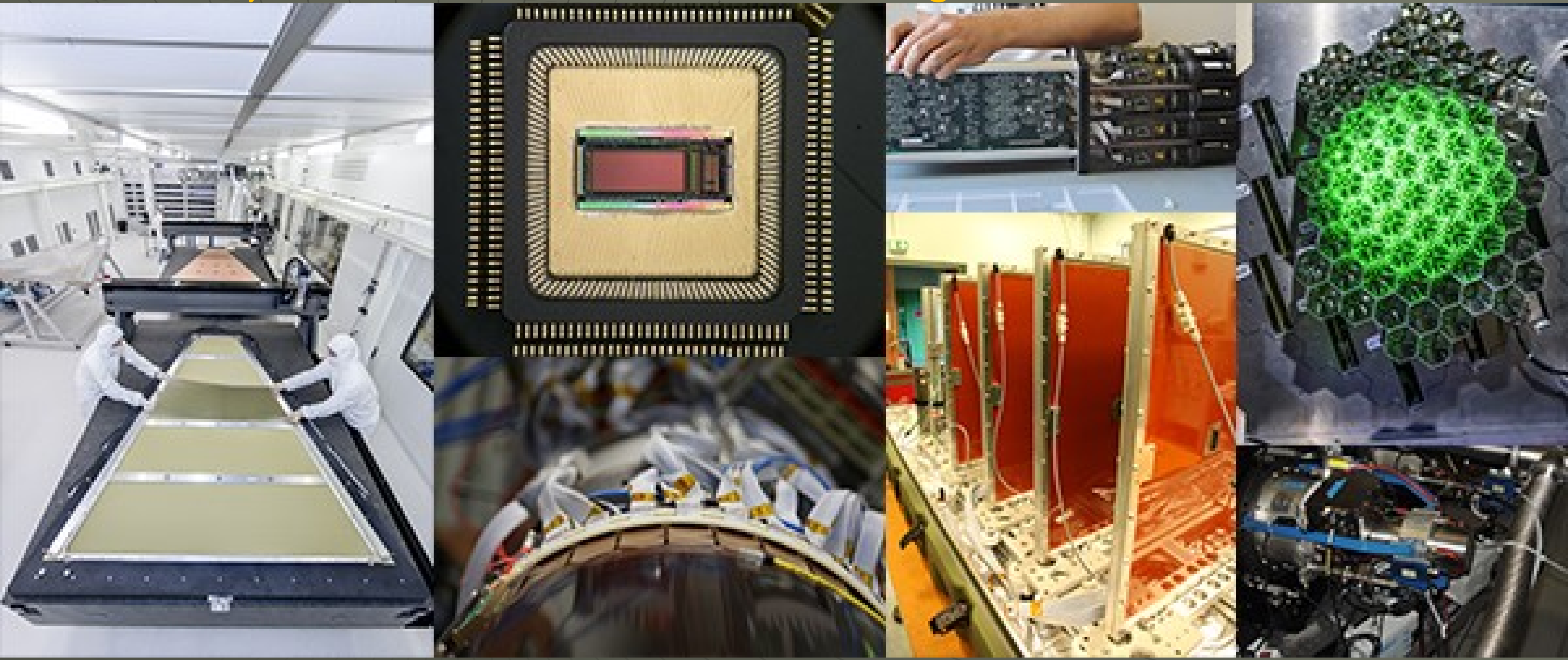
Introduction to Detectors and Electronics Experiments

Science is *spoken* in Mathematics but *done* using detectors and instrumentation.



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List of hardware experiments

1. Basic Electronics (BE)
2. Field Programmable Logic Array (FPGA)
3. A smart sensor and a Microcontroller (µC)
4. Resistive Plate Chamber (RPC)
5. Plastic scintillation detector (Scint)
6. Silicon Strip Detector (SSD)
7. Silicon Photomultiplier (SiPM)
8. Measurement of Muon life time (Muon)
9. High Purity Germanium Detector (HPGe)

Experiments (I Group)

Date	Expt	BE	FPGA	µC	RPC	Scint	SSD	SiPM	Muon	HPGe
&	Slot	C130	CG17	NewLab	C217	NewLab	D204	CG17	C135	LINAC
time	Id	(6hrs)	(4hrs)	(2hrs)	(6hrs)	(6hrs)	(2hrs)	(2hrs)	(2hrs)	(6hrs)
07 5:00	I-1	a	c	d	b	h	e			g
08 2:00	I-2	a	c		b	h		f	d	g
08 4:30	I-3	a	d	e	b	h	c			g
09 2:00	I-4	b	d		c	g		a	e	f
09 4:30	I-5	b	e	h	c	g	d		a	f
10 2:00	I-6	b	e		c	g	a	d	h	f
11 2:00	I-7	c	g	a	d	f	b	e		h
11 4:30	I-8	c	g		d	f			b	h
12 2:00	I-9	c	a	b	d	f	g			h
12 4:30	I-A	d	f	c	e	a				b
14 2:00	I-B	d	f		e	a		h	c	b
14 4:30	I-C	d	h	g	e	a	f	c		b
15 2:00	I-D	e	h		a	c		b	g	d
16 2:00	I-E	e	b	f	a	c	h	g		d
16 4:30	I-F	e	b		a	c			f	d

Experiments (II Group)

