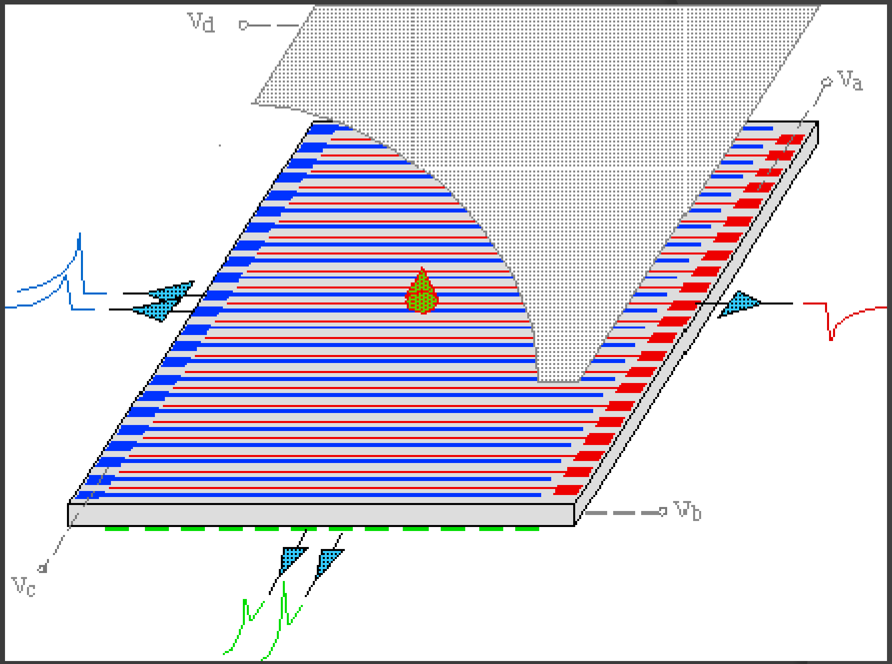
Advantages	Disadvantages
Excellent time resolution	Parallax problem
Large active areas, volumes and custom shapes are relatively easy to build	Elaborate electronics and gas systems, expensive
High dynamic range	Electrostatic instability limits the stable wire lengths
Excellent energy resolution	S/N limited by photon statistics
2/3 dimensional localisation of incident radiation	Widths of induced charges define the pad response function
Spatial resolution of few hundred μm	Wire spacing limits position accuracy, two track resolution to ~2mm
Rate capabilities of a few kHz/mm^2	Limited flux capability, accumulation of positive ions restrict the rate capabilities

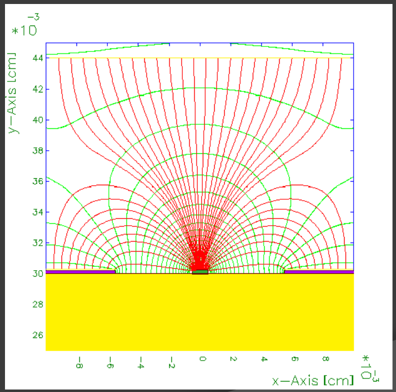


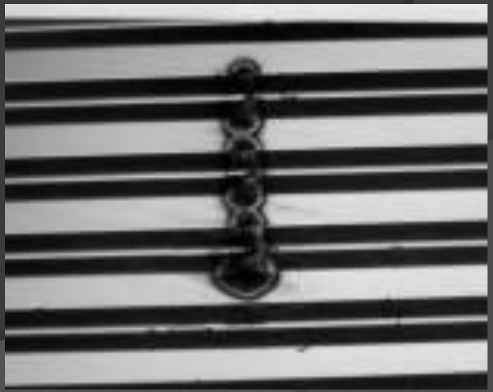


Micro Strip Gas Chamber (MSGC)

- A pattern of thin anodes and cathode strips on a insulating substrate with a pitch of a few hundred µm.
- Electric field setup from a drift electrode above.
- Removes positive ions from the vicinity of avalanches.
- High rate capability; two orders of magnitude higher than MPWC, ~30µm position resolution.
- Streamer to gliding discharge transition damages strips.
- Advances in photolithography and application of silicon foundry techniques heralded a new era in the design and fabrication of "Micro-pattern detectors"



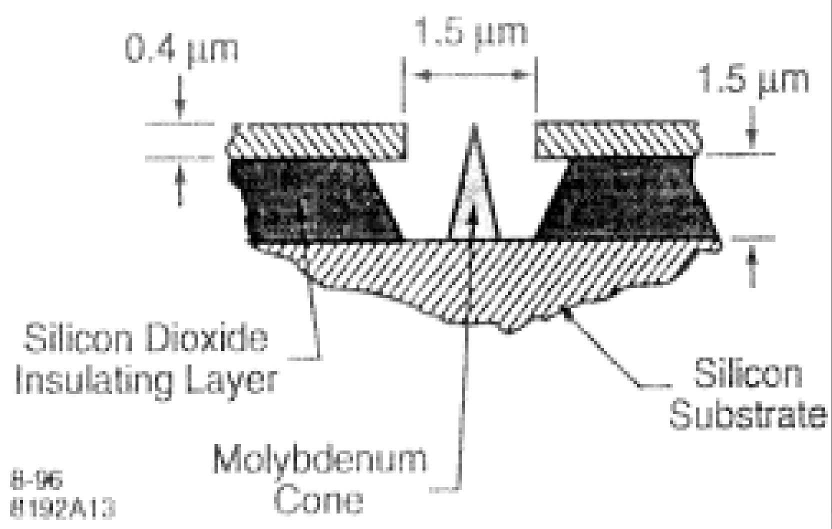




New micro pattern era

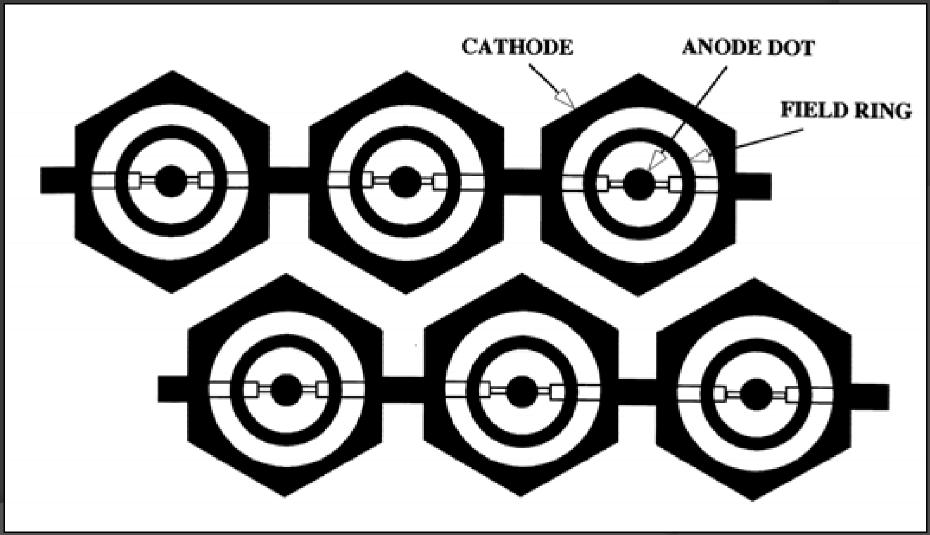
Micro-needle chamber

- Successfully used to emit electrons towards the phosphor screen in high vacuum, for the purpose of creation of the flat TV screens.
- No observable gas gain due to fine needles (<<1μm) and small amplification region.



Micro-dot chamber

- Ultimate gaseous pixel device with anode dotes surrounded by cathode rings, on 4” Si wafers.
- Anode 2 – 20μm, cathodes 20 - 40μm. Anode cathode gap is 75μm.
- Very high gains (~10^6).
- Does not discharge up to very high gains.



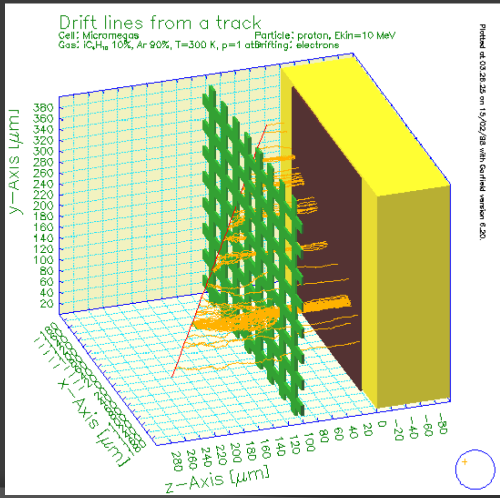
Next generation pattern detectors

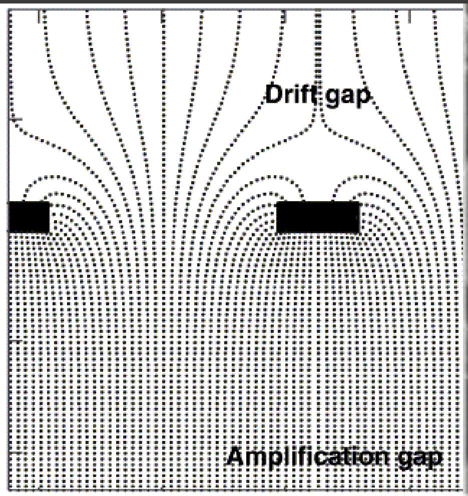
Micro-Megas

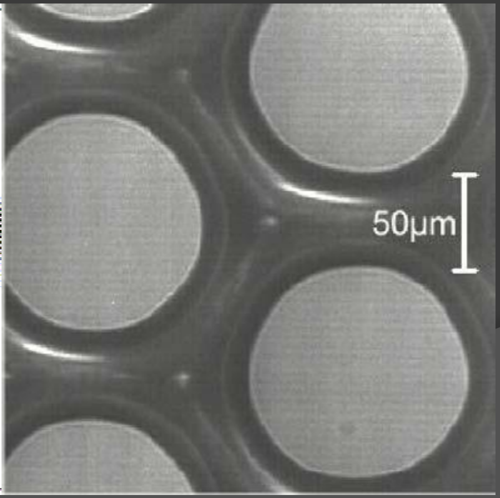
- Very asymmetric parallel plate chamber. Uses the semi-saturation of the Townsend coefficient at high fields (100kV/cm) in several gas mixtures, to ensure stability in operation with MIPs.
- Electrons drifting from the sensitive volume into the amplification volume with an avalanche in the thin multiplying gap.
- Provides excellent energy resolution.

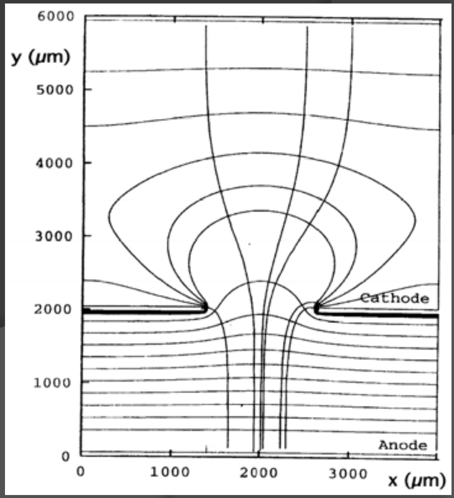
Compteur a Trous (CAT)

- A narrow hole micro-machined in an insulator metallised on the surface as the cathode.
- Anode is the metal at the bottom of the hole.
- Removing the insulator leaves the cathode as a micro-mesh placed with a thin gap above the readout electrode.
- Gains of several 10^4 usually obtained.



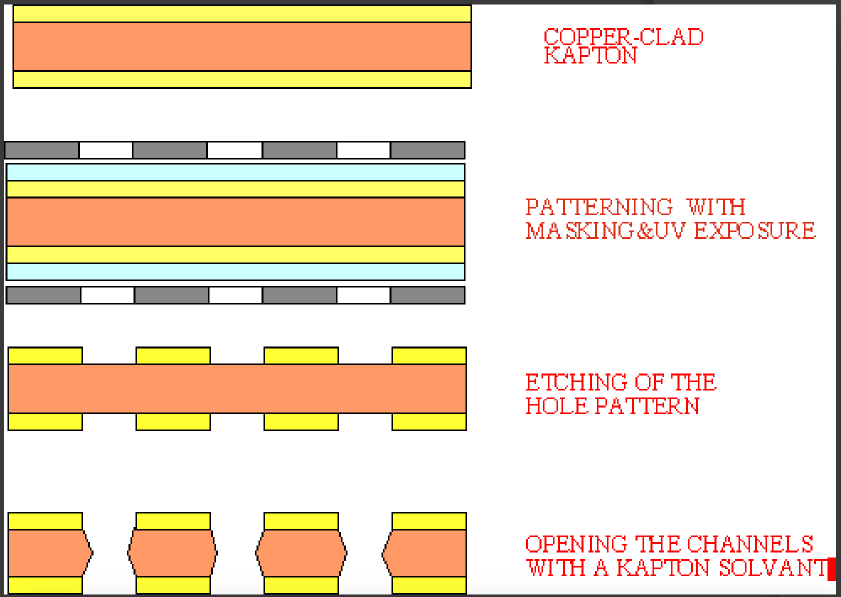


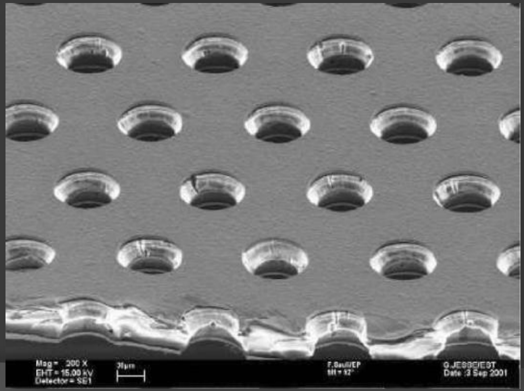


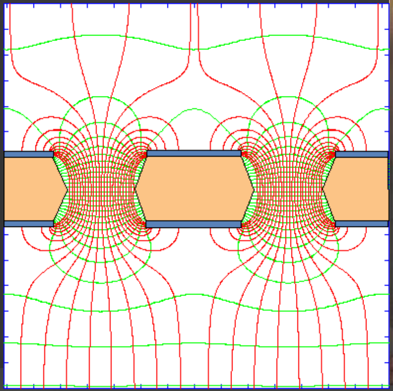


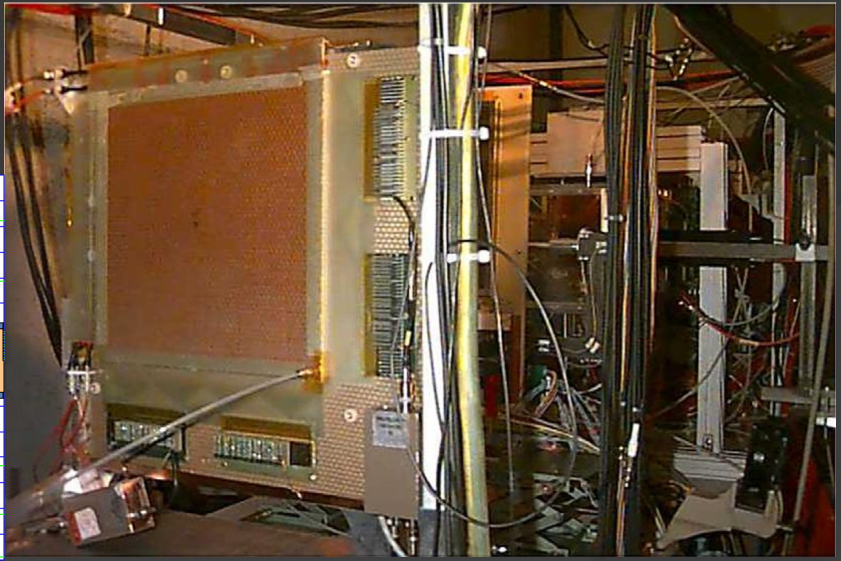
Gas Electron Multipliers (GEMs)

- Manufactured using standard printed circuit wet etching techniques.
- Comprise a thin (~50μm) Kapton foil, double-sided clad with copper and holes are perforated through.
- Two surfaces are maintained at a potential gradient; providing field for electron amplification and an avalanche of electrons.
- When coupled with a drift electrode above and a readout electrode below, it acts as a micro-pattern detector.
- Amplification and detection are decoupled, i.e. readout is at zero potential. This permits transfer to a second amplification device and can be coupled to another GEM.



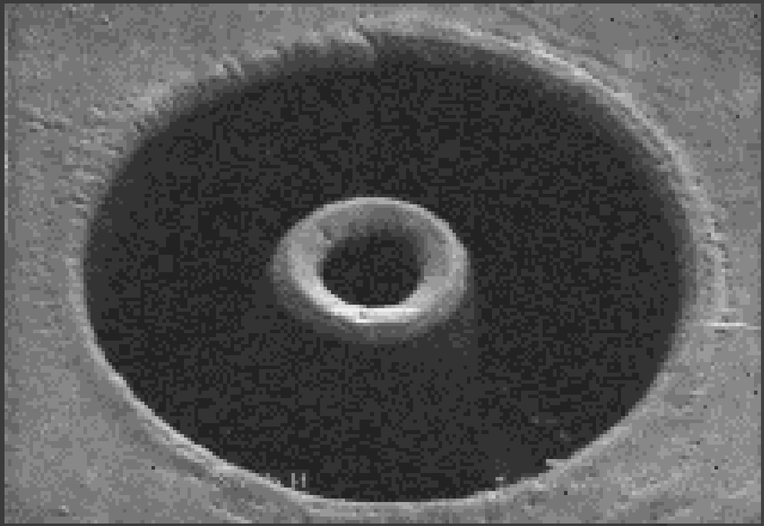


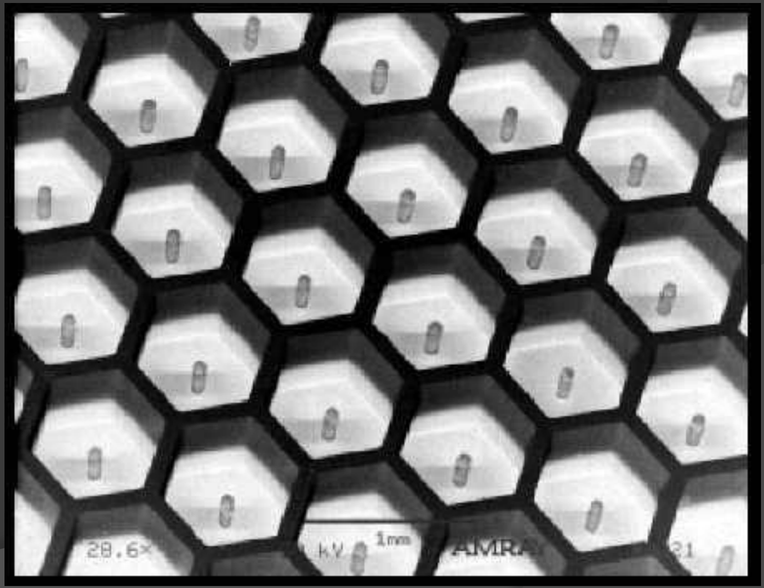




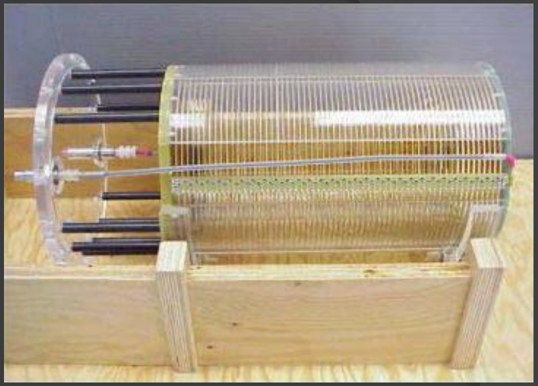
Other micro-pattern detectors

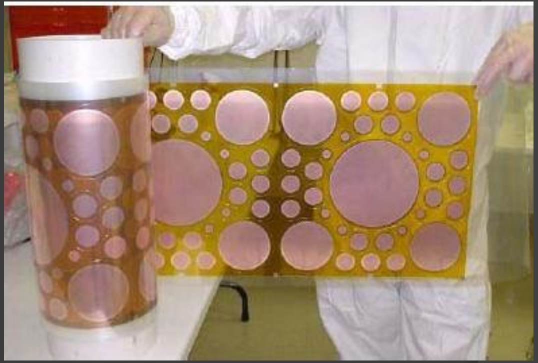
- Many more detectors were developed using the GEM concept, such as:
  - Micro-Wire (μDOT in 3-D)
  - Micro-Pin Array (MIPA)
  - Micro-Tube
  - Micro-Well
  - Micro-Trench
  - Micro-Groove
- Studies have shown that discharges in the presence of highly ionising particles appear in all micro-pattern detectors at gains of a few thousand.
- Can obtain higher gains with poorly quenched gases (lower operating voltage and higher diffusion)
  - Lowers charge density
  - Lowers photon feedback probability
- Safe operation of a combination of an MSGC and a GEM has been demonstrated up to gains of ~10000s.

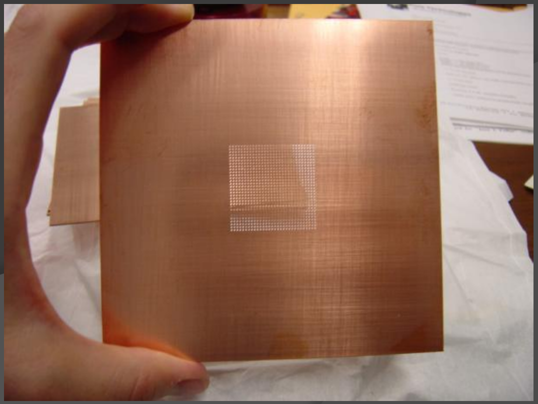




Current trends and directions







Scintillation light imaging
- A novel application was developed by integrating a MSGC in a gas proportional scintillation counter (GPSC).
- A reflective CsI photocathode was deposited on the micro-strip plate surface of the MSGC that serves as the VUV photo sensor for the scintillation light from Xenon GPSC.

Čherenkov ring imaging
- Very high gains observed with cascade of four GEMs and using pure ethane as the operating gas.

Mass production of GEMs
- 3M Microinterconnect Systems Division Reel-to-reel process, rolls of 16’x16’ templates of detachable GEMs in any patterns.

What is a LEM?
- A large scale GEM (x10) made with ultra-low radioactivity materials (OFHC copper plated on Teflon).
- In-house fabrication using automatic micro-machining.
- Modest increase in V yields gain similar to GEM.
- Self-supporting, easy to mount in multi-layers.
- Extremely resistant to discharges (lower capacitance).
- Adequate solution when no spatial info needed.
- Copper on PEEK under construction (zero out-gassing).

Birth of the RPC

- **Spark Counters**
  - Planar metal electrodes.
  - Streamer mode, leading to conducting plasma filament connecting two electrodes.
  - Rapidly growing anode current is the signal - large and very fast.
  - Small detector areas, large dead time.
- **Parallel Plate Avalanche Counters (PPACs)**
  - Avalanche mode, increased rate capability, good time resolution.
  - External amplification.
- **Pestov Counters**
  - Narrow gap, ultra high fields (500kV/cm), high pressure (12 bar).
  - Excellent time resolution, 25ps.
  - Demands good surface finish of electrodes.

DEVELOPMENT OF RESISTIVE PLATE COUNTERS

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Istituto di Fisica dell'Università di Roma, Roma, Italy; Istituto Nazionale di Fisica Nucleare, Sezione di Roma, Italy

Received 12 January 1981

A dc operated particle detector has been developed and tested, whose constituent elements are two parallel electrode bakelite plates between which, in a 1.5 mm gap, a gas mixture of argon and butane at ordinary pressure is circulated. The counter has 97% efficiency and ~1 ns time resolution at an operating voltage of about 10 kV. The output pulse needs no amplification, being typically 300 mV over 25 Ω.

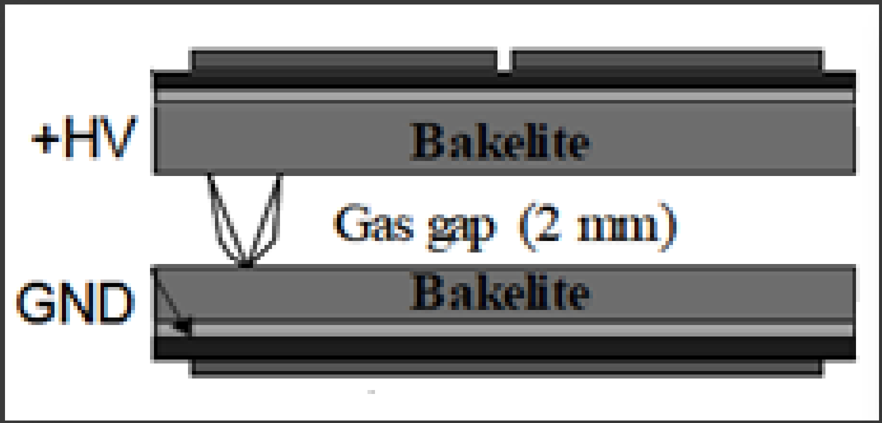
The detector presented in this paper, which will be called "Resistive Plate Counter" (RPC) is based on essentially the same principle as that recently developed by Pestov and Fedotovich [1]. Nevertheless the drastic simplifications introduced in its realization, such as the absence of high pressure gas, the low requirements of mechanical precision, and the use of plastic materials instead of glass, makes it of potential interest in a different and possibly wider range of applications. In particular it could replace with great economic advantages plastic scintillators, whenever large detecting areas are needed under not exceedingly high fluxes of particles.

... the possibility to originate secondary discharges in other points of the detector.

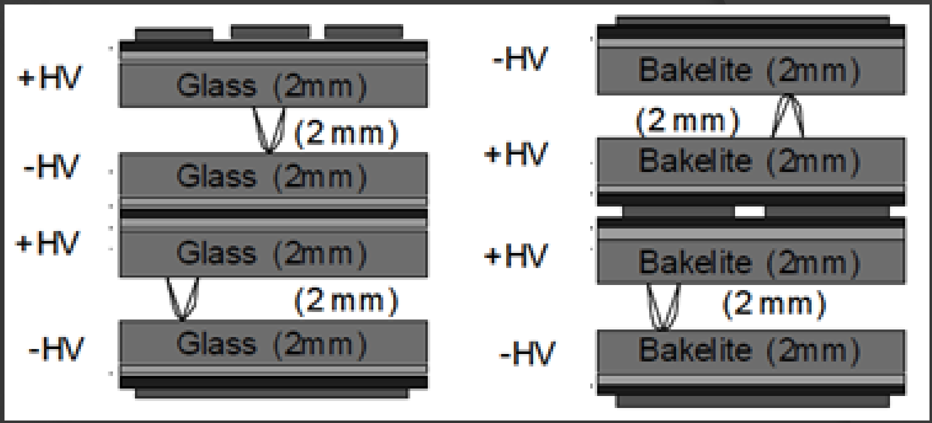
RPCs exhibit much better time resolution than

* The cement used here and in the following is epoxy resin which has been proven to guarantee a sufficient electrical contact between copper and bakelite. Its conductivity can be increased, if needed, by adding a small amount of graphite.

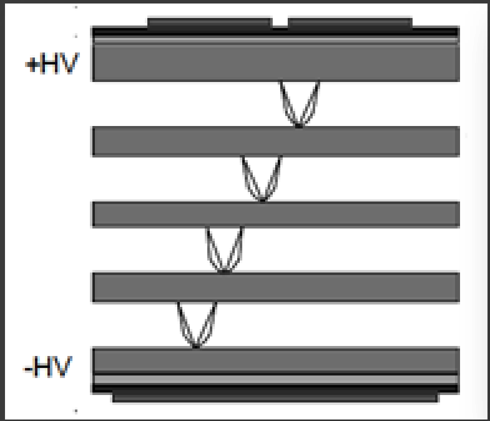
Application driven RPC designs



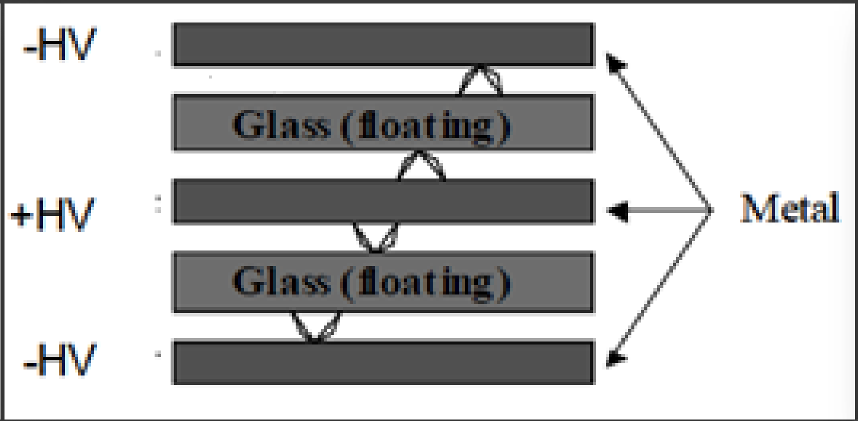
Single gap RPC



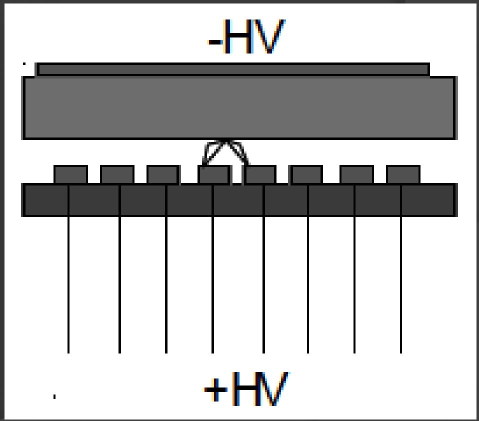
Double gap RPC



Multi gap RPC

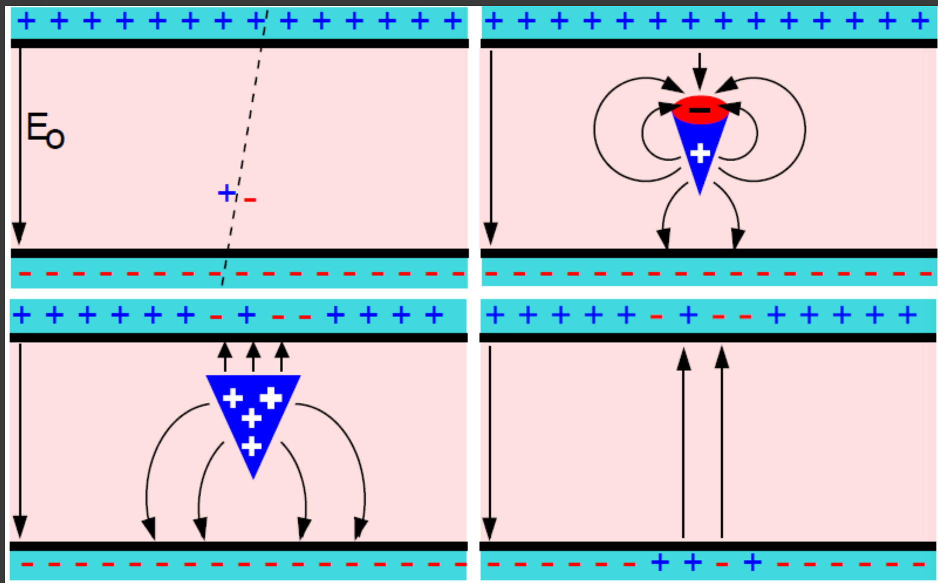


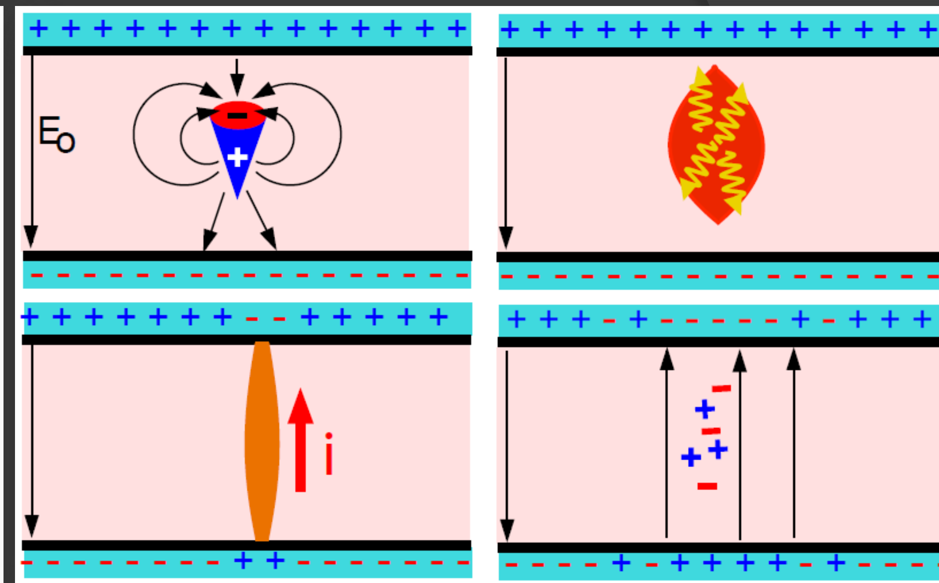
Hybrid RPC



Micro RPC

Two modes of RPC operation





Avalanche mode

- Gain of the detector << 10^8
- Charge developed ~1pC
- Needs a preamplifier
- Longer life
- Typical gas mixture Fr:iB:SF_6::94.5:4:0.5
- Moderate purity of gases
- Higher counting rate capability

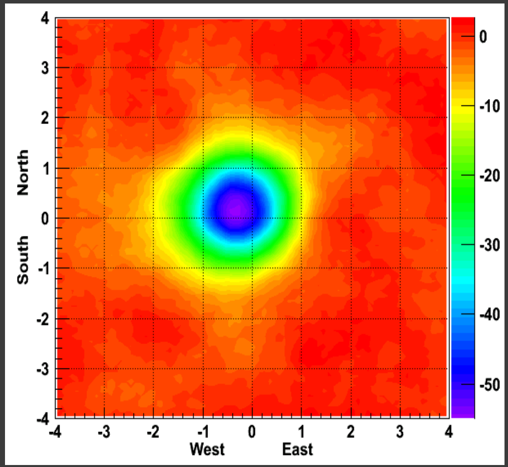
Streamer mode

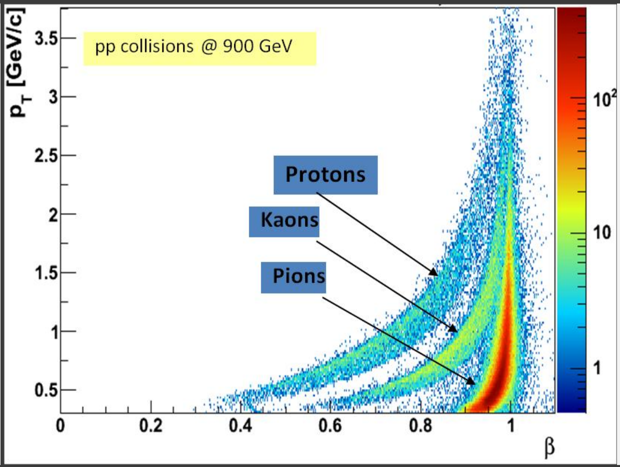
- Gain of the detector > 10^8
- Charge developed ~ 100pC
- No need for a preamplier
- Relatively shorter life
- Typical gas mixture Fr:iB:Ar::62.8:30
- High purity of gases
- Low counting rate capability