Date	Expt	BE	FPGA	µC	RPC	Scint	SSD	SiPM	Muon	HPGe
&	Slot	C130	CG17	NewLab	C217	NewLab	D204	CG17	C135	LINAC
time	Id	(6hrs)	(4hrs)	(2hrs)	(6hrs)	(6hrs)	(2hrs)	(2hrs)	(2hrs)	(6hrs)
17 2:00	II-1	a	c	d	b	h	e			g
18 2:00	II-2	a	c		b	h		f	d	g
18 4:30	II-3	a	d	e	b	h	c			g
19 2:00	II-4	b	d		c	g		a	e	f
19 4:30	II-5	b	e	h	c	g	d			f
21 2:00	II-6	b	e		c	g	a	d	h	f
21 4:30	II-7	c	g	a	d	f		b		h
22 2:00	II-8	c	g	b	d	f		e	a	h
22 4:30	II-9	c	a		d	f			b	h
23 2:00	II-A	d	f	c	e	a	g	h		b
23 4:30	II-B	d	f		e	a			c	b
24 2:00	II-C	d	h	g	e	a	f	c		b
25 2:00	II-D	e	h		a	c	b		g	d
25 4:30	II-E	e	b	f	a	c		g		d
26 2:00	II-F	e	b		a	c	h		f	d

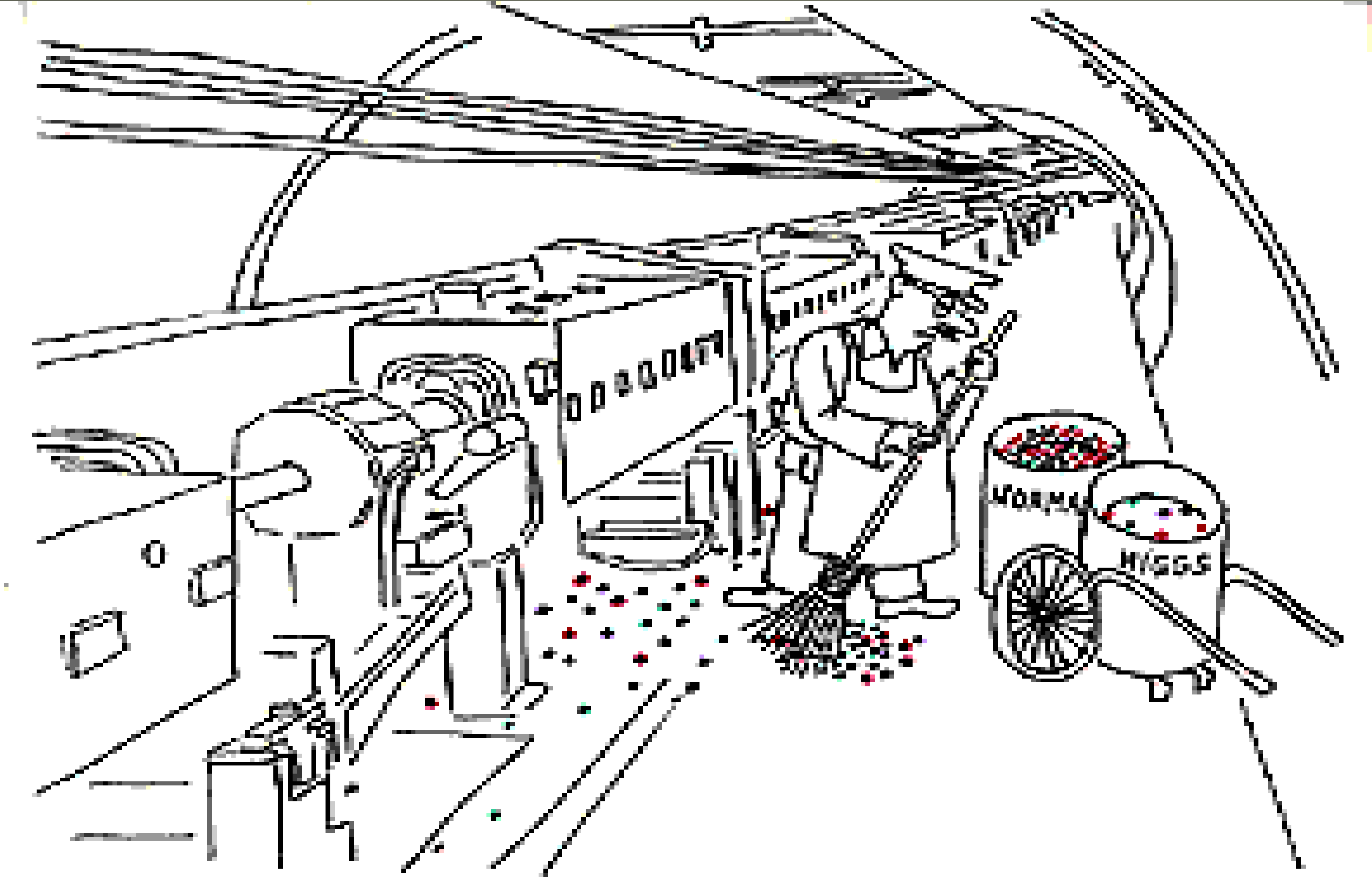
A few general comments

- Most of the experiments are designed using the actual research work which is going on in the hosting groups. Most are also setup in their actual laboratories.
- So make the best use of your time in these laboratories. You could also look at what's main research happening in the laboratories, if time permits.
- Systematically performing the designed experiments – including data analysis and results, and actively interacting with the instructors and your co-students are earnestly expected. At the end, you are supposed to answer some questions by your instructors, related to that experiment. This will help organisers gauge how much you understood and learnt from that experiment.
- Best nine batches will be invited to give seminars on the concluding day of the School ☺

Some dos and don’ts

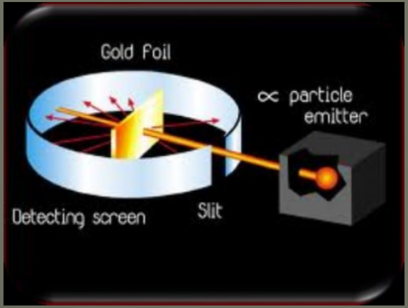
- Some experiments use high voltages, gases and radioactive sources, etc. But all the necessary precautions are already taken by the experiment designers for your safety. But it is advised that you strictly follow their instructions.
- Please also handle/operate the equipment gently/carefully while performing your experiments so that there is no damage caused to the apparatus.
- It will be great if you could switch your cell phone to off/silent mode while you are in lab.
- Most of your experiments are housed with in regular research labs/facilities. Please don’t stray away into other areas or interact with other equipment without guidance of your instructors.