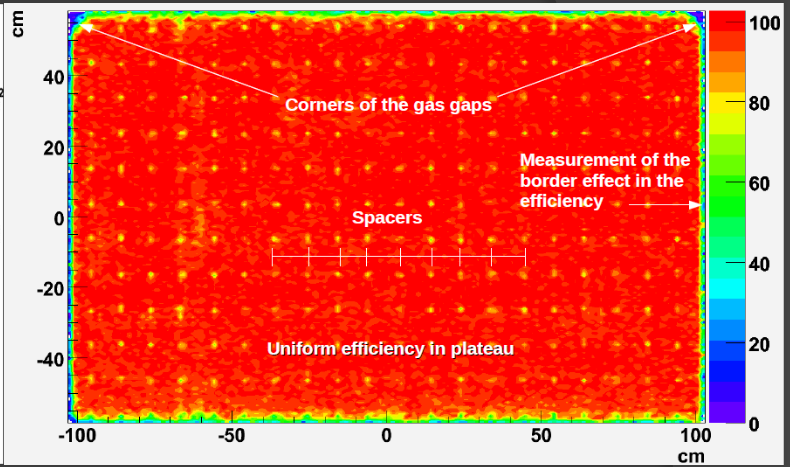
Deployment of RPCs in experiments

Experiment	Area (m^2)	Electrodes	Gap(mm)	Gaps	Mode	Type
PHENIX	?	Bakelite	2	2	Avalanche	Trigger
NeuLAND	4	Glass	0.6	8	Avalanche	Timing
FOPI	6	Glass	0.3	4	Avalanche	Timing
HADES	8	Glass	0.3	4	Avalanche	Timing
HARP	10	Glass	0.3	4	Avalanche	Timing
COVER-PLASTEX	16	Bakelite	2	1	Streamer	Timing
EAS-TOP	40	Bakelite	2	1	Streamer	Trigger
STAR	50	Glass	0.22	6	Avalanche	Timing
CBM TOF	120	Glass	0.25	10	Avalanche	Timing
ALICE Muon	140	Bakelite	2	1	Streamer	Trigger
ALICE TOF	150	Glass	0.25	10	Avalanche	Timing
L3	300	Bakelite	2	2	Streamer	Trigger
BESIII	1200	Bakelite	2	1	Streamer	Trigger
BaBar	2000	Bakelite	2	1	Streamer	Trigger
Belle	2200	Glass	2	2	Streamer	Trigger
CMS	2953	Bakelite	2	2	Avalanche	Trigger
OPERA	3200	Bakelite	2	1	Streamer	Trigger
YBJ-ARGO	5630	Bakelite	2	1	Streamer	Trigger
ATLAS	6550	Bakelite	2	1	Avalanche	Trigger
ICAL	97,505	Both	2	1	Both	Trigger

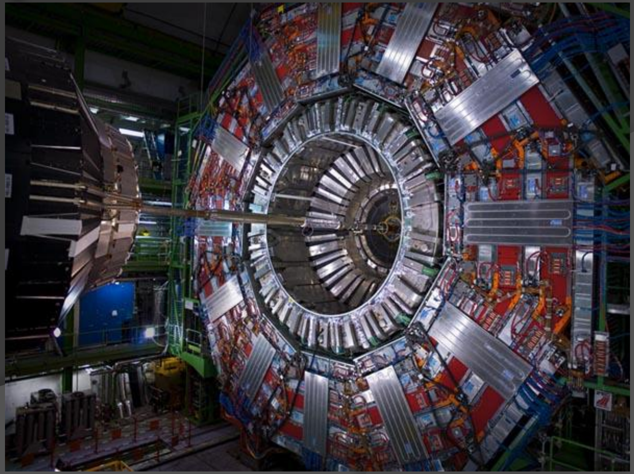
Performance of RPC systems







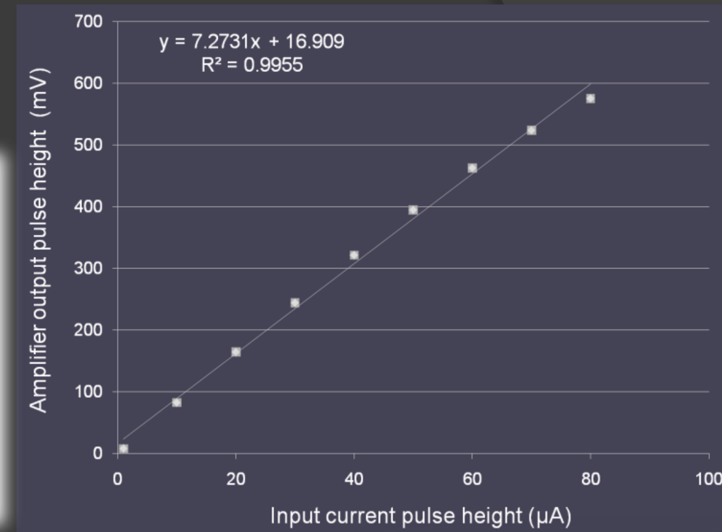
Argo	Alice	CMS

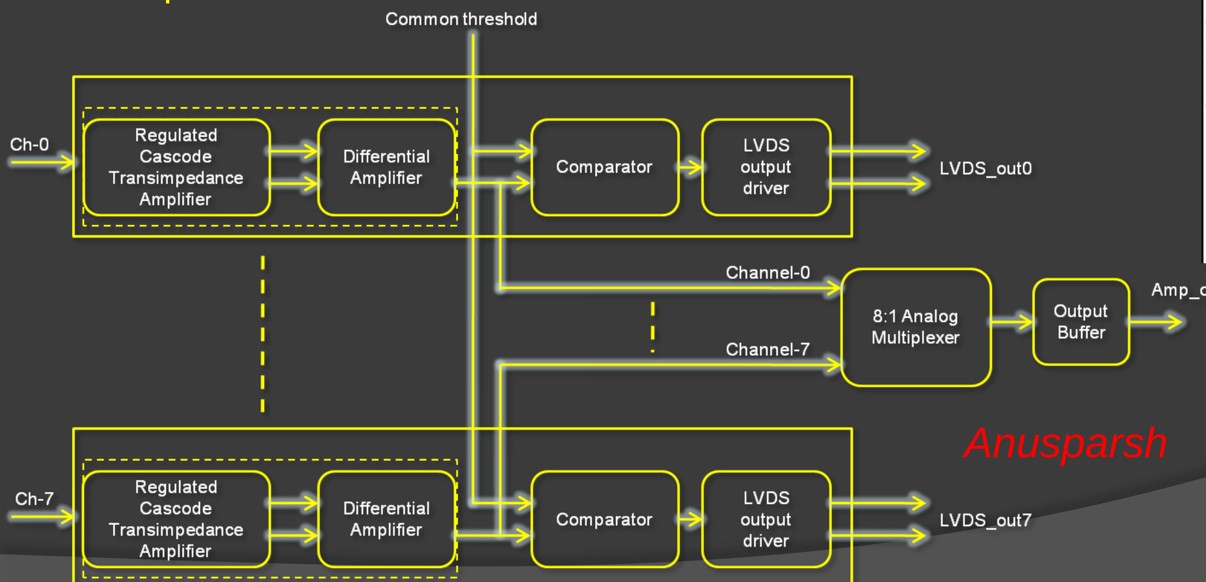


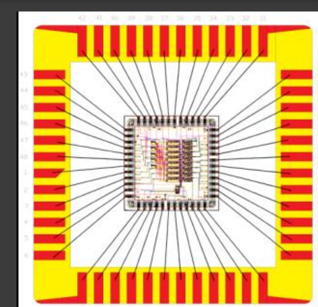
Picking up the tiny charges

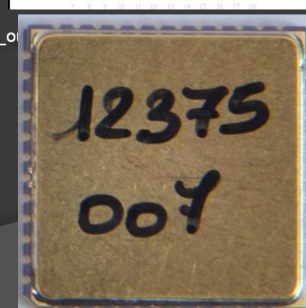
- Process: AMSc35b4c3 (0.35um CMOS)
- Input dynamic range:18fC – 1.36pC
- Input impedance: 45Ω @350MHz
- Amplifier gain: 8mV/µA
- 3-dB Bandwidth: 274MHz
- Rise time: 1.2ns
- Comparator's sensitivity: 2mV
- LVDS drive: 4mA
- Power per channel: < 20mW
- Package: CLCC48(48-pin)
- Chip area: 13mm^2

Manas









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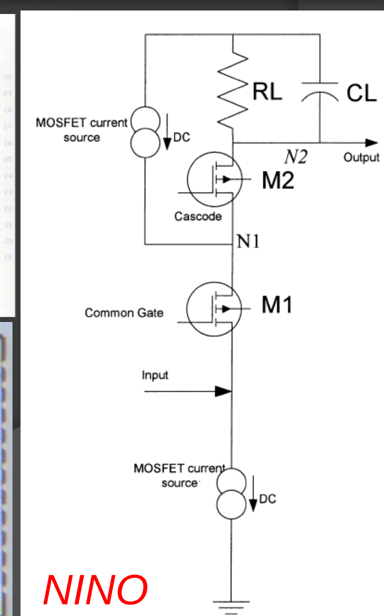
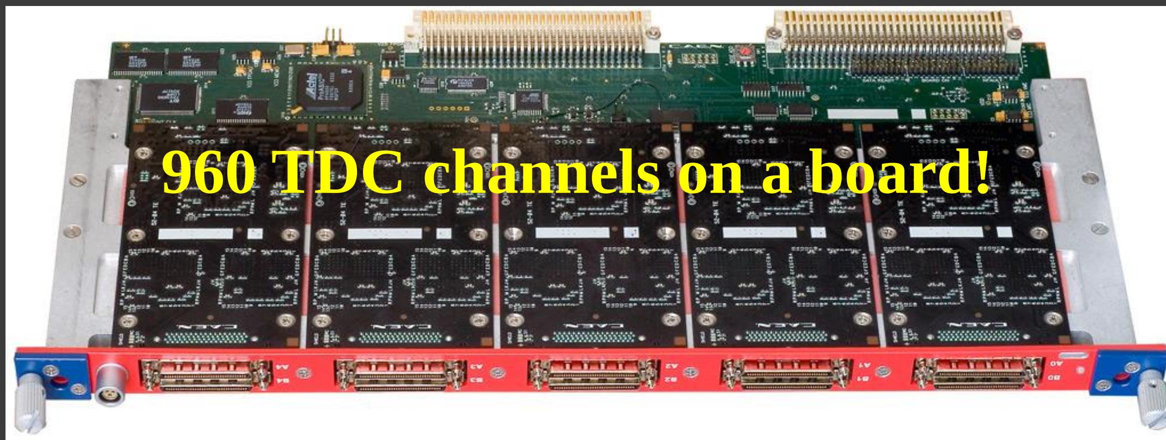
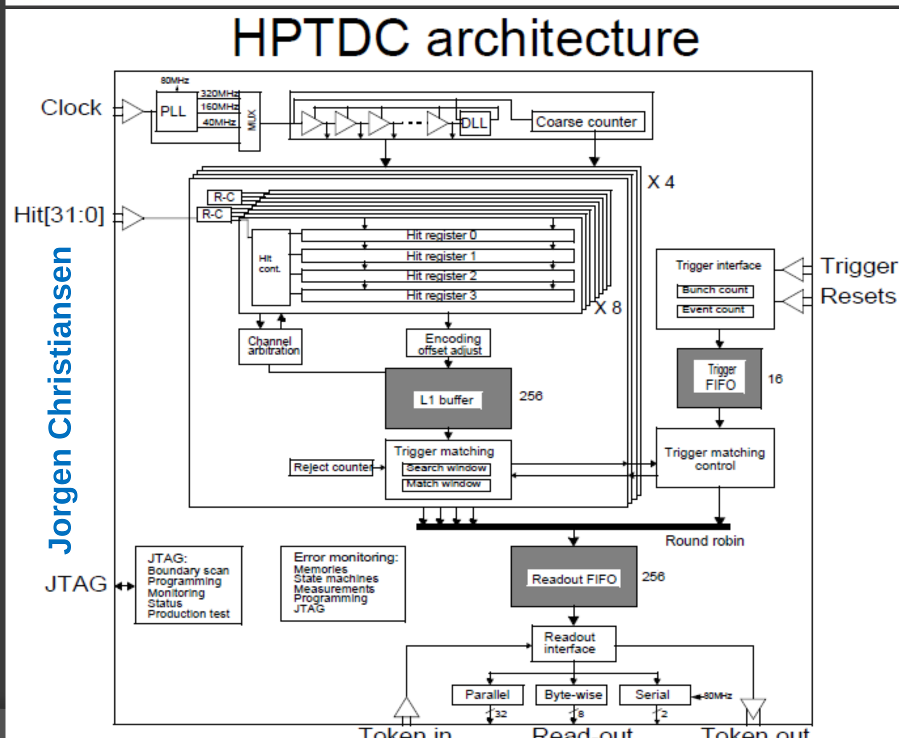
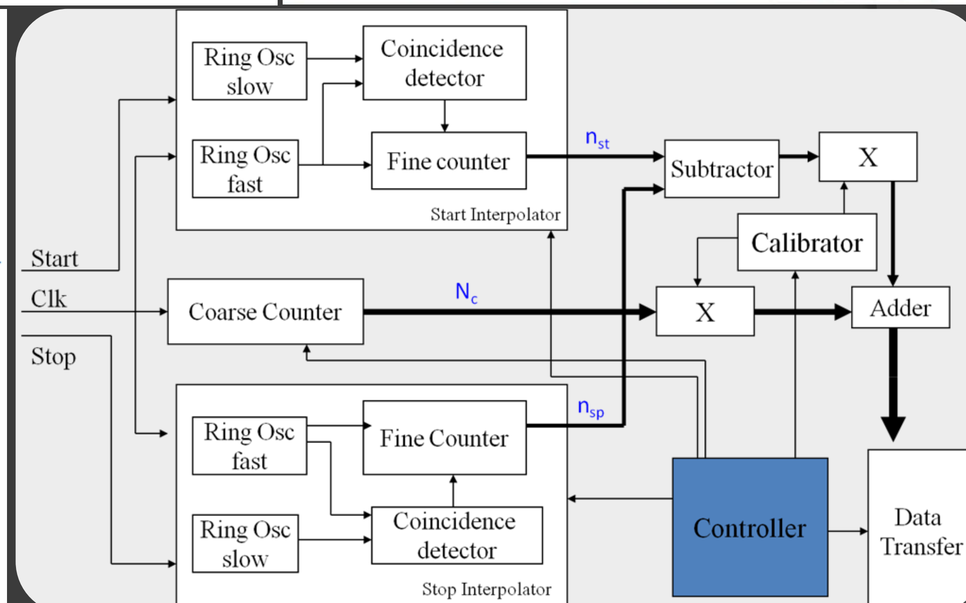