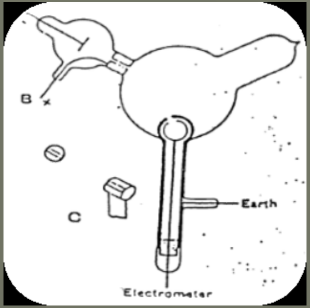
Wish it is that simple!

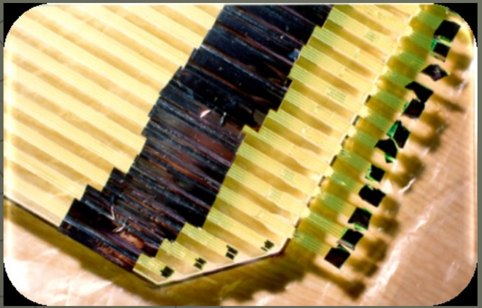


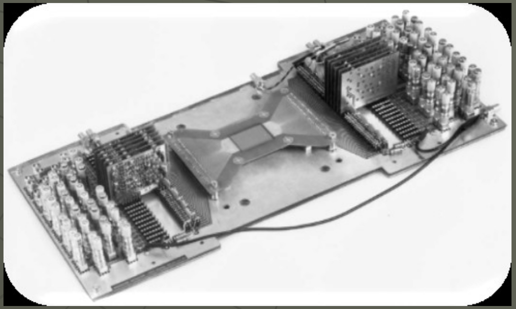
Detectors and major discoveries

- Crookes Tubes: Sir William Crookes (1869-75)
- Cloud chamber: Charles Thomas Rees Wilson (1894), Nobel Prize (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) CC and GM
- Charged Pion: C.Powell (1947) photographic emulsions flown by balloons
- Lambda: (1947)
- Neutral Pion: R.Bjorkland (1949)
- Bubble chamber : D.Glaser (1952), Nobel Prize (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 (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 (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)

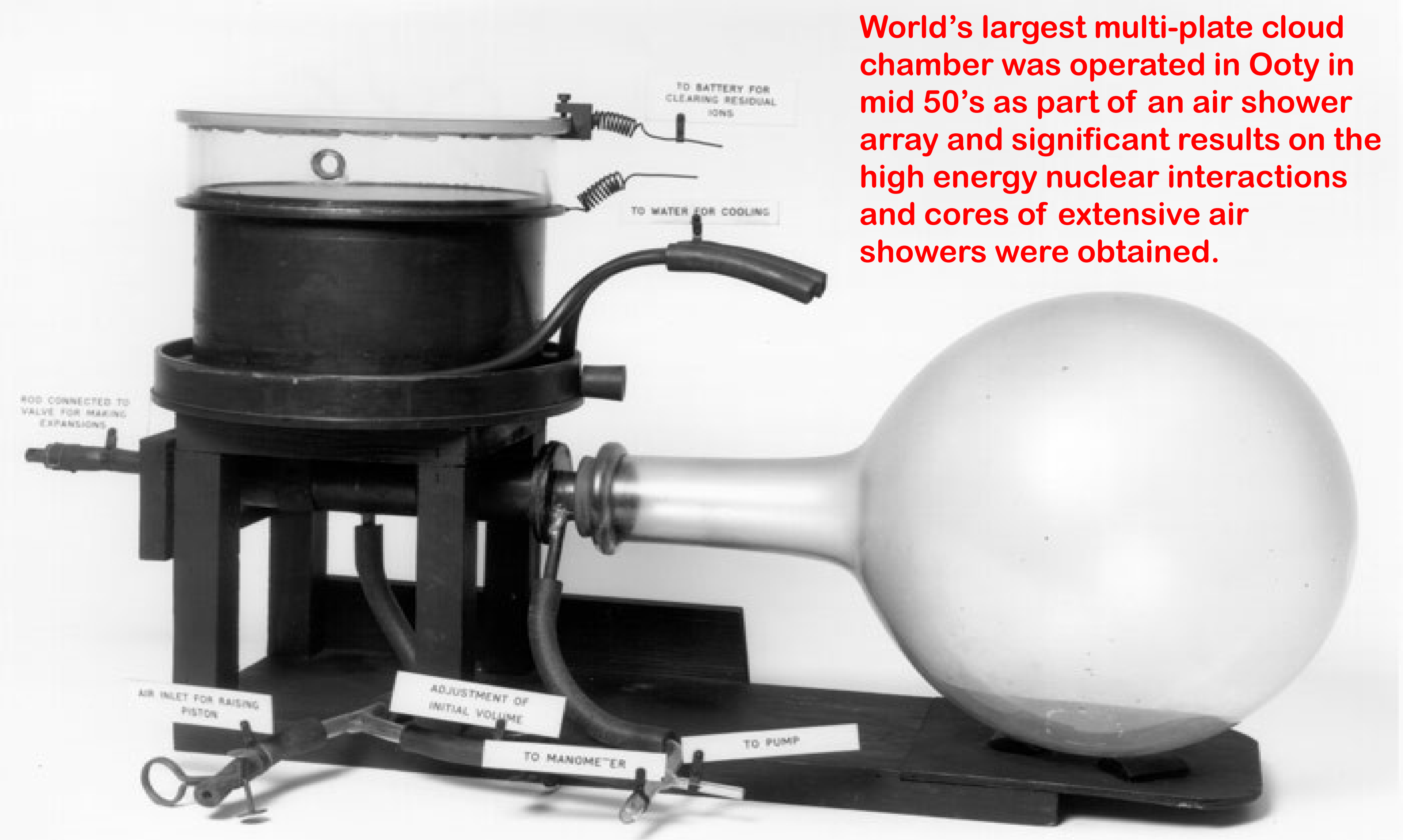








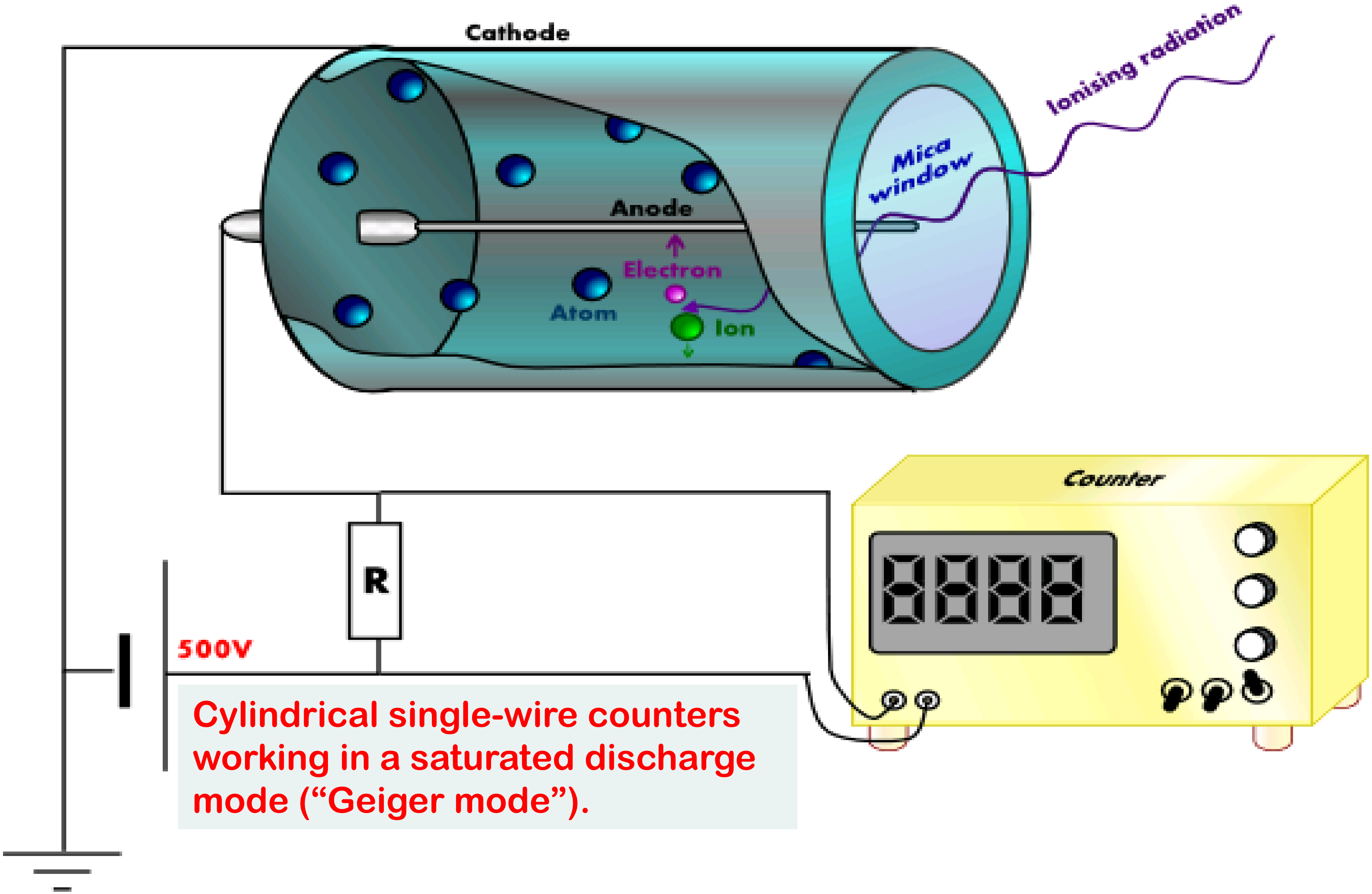
Wilson’s Cloud Chamber (1894)



World’s largest multi-plate cloud chamber was operated in Ooty in mid 50’s as part of an air