Timing the timing devices

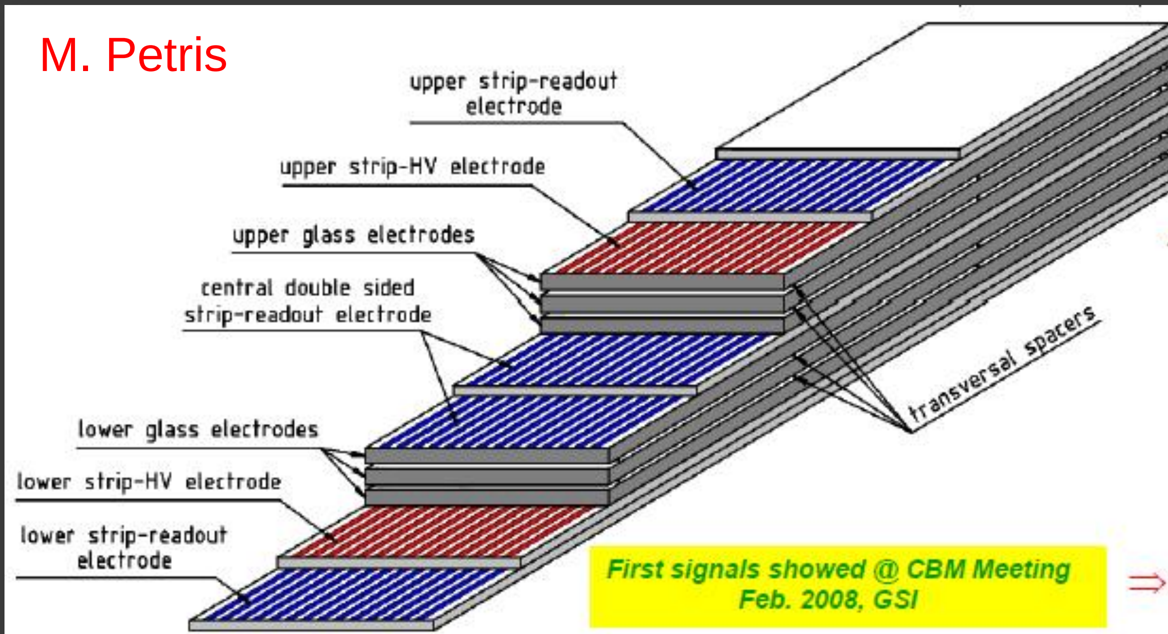






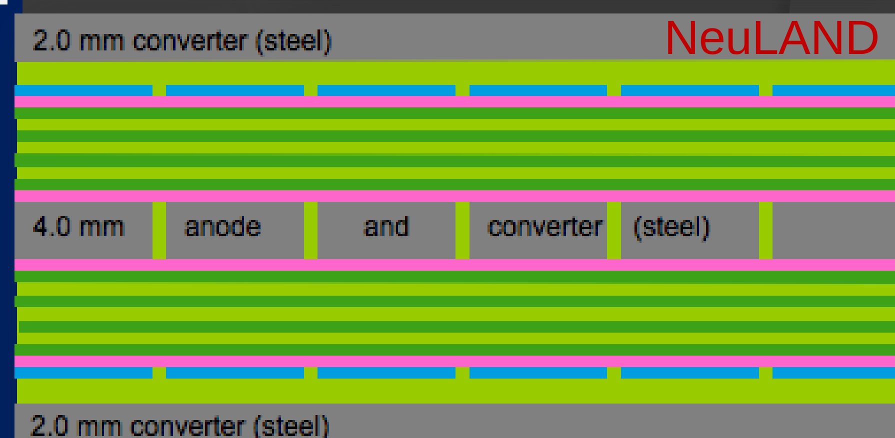
FPGA based TDC architecture

Latest designs and developments

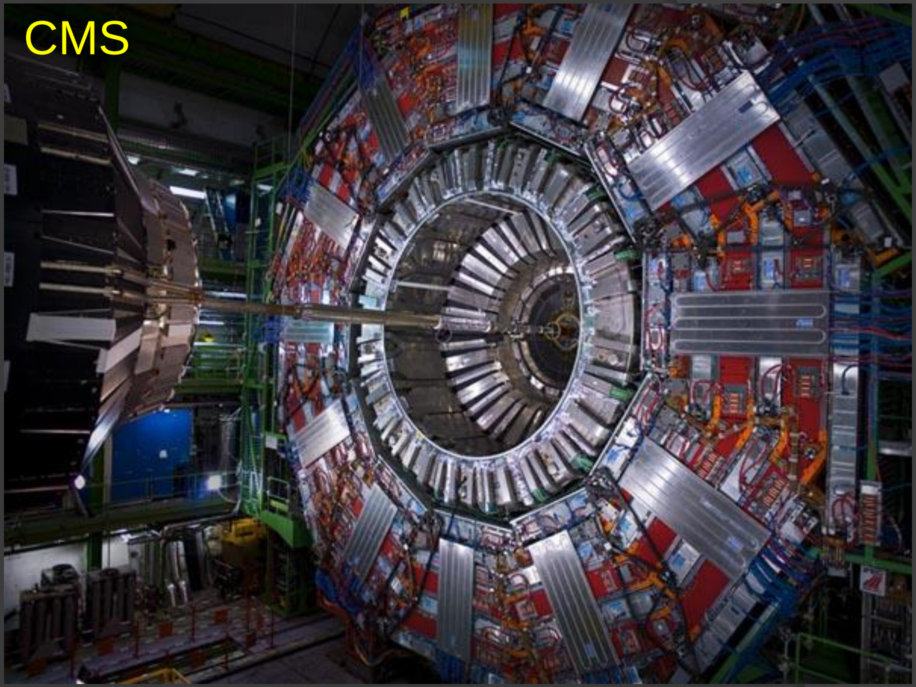


M. Abbrescia

- New mixtures containing Helium
- Ideally, operating RPC at ½ Atm would reduce the the operating voltage by a factor of 2.
- Helium undergoes elastic scattering with electrons
- Takes part only partially in the avalanche processes
- In first approximation behaves like a space holder
- Reduces the partial pressure of the *active mixture*
- Effect similar to operating at a reduced pressure



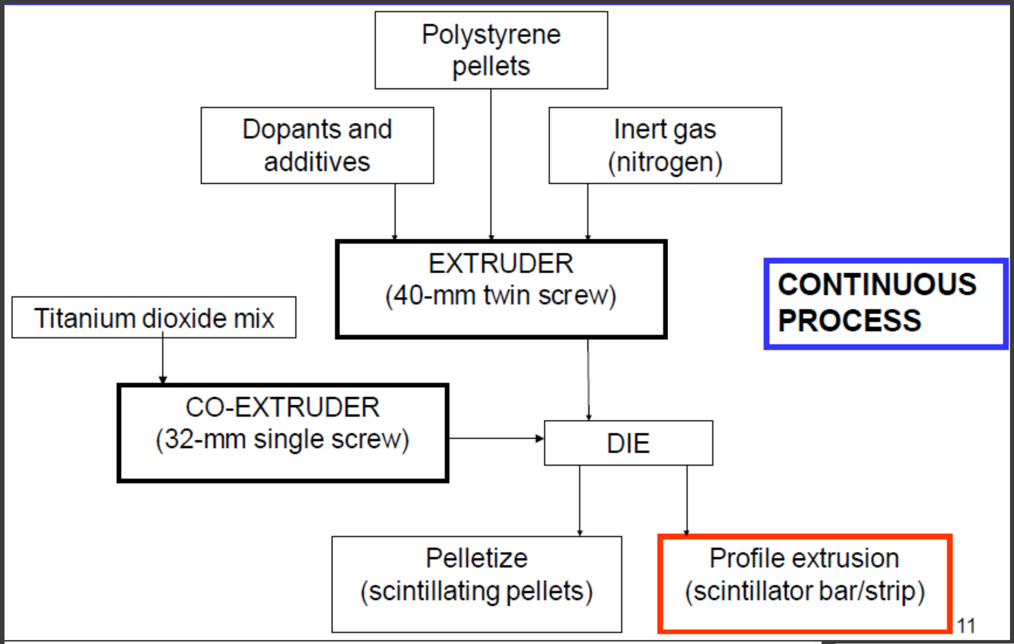
Large scale deployment of scintillators

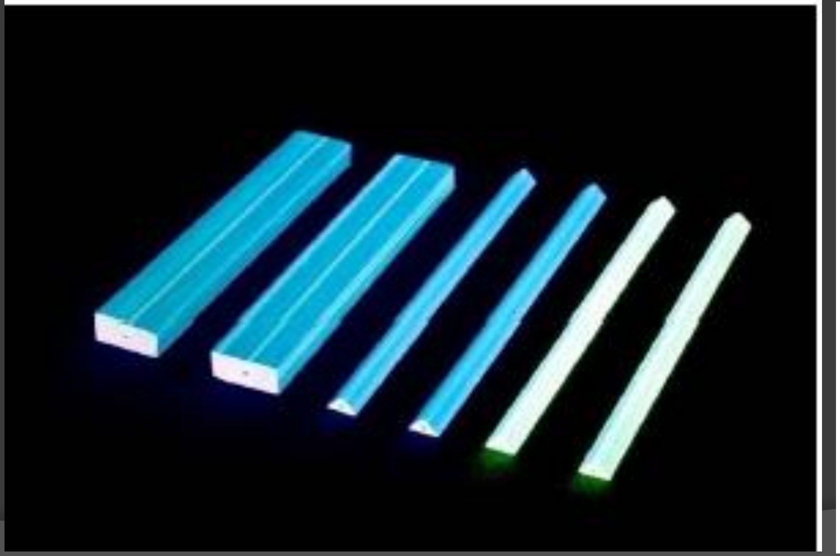


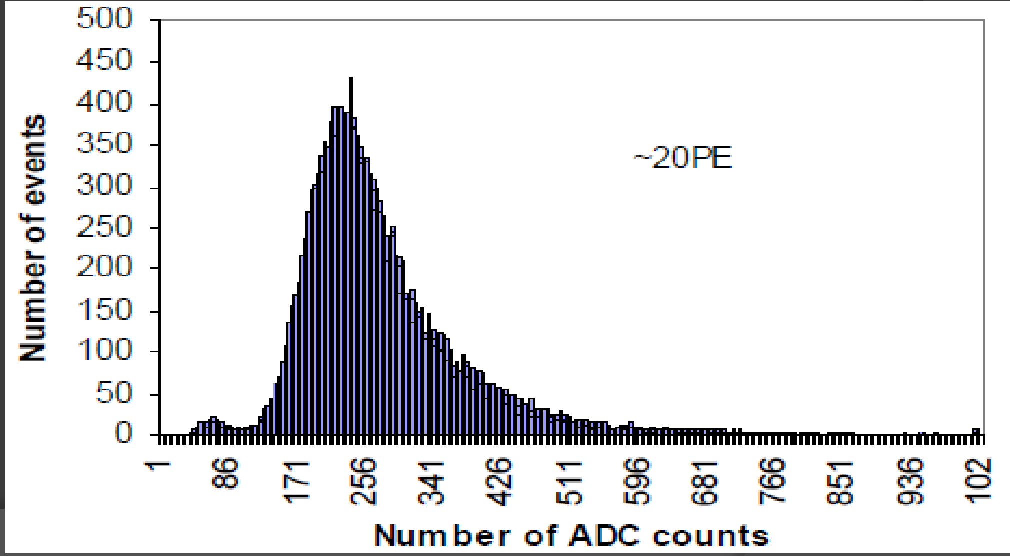
FNAL-NICADD extrusion Line

- Fermilab and Northern Illinois Center for Accelerator and Detector Development.
- For ALICE upgrade, the ILC calorimetry program, MINOS and MINERνA experiments.
- Simple, inexpensive and robust extrusion procedure.
- Co-extruded hole and TiO_2 coating or Tyvek.
- In some cases no alternative to the extrusion because of geometry requirements.
- Polystyrene pellets are used as the base material, along with % PPO (2.5-Diphenyloxazole) and 0.03% POPOP (1,4-bis(5-phenyloxazol-2-yl) benzene) dopants.
- This is a blue-emitting scintillator, absorption cut-off at 400nm and emission at 420nm.
- Light Attenuation Lengths of long and short components are 42cm & 30cm.
- Fiber hole diameter and number of fibres are some of the considerations.
- Readout by Solid State Photomultipliers (SSPM).
- New development: Co-extrude fibres with the scintillator profile.

Extrusion scintillator technology





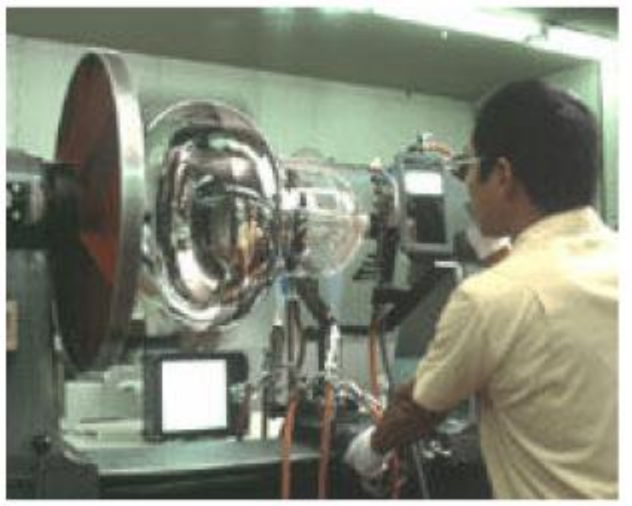


New hybrid scintillators

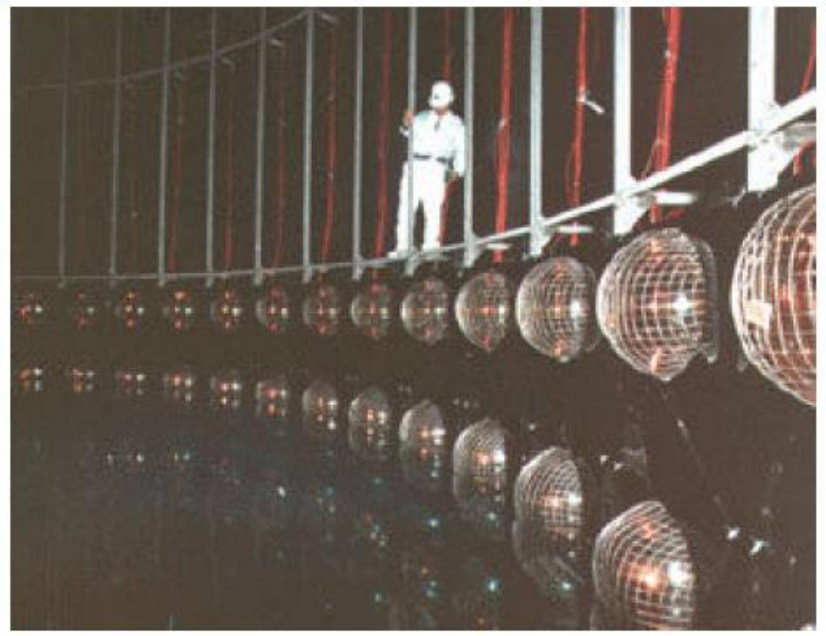
- New generation experiments require large volume, cheap scintillation materials with high light yields and short scintillation decay times.
- Extruded scintillators suffer from poorer optical quality, particulate matter and additives in polystyrene pellets.
- New single-component and multi-component polymer mixtures.
- Hybrid scintillators using luminescent salts as scintillation dyes.
- Introduction of fusible inorganic fillers found to alter optical transmission spectra and rapid shortening of the scintillation decay times of the hybrid scintillators.
- Polymer based hybrid glasses in which the components do not chemically react with each other during the manufacturing process.
- Conventional hybrid materials in which all or a part of the inorganic components participate in chemical reactions with organic components. For example, a reaction between the $AlCl_3$ inorganic filler and the polystyrene matrix during the injection moulding process.

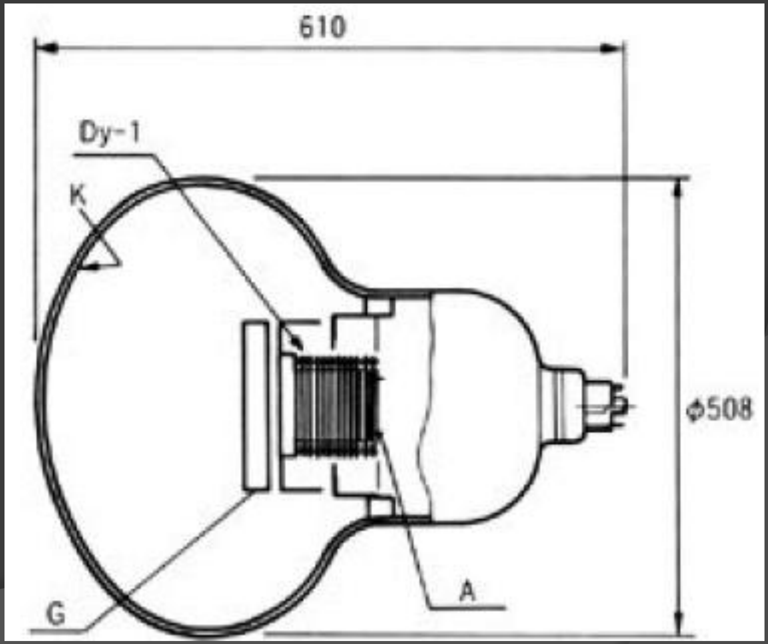
R1449 PMTs & neutrino astronomy

- In 1979, Masatoshi Koshiba came up with a challenging proposal to Hamamatsu's President Hiruma "Hey, could you make me a 25" PMT?"
- A number of previously acquired highly sophisticated technologies were collectively used to develop the 20" PMT.
- 50Kt water Čherenkov detector uses 11.2K PMTs.



Kamiokande detector

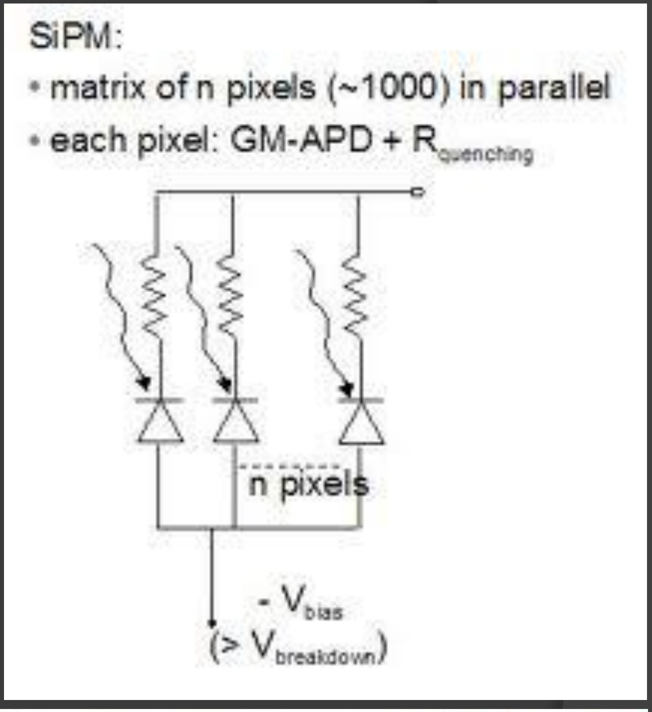


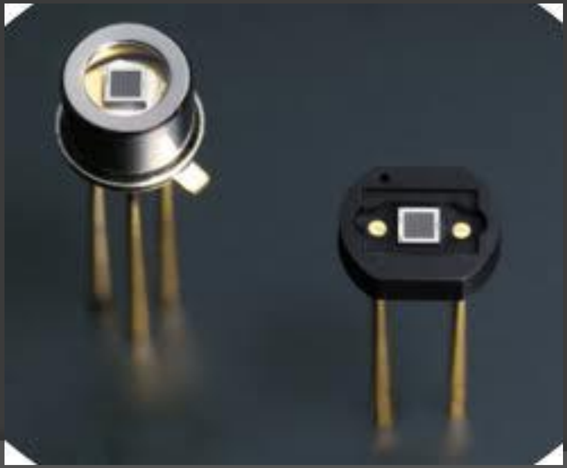


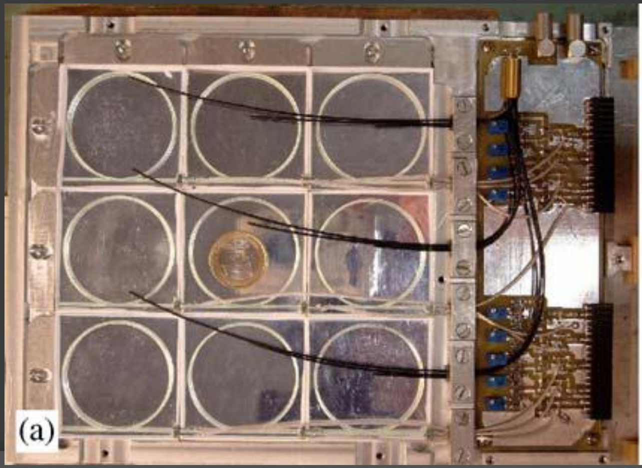
Hamamatsu

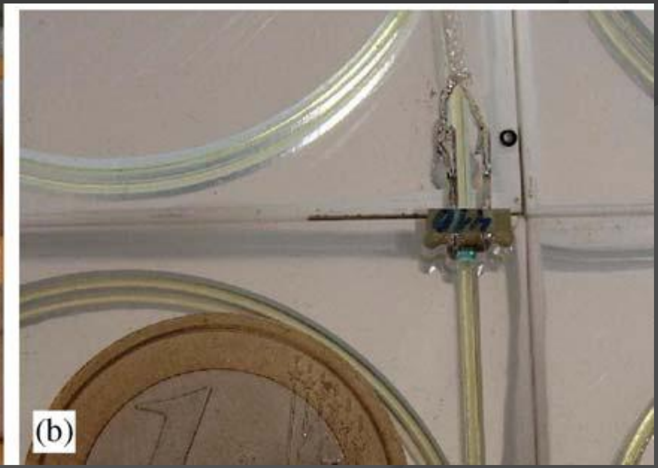
GM APDs and SiPMs

- Very small (few mm)
- Pixelated active surface structure
- Insensitive to magnetic fields
- Works at low bias voltage (<100V)
- *Relatively* inexpensive
- Single photon counting capability
- Very fast time resolution (200ps)
- Good linear response