shower array and significant results on the high energy nuclear interactions and cores of extensive air showers were obtained.

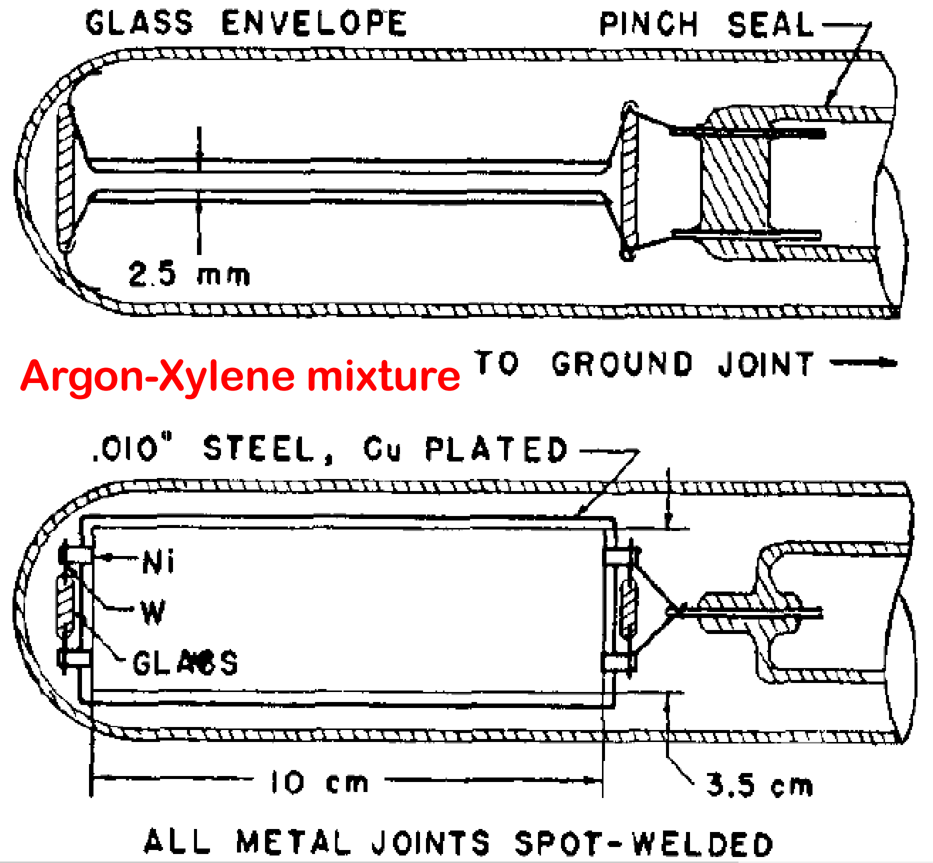
Contributed to the discoveries of e+, μ and K.

Geiger–Müller tube (1928)

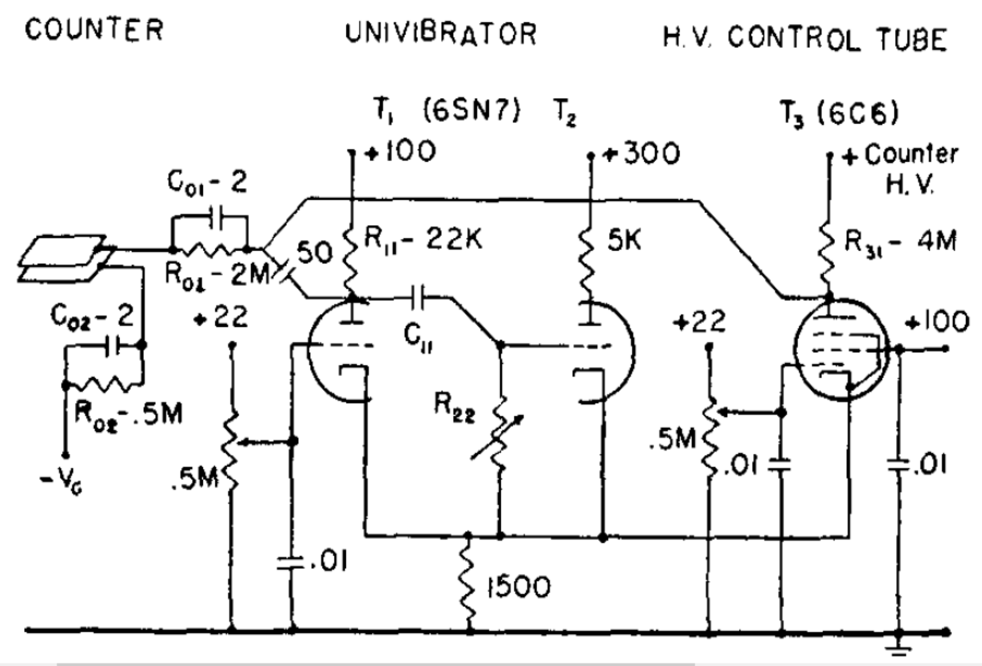


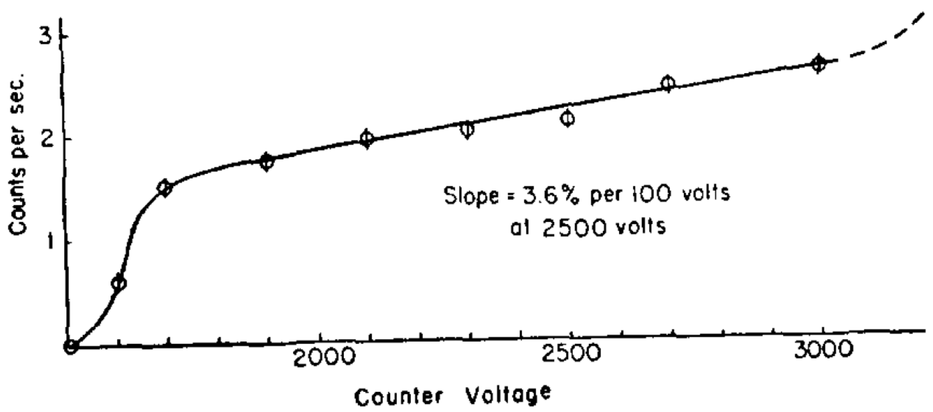
Cylindrical single-wire counters working in a saturated discharge mode (“Geiger mode”).

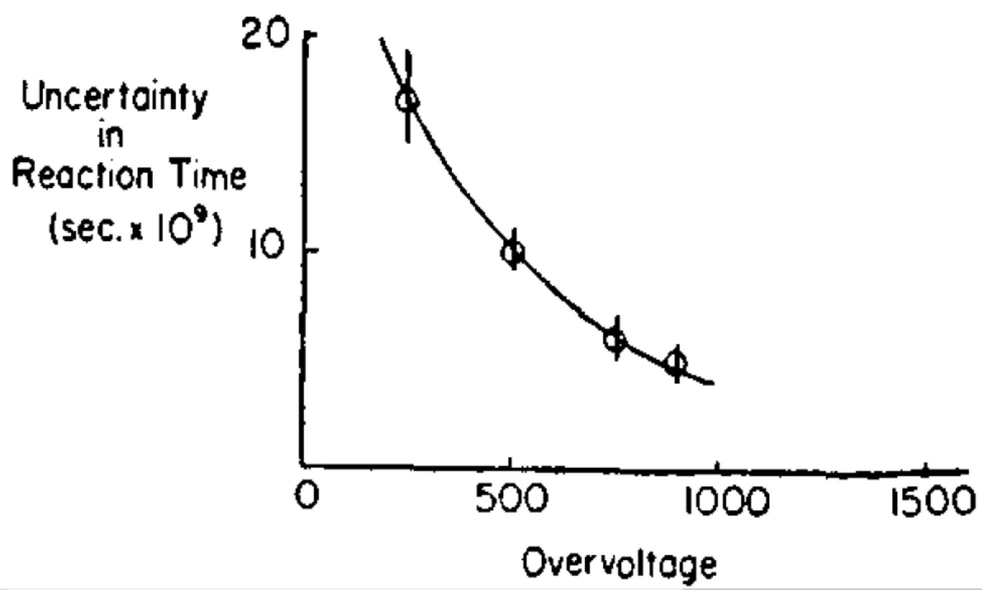
Keuffel's Parallel Plate Counters (1949)