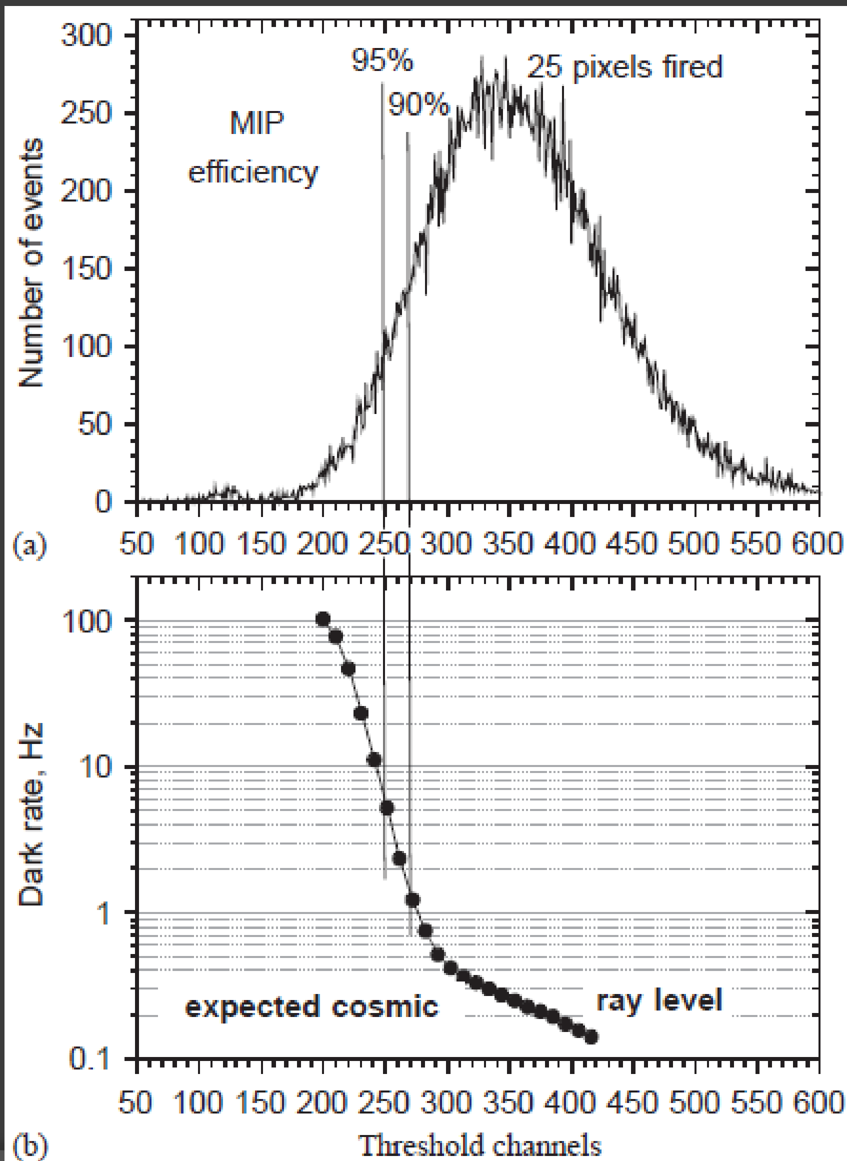
A 1-minute tutorial on SiPM

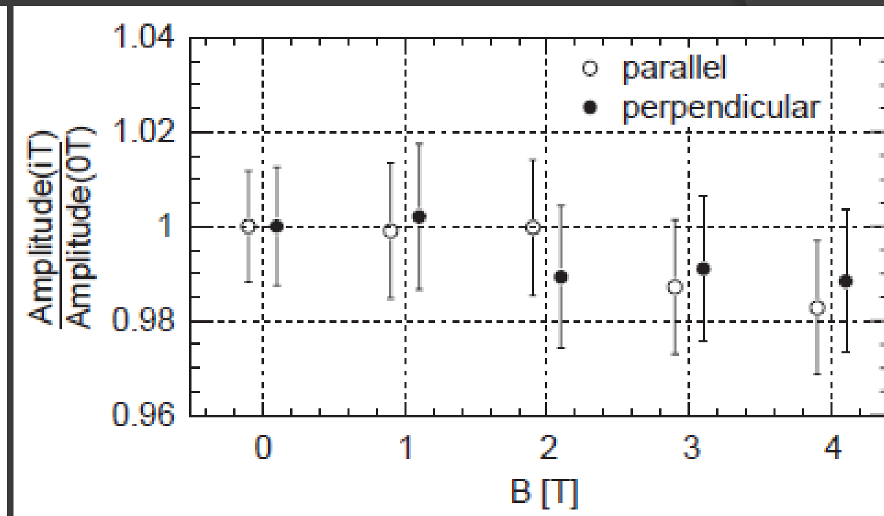
- SiPM is a pixelated avalanche photodiode operated in the limited Geiger mode.
- For example, a detector surface of $1\times1mm^2$ is divided into 1024 pixels.
- Operated with a reverse bias which is slightly above the breakdown voltage.
- Current flow in a pixel limited by an individual poly-silicon resistor (R_{pixel} = 400 kΩ).
- Signal from a pixel is determined by the charge accumulated in the pixel capacitance, C_{pixel};

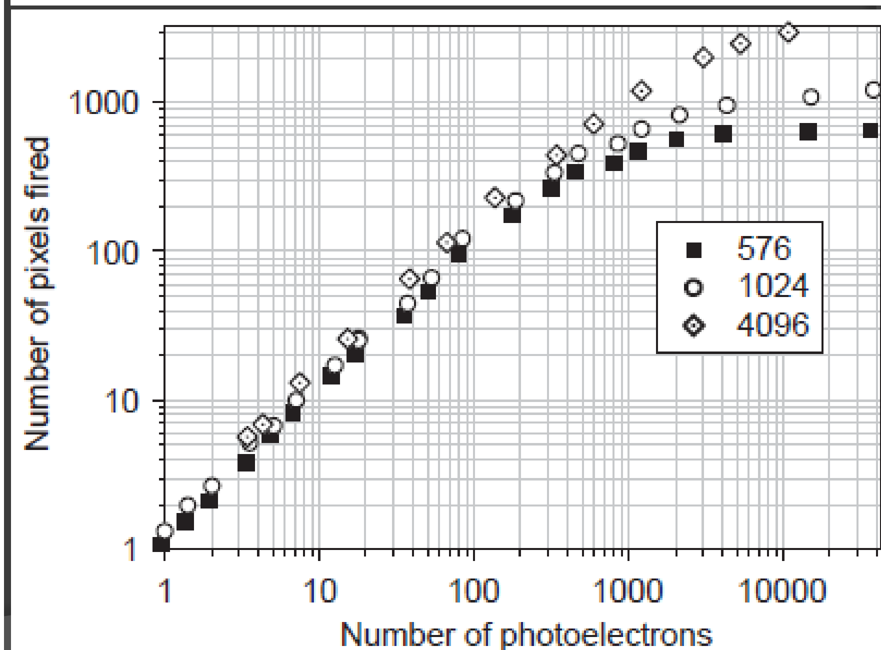
  i.e. $Q_{pixel} = C_{pixel} \times \Delta V = C_{pixel} \times (V_{bias} - V_{breakdown})$

  where ΔV is ≈ a few volts, C_{pixel} is ~50 fF, yielding $Q_{pixel} \approx$ 150 fC or 10^6 electrons.
- SiPM pixel signal doesn't depend on the number of primary carriers (Geiger mode).
- Each pixel detects the carriers created by a photon, ionization of a charged particle, or thermal noise with the same response signal of 10^6 electrons.
- Analog information obtained by adding response of all fired pixels.
- The dynamic range is determined by the finite number of pixels, presently 10^3:
- The SiPM photon-detection efficiency is comparable to the QE of PMTs for blue light and larger for green light, which is important for the usage of WLS fibres.
- For stable operations, the sensitivity of the SiPM gain and efficiency to temperature and bias voltage are important issues.
- The total temperature and bias voltage dependence of the SiPM gain at room temperature is measured to be 4.5%/^{o}C and 7%/0.1V.

Some of the basic characteristics

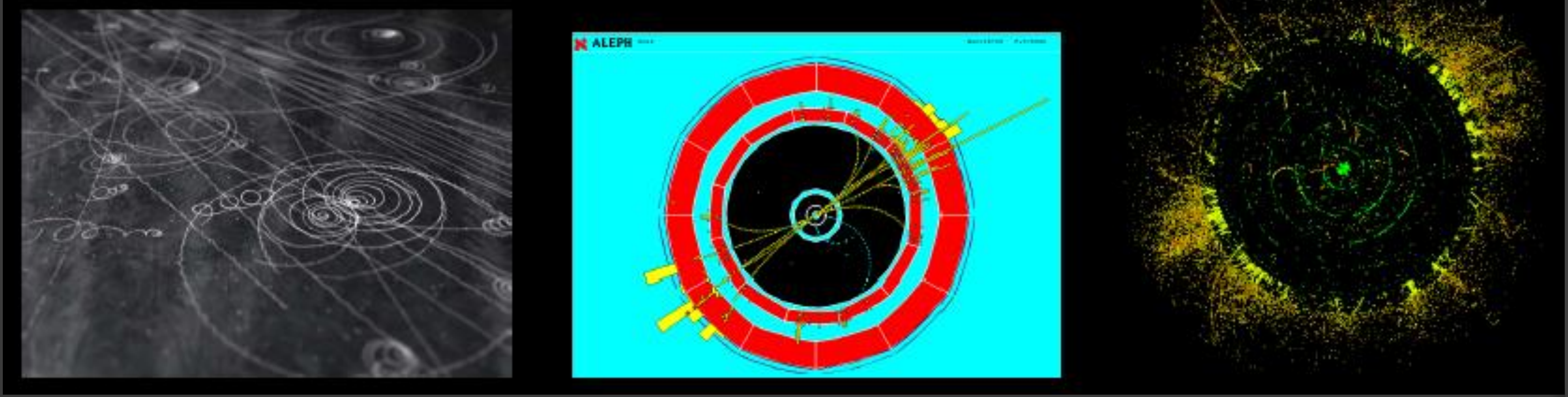




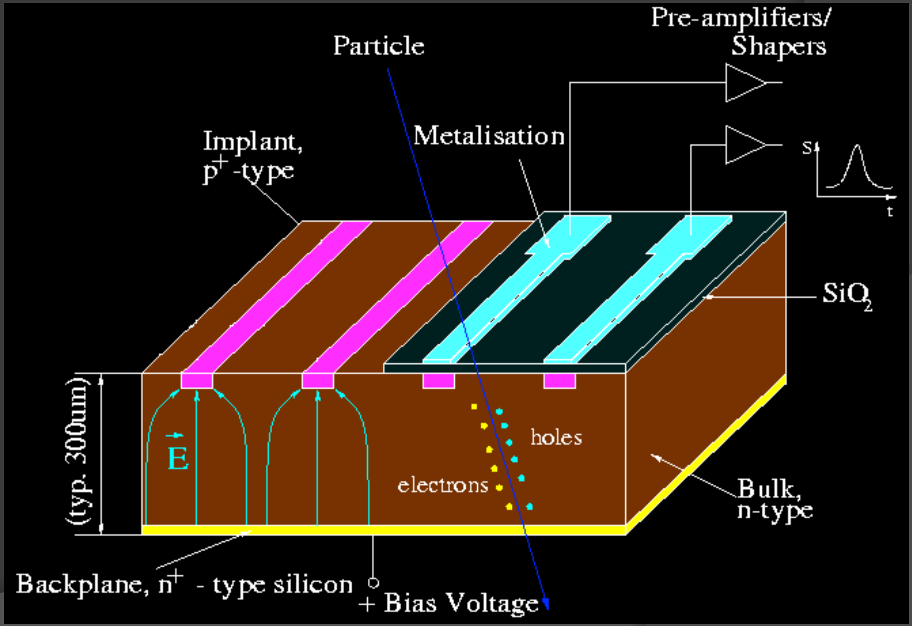


Silicon detectors

Silicon detectors are transforming the way we look at particles

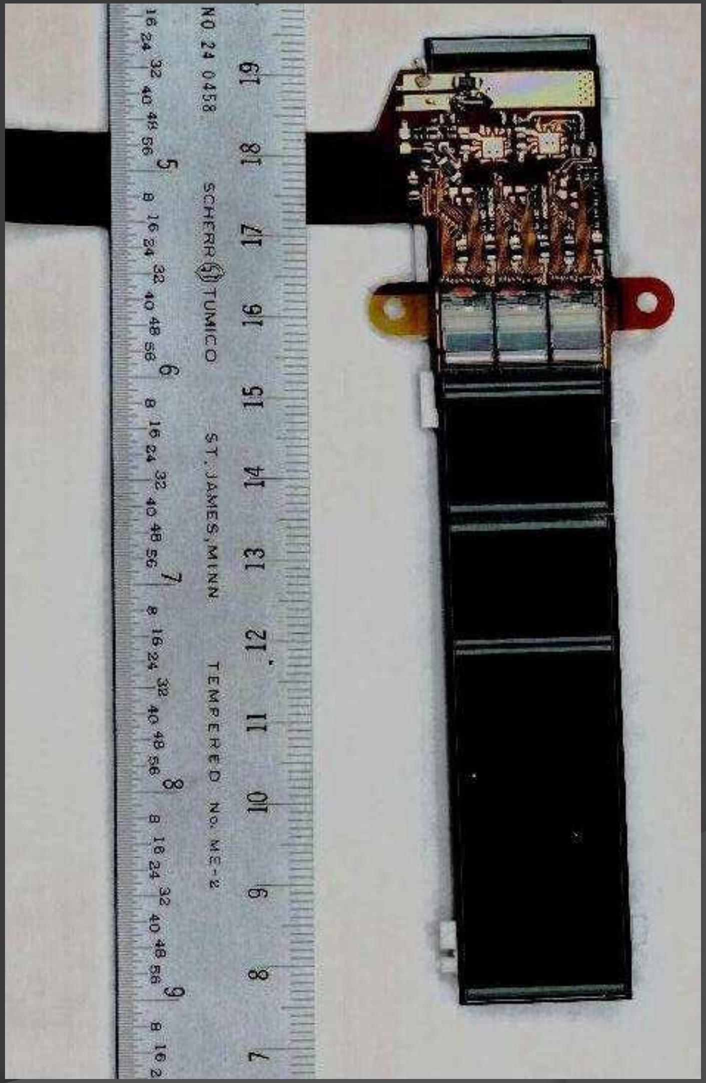


- Essentially diode with reverse bias.
- Depleted of free charge carriers.
- High resistance, only small leakage current.
- Charge deposition by ionising particle causes current.
- Use segmented electrodes (strips or pixels).
- Can localise charge deposition.
- Much better resolution than strip pitch if taking charge sharing into account.
- Only few eV per ionisation (gases: factor 10 more).
- Good amplitude signal.



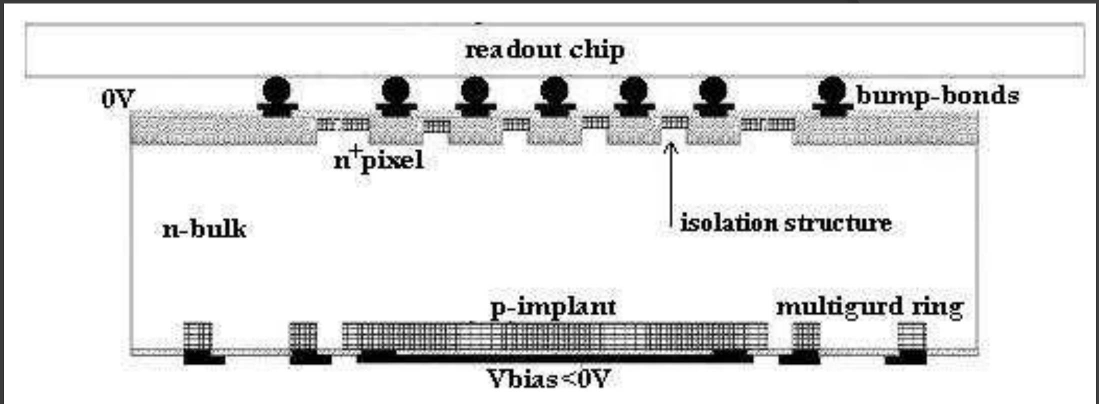
Strip detectors

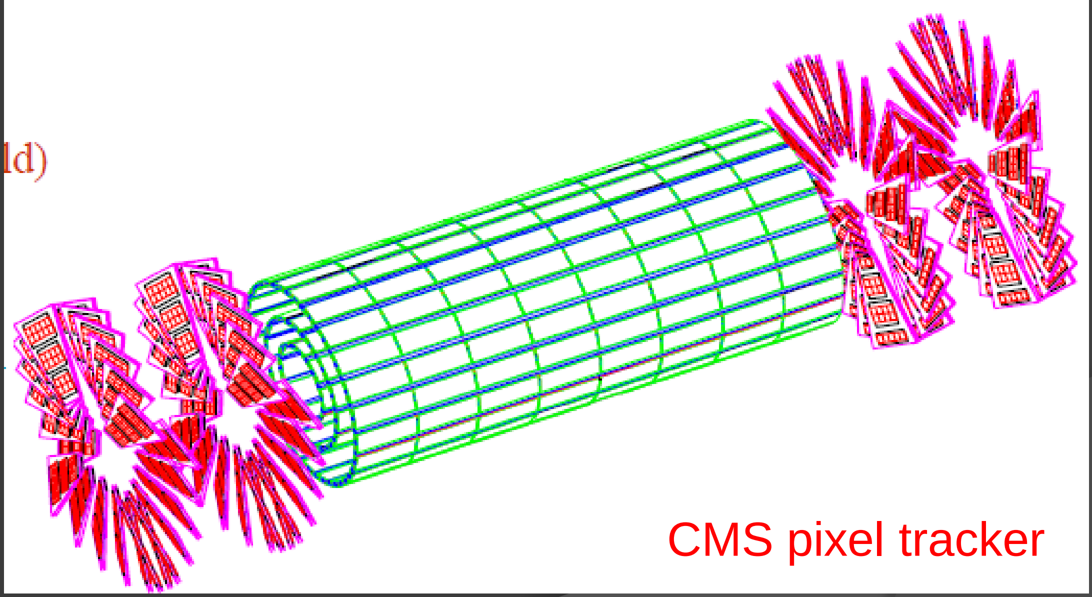
- Reading out strips is comparatively easy - just attach chips to the end.
- Readout of strip sensor, power distribution and control → hybrids.
- Custom readout chips wire bonded to electrodes on the sensor.
- Chips have amplifiers, ADCs, zero suppression, cluster finder, storage, digital communication with outside world.
- Some drawbacks:
- Strip detectors would often exceed useful occupancy in many modern systems.
- Strip information can make hit reconstruction ambiguous.



Pixel detectors

- Silicon pixel detectors do much better on the hit reconstruction problems.
- However, reading pixel detectors is non-trivial.
- Options for pixel detector readout:
  - Place readout chips all over the sensors (more material budget).
  - Integrate readout electronics into sensor (larger pixels).
  - Sequentially clock signals through to end of sensor (slower readout).

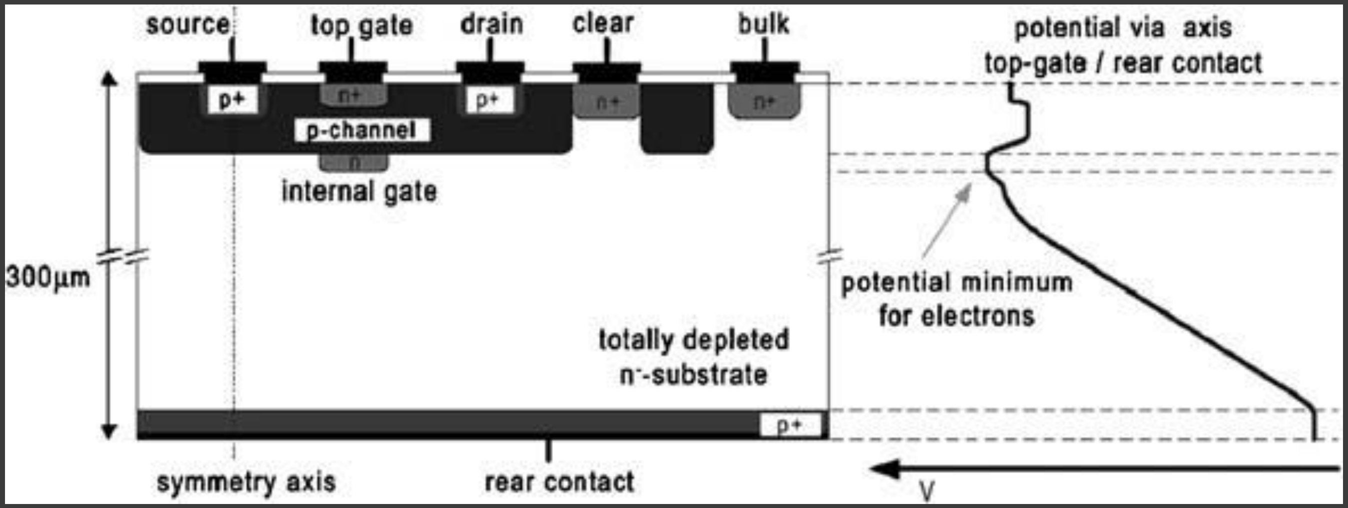




Integration of detectors & readout

- Compatible integration of detectors and readout electronics on the same silicon substrate is of growing interest.
- As the methods of microelectronics technology have already been adapted for detector fabrication, a common technology basis for detectors and readout electronics is available.
- CMOS technology exhibits most attractive features for the compatible realisation of readout electronics where advanced LSI processing steps are combined with detector requirements.
- The essential requirements for compatible integration are the:
  - availability of high resistivity oriented single crystalline silicon substrate
  - formation of suitably doped areas for MOS circuits
  - isolation of the low voltage circuits from the detector, which is operated at much higher supply voltage.
- Junction isolation as a first approach based on present production technology and dielectric isolation based on an advanced SOI-LSI technology are the most promising solutions for present and future applications, respectively.
- Some examples: MAPS (Monolithic Active Pixels), DEPFET, WIPS, SOI sensors.

Integrated silicon detectors



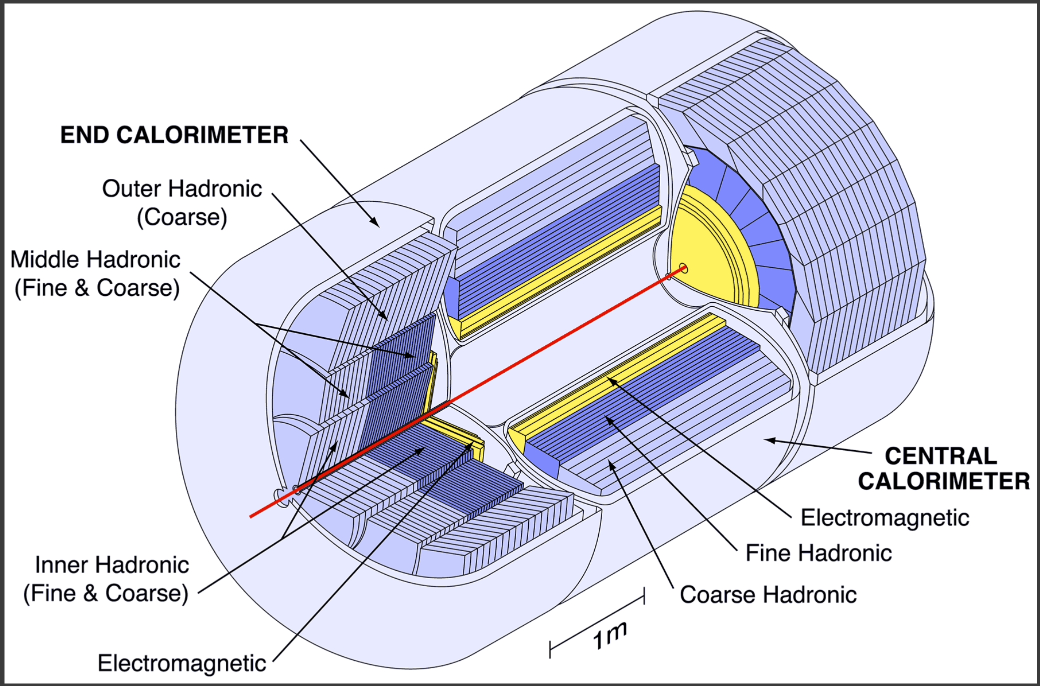
Norbert Wermes

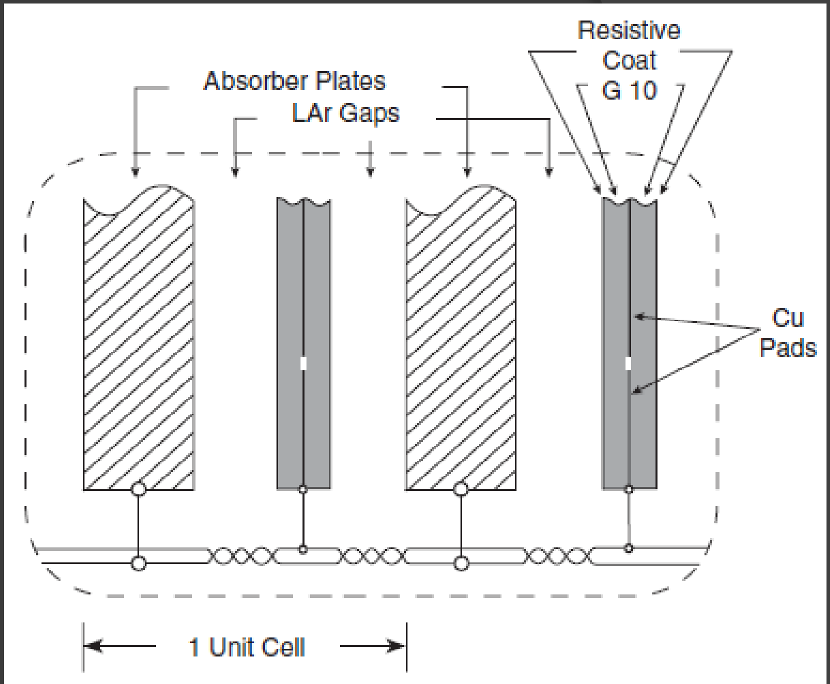
- DEPFET was developed for X-ray applications
  - Consists of high-resistivity silicon substrate fully depleted through an n^+ contact at the side of the sensor.
  - The first amplifying transistors are integrated directly into the substrate and form the pixel structure.
  - Electrons from ionizing particles are collected in this internal gate and modify the transistor current yielding a signal.
  - A matrix containing 64 × 64 square pixels of 50 µm size achieved a resolution of 9.5 µm and 40 e^- noise.
- MAPS integrate sensors and readout electronics on the same substrate using a technology similar to the one used in visible light CMOS cameras.

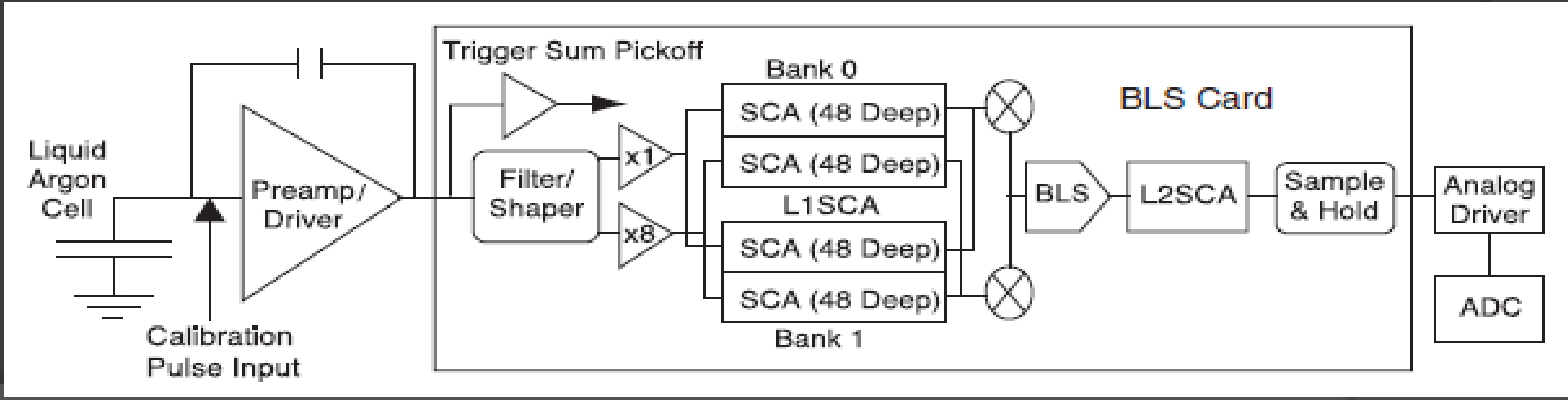
Challenges facing Si detectors

- Main issue is radiation damage.
- Silicon detectors are invariably located in the high dose region (mostly used in trackers).
- Surface damage: charge build-up, noise
- Bulk damage: displacements in crystal lattice
  - reduced charge collection efficiency (charge lost in traps).
  - changes dopant levels and distribution (affects bias voltage).
  - increased leakage current (noise).
  - increase in the voltage required for full depletion.
  - increase in capacitance between the detecting elements.