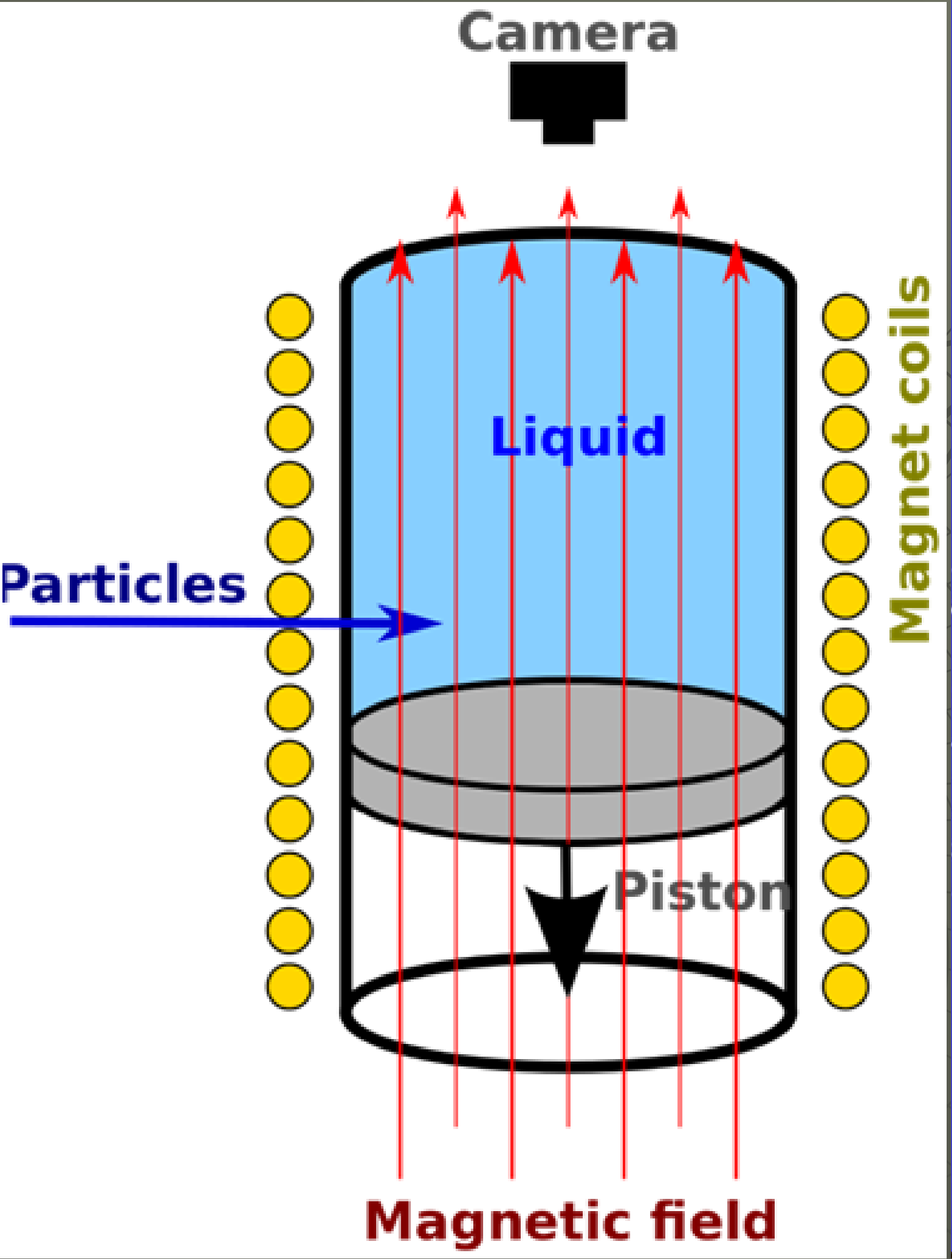
Argon-Xylene mixture

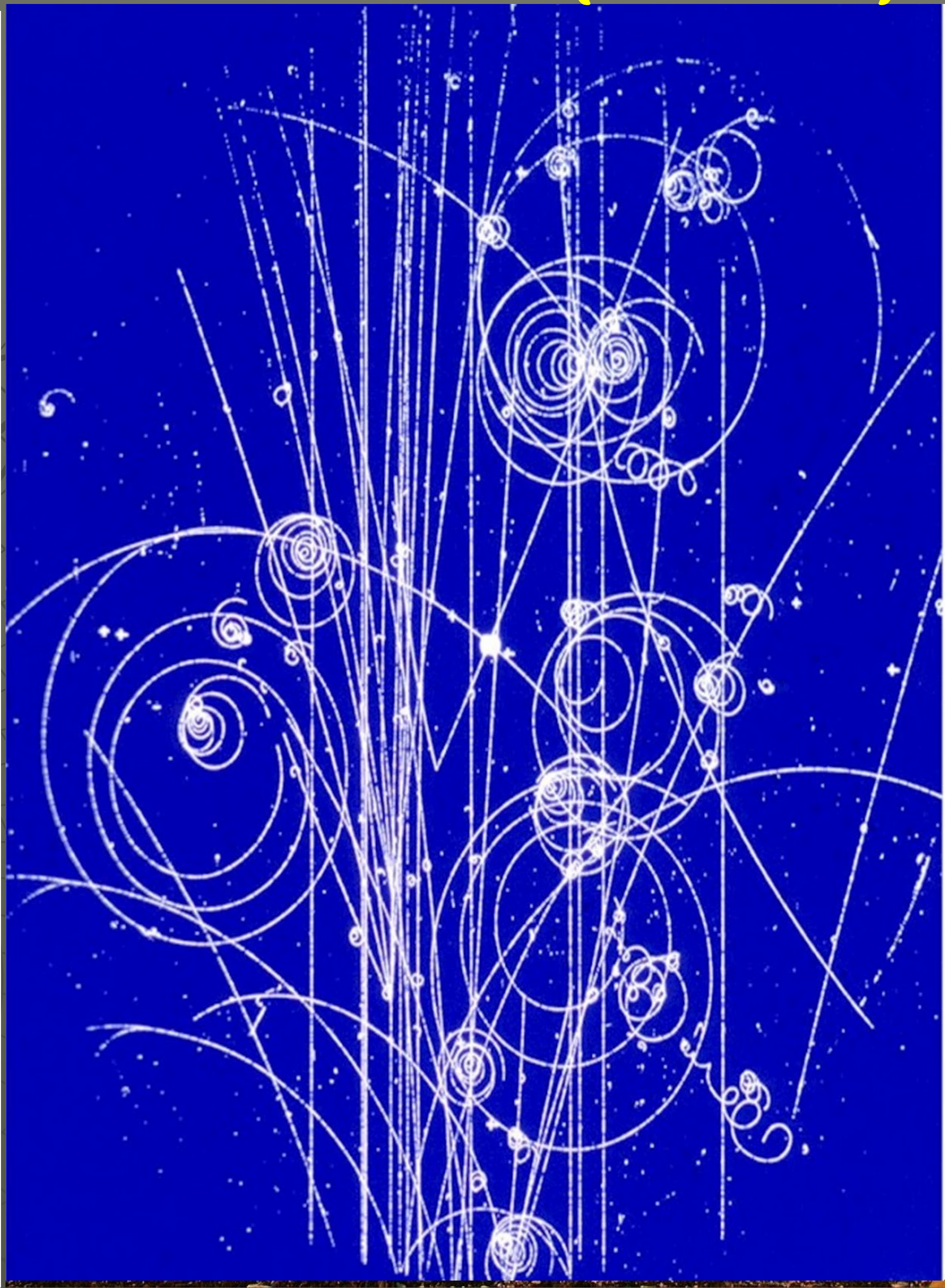






Glaser’s Bubble Chamber (1952)