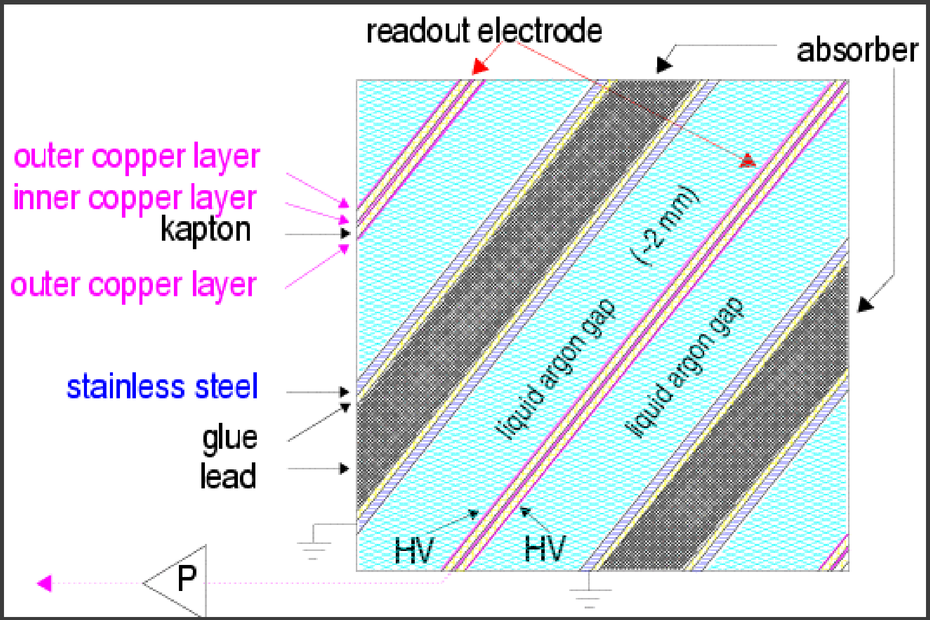
DZERO LAr calorimeter

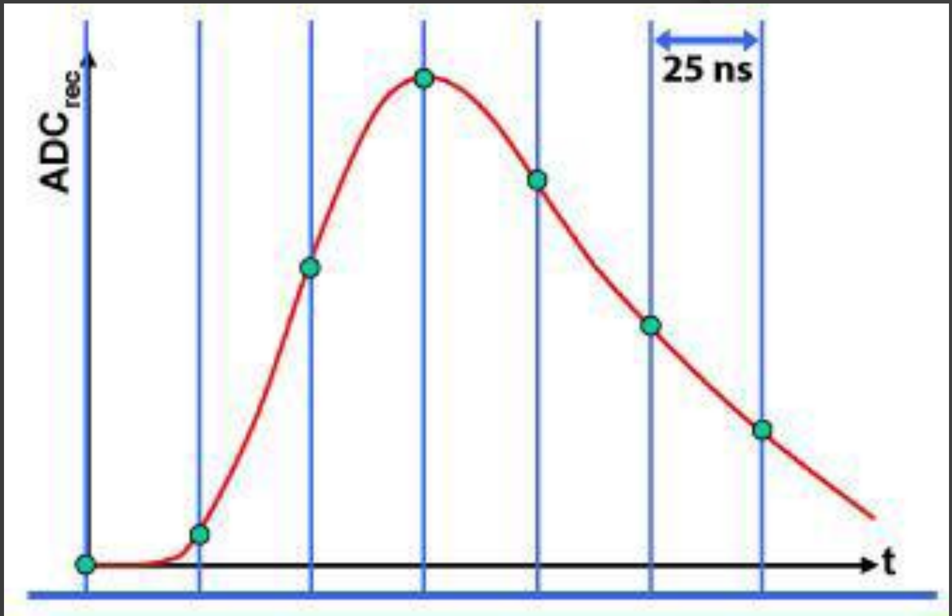


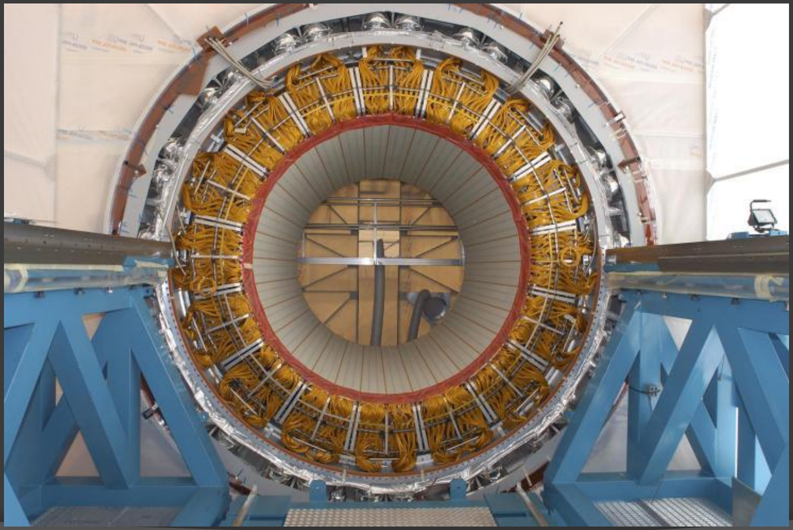


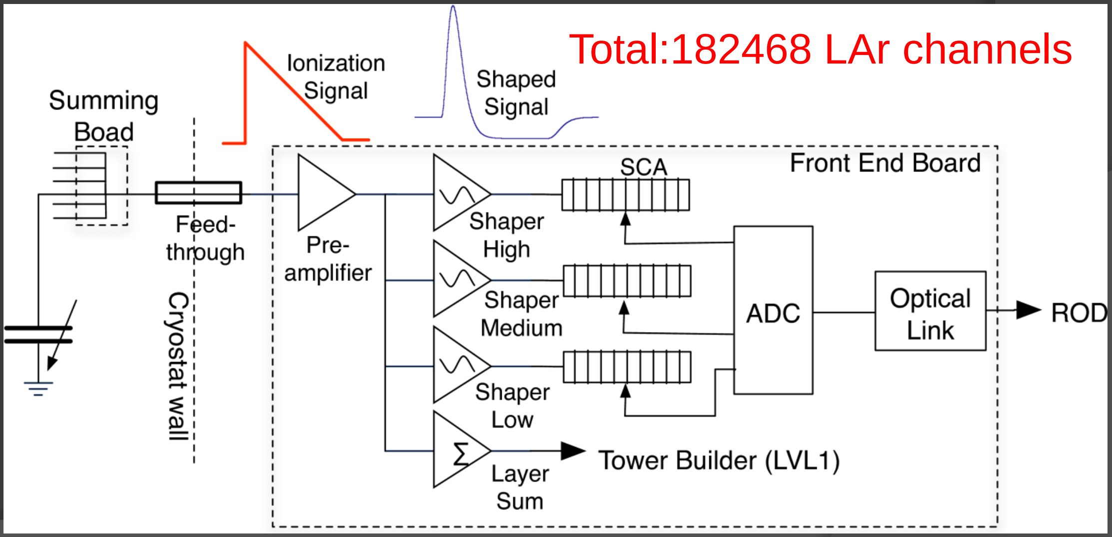


Readout of ATLAS LAr calorimeter

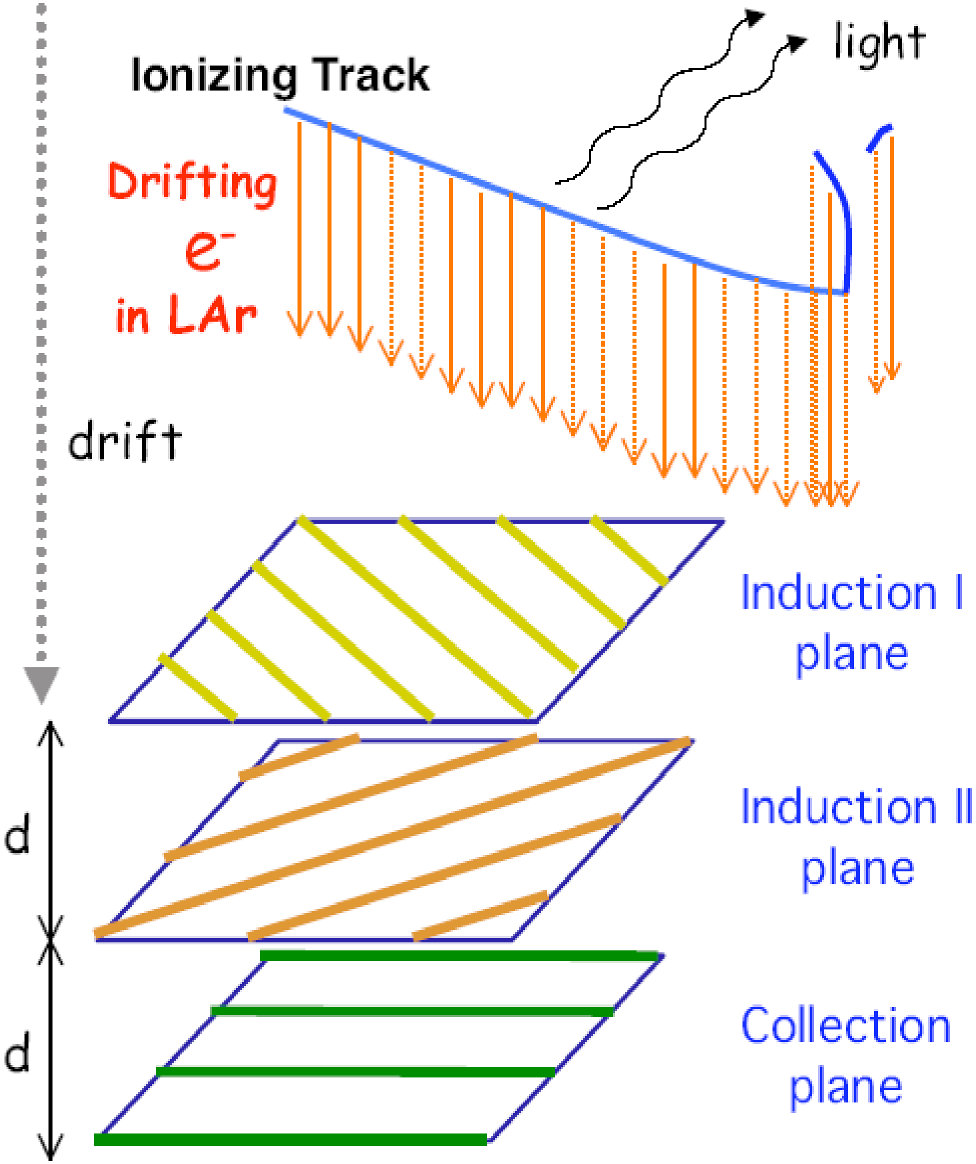








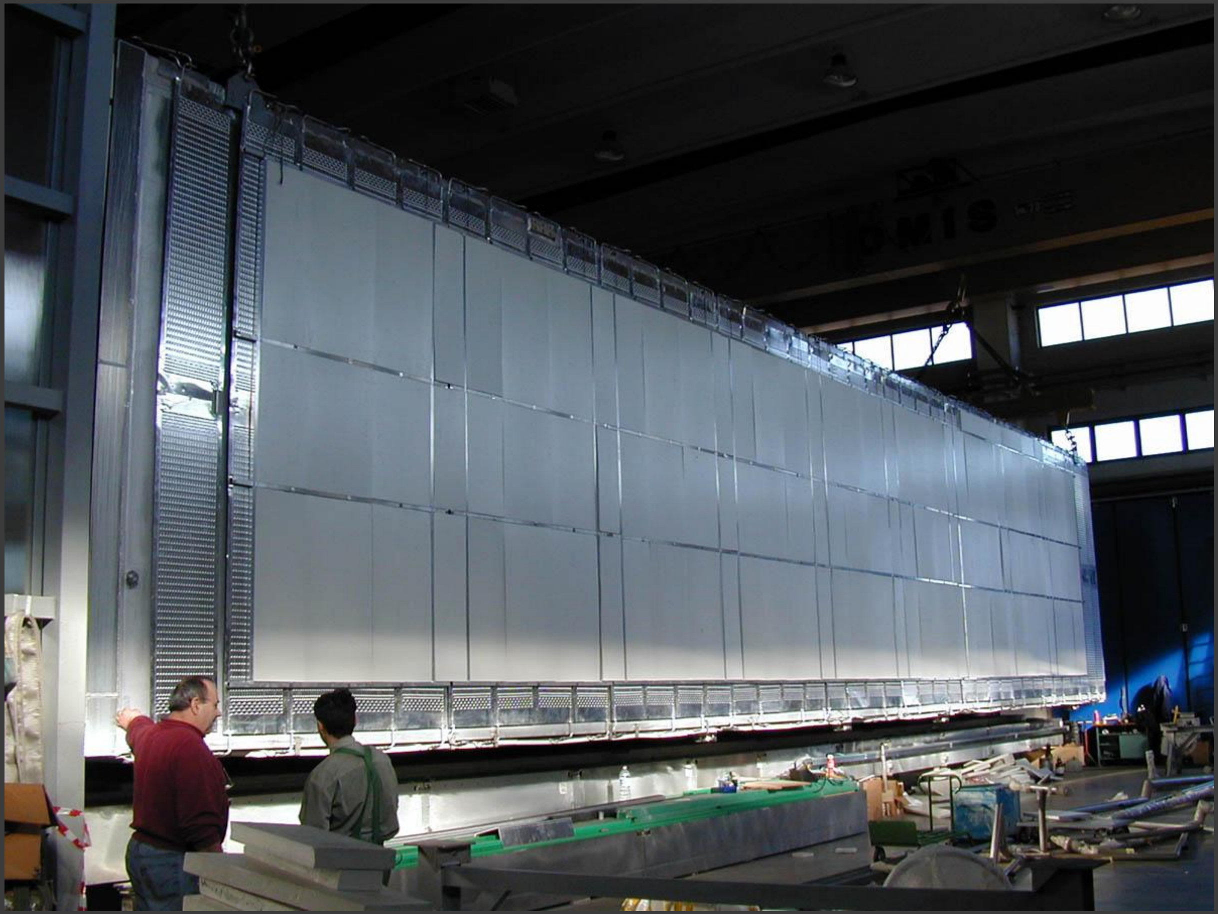
Principle of LArTPC

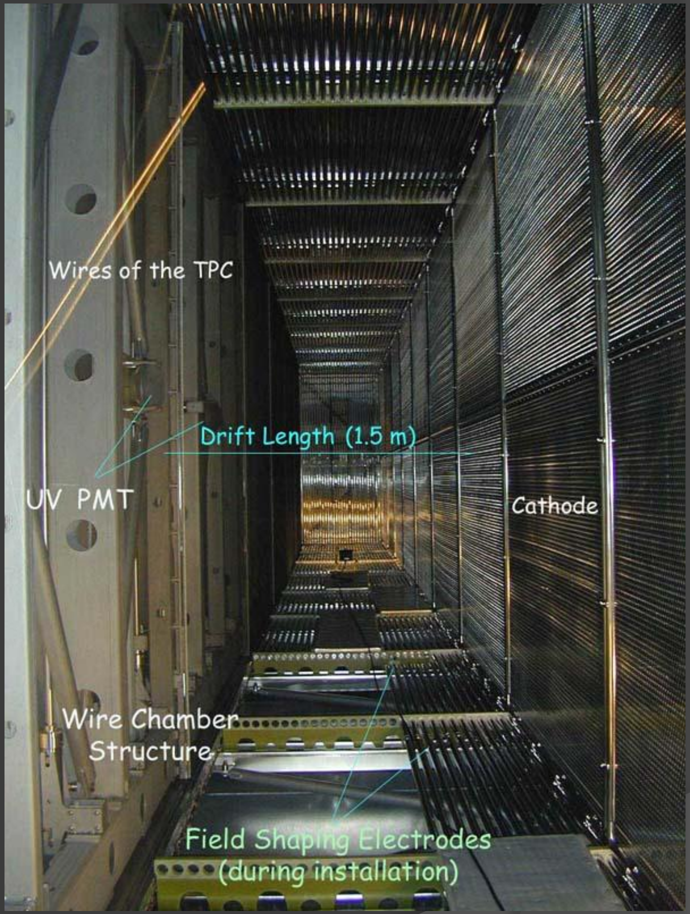


Density 1.4 g/cm^3
Radiation length 14 cm
Interaction length 80 cm
dE/dx(mip) = 2.1 MeV/cm
T=88K @ 1 bar

- ✓ About 12000 electron-ion pairs per mm of mip track are produced. About 40% recombine in our nominal drift field. When the left-over charges drift, they induce a signal on the wires.
- ✓ Since the mobility of electrons is much higher than that of ions, only electrons contribute to the observed signal.
- ✓ Electrons can drift over macroscopic distances if argon very pure (e.g. ≈ meter drift requires purity of <1 in 10^{10} atoms)
- ✓ Multiple non-destructing readout wire plans can be assembled for multi-views.

600t LAr TPC for ICARUS





- Number of independent containers = 2
- Single container internal dimensions: L = 19.6 m, W = 3.9 m, H = 4.2 m
- Total (cold) internal volume = 534 m^3
- Sensitive LAr mass = 600 ton

Methods of TPC readout

- Single-phase devices do not show any internal gain and therefore rely on small signal-to-noise ratios and extremely sensitive front-end electronics.
- Double-phase readout, benefits from internal gain due to readout in the gas-phase where avalanches in argon can increase the primary signal substantially. The price for this advantage is the restriction to one-sided, gas readout which enforces either unprecedented long drift lengths or very large surface area (shallow tank). In addition this technique battles with space-charge effects at the gas–liquid interface and necessary tight control of the liquid level, temperature, etc.
- Third alternative is liquid argon readout technology. It combines the separate advantages of both, single-phase operation for the wire readout and an amplified signal in a double-phase readout. The idea is to stick to the robust and mature single-phase TPC concept and implement an optical readout of light produced by electroluminescence in liquid argon.

Current work on LAr TPC detectors

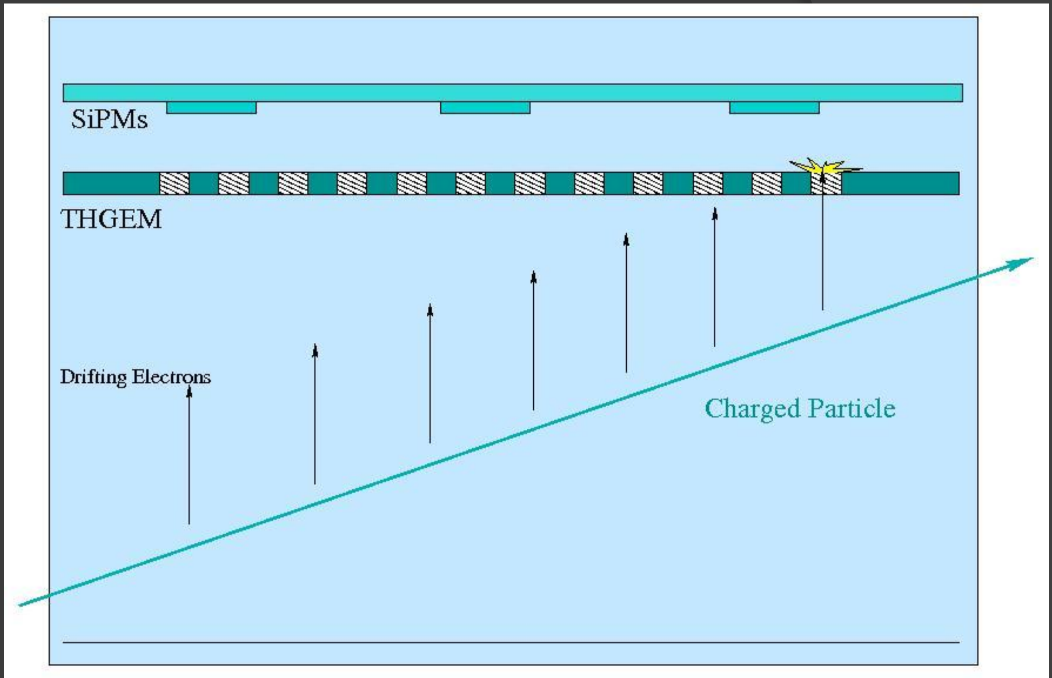
- Liquid Argon Time Projection Chambers (LArTPC) technology is now proven for up to 600t mass. A detector capable of delivering the neutrino physics program of the future will however need to be on a grander scale still with a fiducial volume of perhaps up to 100 kt.
- MODULAr essentially stacks together many ICARUS modules to achieve the final volume.
- GLACIER drifts charge up to 20m through a single huge liquid Argon volume to be amplified and readout in the gas directly above the liquid volume.
- FLARE and LANNDD are also based on a single volume of liquid Argon but which are internally segmented to limit the maximum charge drift distance and read signals using wire planes, similar to ICARUS.
- The latest project founded on the basis of a LArTPC detector using wire-plane readout is the ArgoNeuT project, currently taking data in the FNAL neutrino beam.
- Targeted experiments of this detector technology:
  - LAGUNA proton decay and neutrino physics project
  - RD51 initiative
  - Upgrades to the T2K experiment
  - Proposed neutrino factory project
  - ArDM dark matter experiment

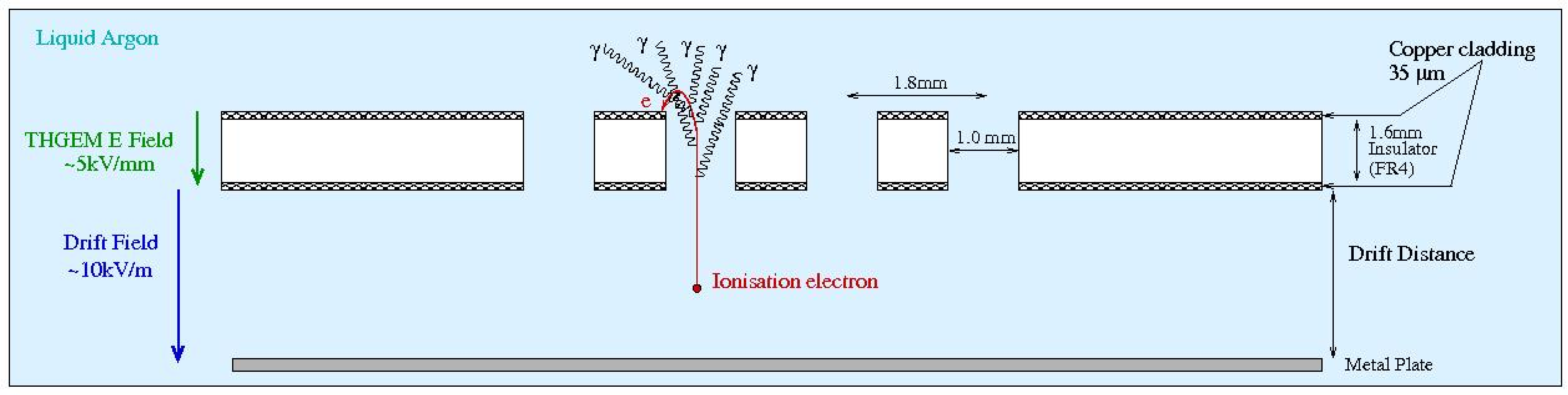
THGEM readout for TPC

- The new concept of operating a Thick Gas Electron Multiplier (THGEM) directly in the liquid opens the exciting possibility of fine grained tracking (spatial resolution of order mm) with high signal to noise ratio using only low-cost, robust components.
- Utilising electroluminescence, i.e. light emitted in the THGEM holes, for optical readout, for instance with silicon photomultipliers (SiPM), directly in the liquid volume would be the key new effect in this technology.
- The THGEM provides an excellent imaging plane for electroluminescence.
- Electrons initially released by ionisation drift towards the holes, mechanically drilled through the printed-circuit board, where the presence of strong electric fields inside the holes results in a grid of well-localised light sources.

Optical readout for LAr detectors

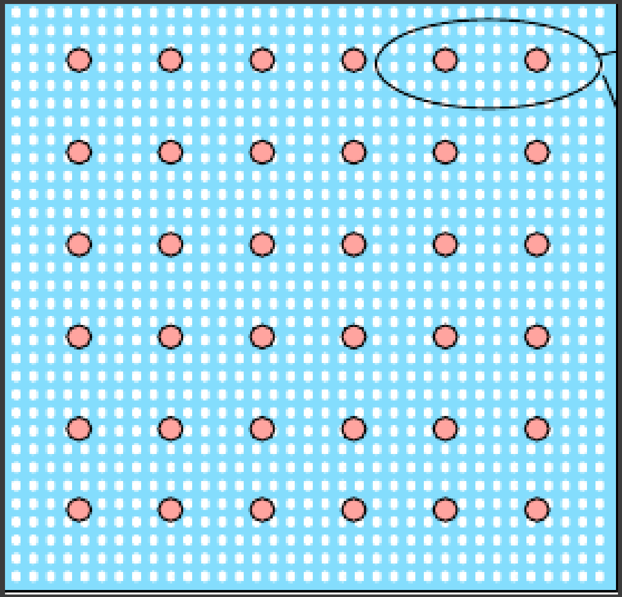
- ICARUS has shown that Liquid Argon is a suitable medium for TPCs for:
  - Calorimetry
  - Fine Grain tracking
- Design of readout planes must keep electronics cost reasonable.
- Optical readout is feasible alternative to the wire based readout for Liquid Argon TPC of the future.
- Liquid Argon TPC with Thick Gas Electron Multiplier (THGEM) and optical readout using Silicon Photomultipliers (SiPM).

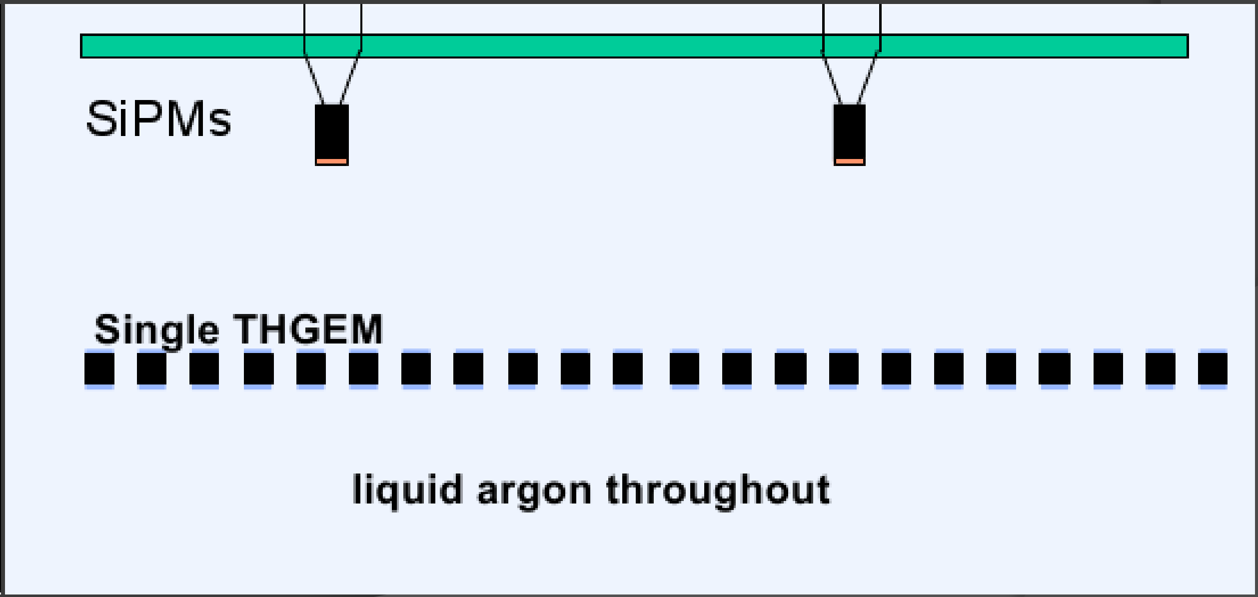




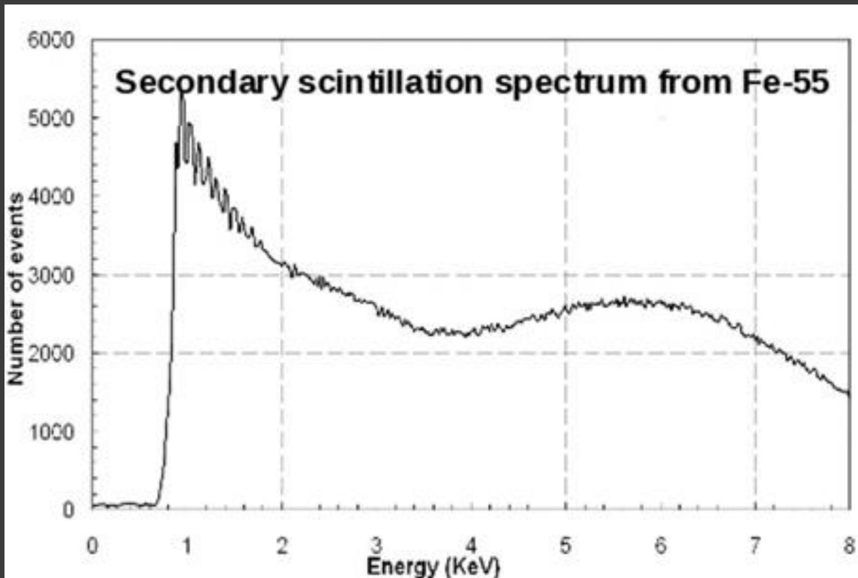
Light readout concept for tracking

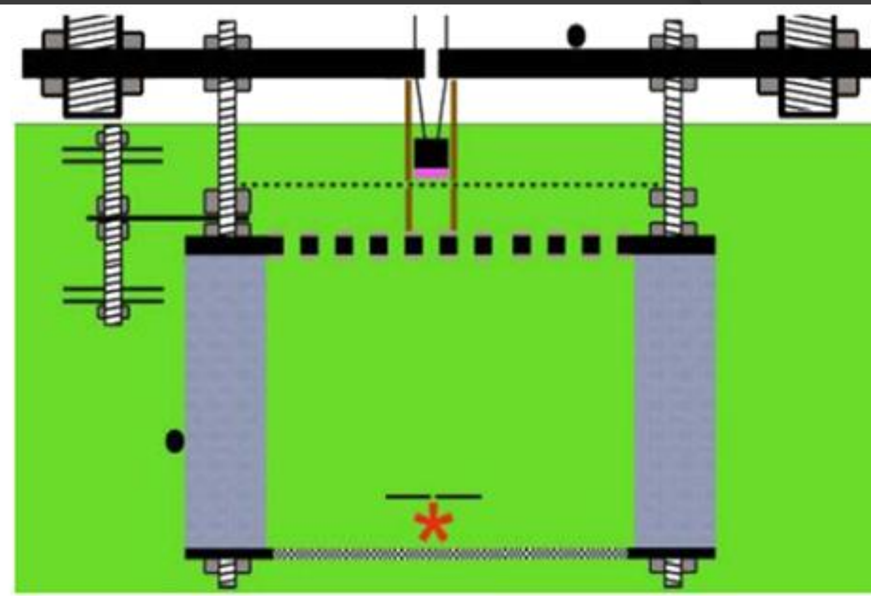
- The electroluminescence from the THGEM holes can be imaged by an optical readout device.
- Silicon Photomultipliers (SiPMs) from SENSL were used in this study.
- Strong signal output, gain 10^6.
- Arranging sensors in a sparse array above the THGEM allows fewer readout channels than holes, with no reduction in resolution.
- Row and column readout gives 2N readout channels rather than N^2.

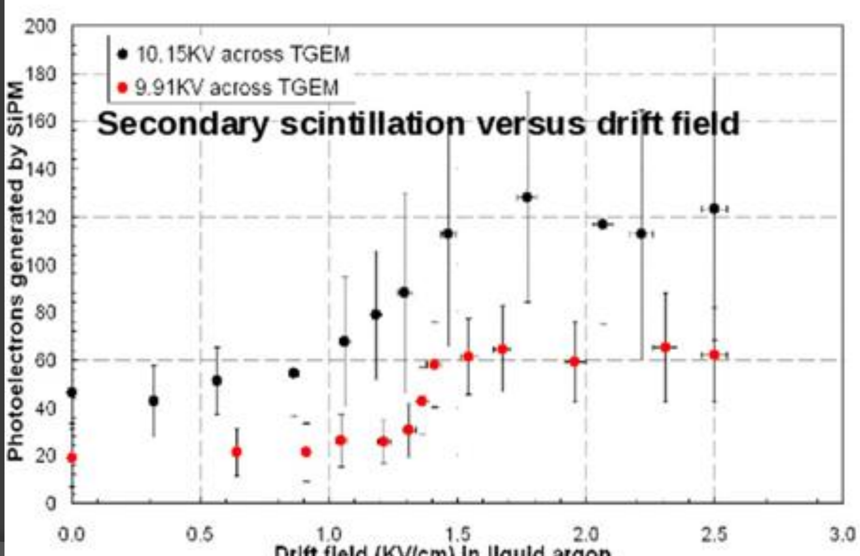


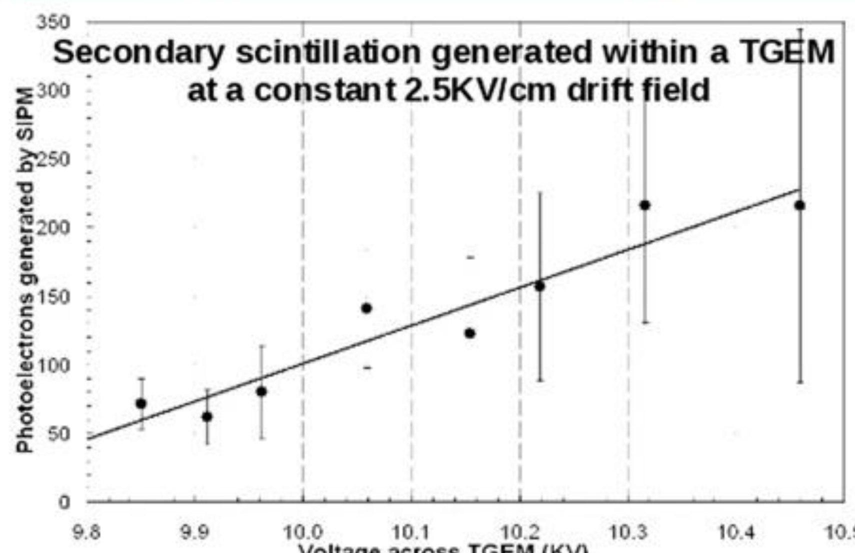


Proof of principle









Summary and outlook

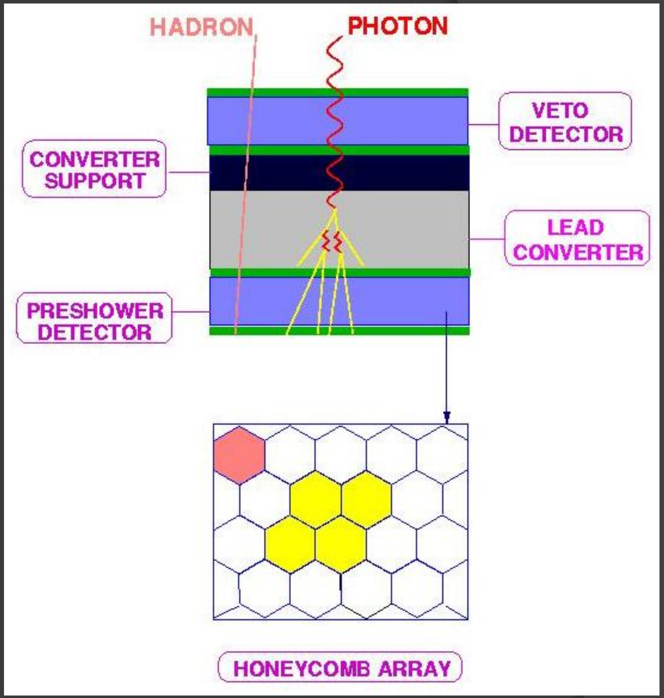
- No detector technology is ready to give up its share or future stack, even as new players are joining the ring; detectors and electronics dictating each other's agenda.
- Innovative designs of GEMs, massive research and industrial projects, hybrid designs with micro-pattern and liquid argon TPCs.
- Novel structures and new applications of MRPCs, work in progress in the areas signal readout and gas systems, 100,000 m^2 of single gap RPCs at INO's ICAL!
- Radiation hard silicon detectors, search for new materials, detectors with larger band gap, integrated devices.
- CVD diamond detectors showing a lot of promise, though not covered in this talk.
- Liquid reinventing itself as future detecting medium both at accelerator and non-accelerator physics experiments for a variety of detecting tasks.
- ASICs, FPGAs, high speed data links are no more buzz words, but are basic needs.
- Switchable power schemes to the front-end and signal processing electronics.
- Industries and applied research units are increasingly being added to the scientific collaborations' list!
- **And finally, high energy physics experiments are increasingly inheriting modus operandi of huge international level infrastructure projects – funding, planning, management, inventions, technology development, costing , manufacturing, QA/QC, heterogeneous skills, personnel and even more …**

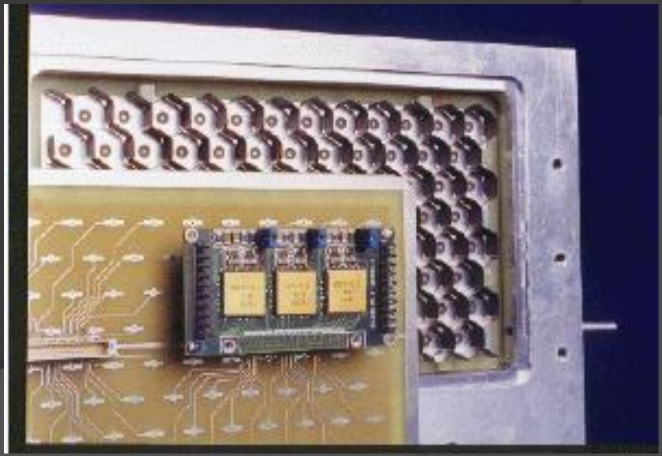
Thanks

- To the organisers for giving me this wonderful opportunity. I feel honoured.
- To all the researchers whose work I have used freely in this talk.
- To you for your attention.

Photon Multiplicity Detector (PMD)

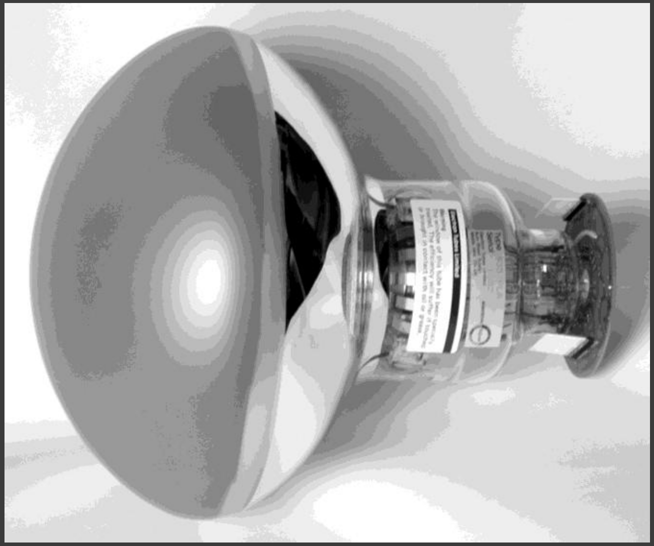
- PMD a pre-shower detector measuring spatial distribution of photons in the forward rapidity region.
- Complements the study of photons in the forward region where calorimeter cannot be used due to high particle density.
- Honeycomb (rectangular) proportional counter, the cells of which are 5 mm deep with a surface of about $1cm^2$ ($0.22cm^2$) in START(ALICE) design.
- Confines charged particle hits to single cell.
- Copper walls separate the cells in order to prevent signals from blowing up by confining low-energy electrons to a single cell.
- In the assembled version, the PCBs form part of a gas-tight chamber having a high voltage connection and inlet/outlet for the gas.
- Readout by GASSIPLEX (Manas) chips in STAR (ALICE) design.





LAr TPC readout by large area PMT

- Commercial PMT with large area
- ⇙Glass-window
- Scintillation VUV λ = 128 nm
- ⇙Wavelength-shifter (TPB)
- Immersed T(LAr) = 87 K



Electron Tubes 9357FLA

8" PMT (bialkali with Pt deposit)

G = 1 x 10^7 @ ~1400 V

peak Q.E. (400-420 nm) ~ 18 % (≈10% cold)

T_{rise} ~ 5 ns, FWHM ~ 8 ns