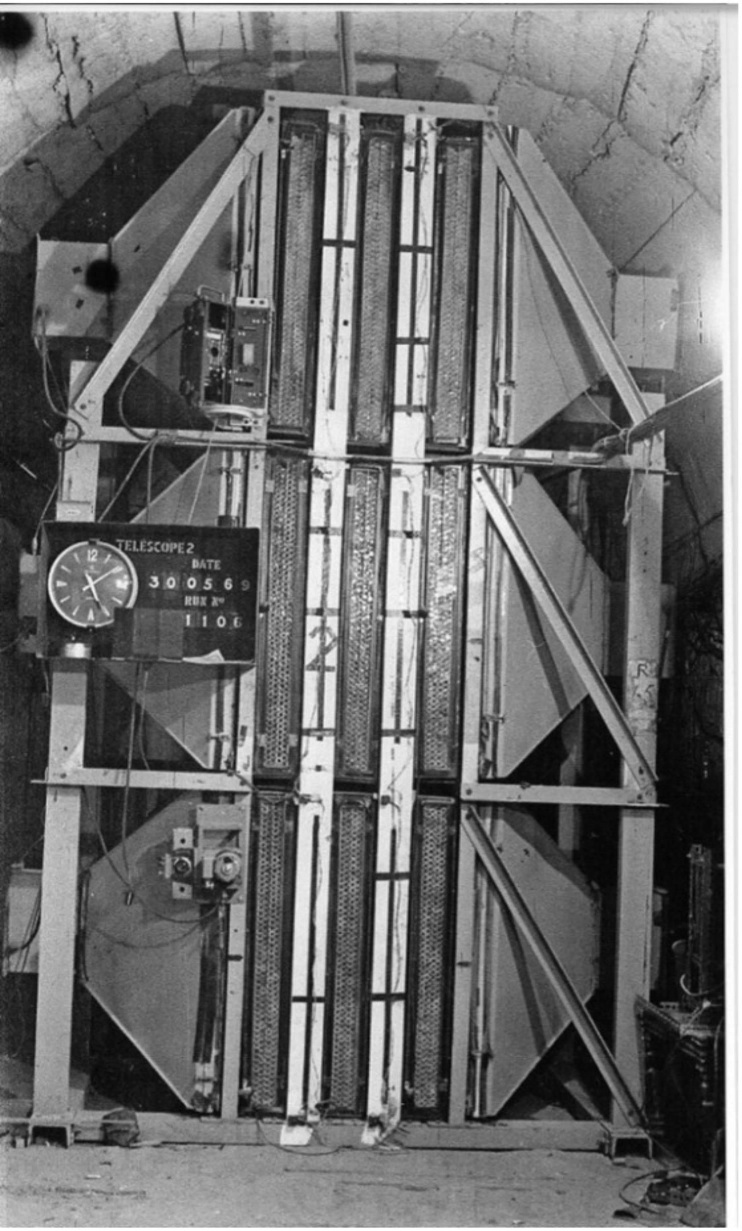


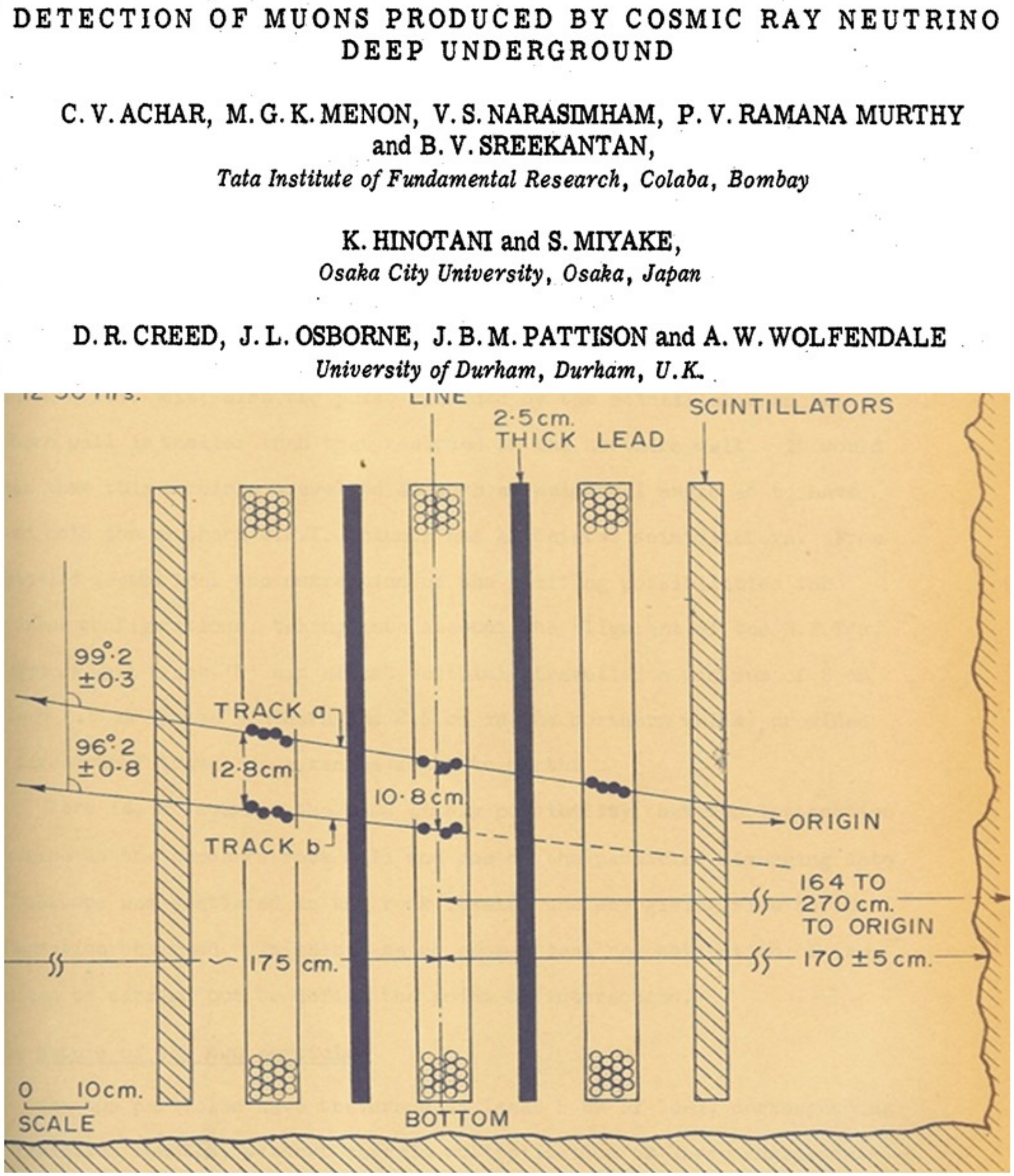


Georges Charpak's MWPC (1968)

The first modern electronically-readout gaseous detector.
Contributed to the discoveries of W, Z, c and t.

Simple detector, but a major discovery





DETECTION OF MUONS PRODUCED BY COSMIC RAY NEUTRINO DEEP UNDERGROUND

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University of Durham, Durham, U.K.

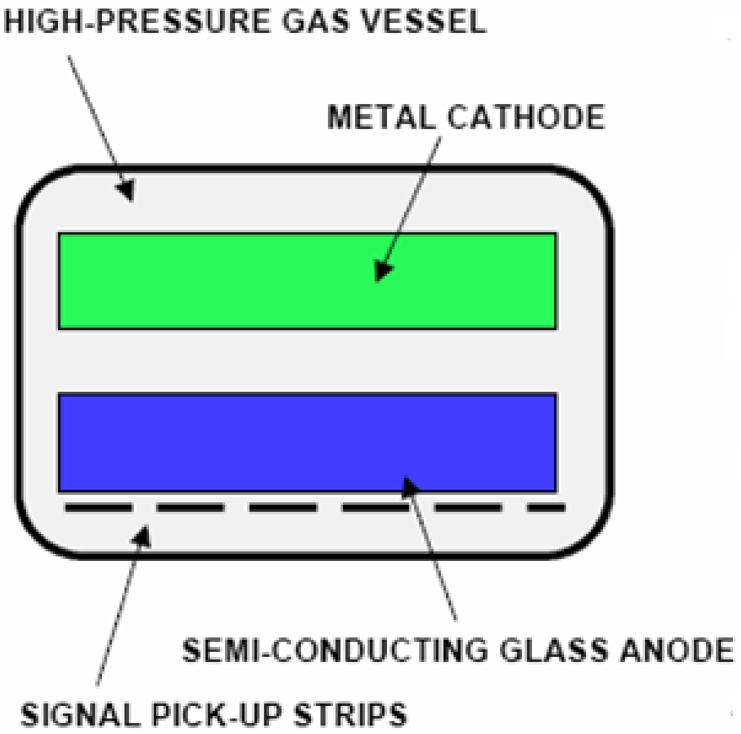
Physics Letters 18 (1965) 196, 15 Aug 1965

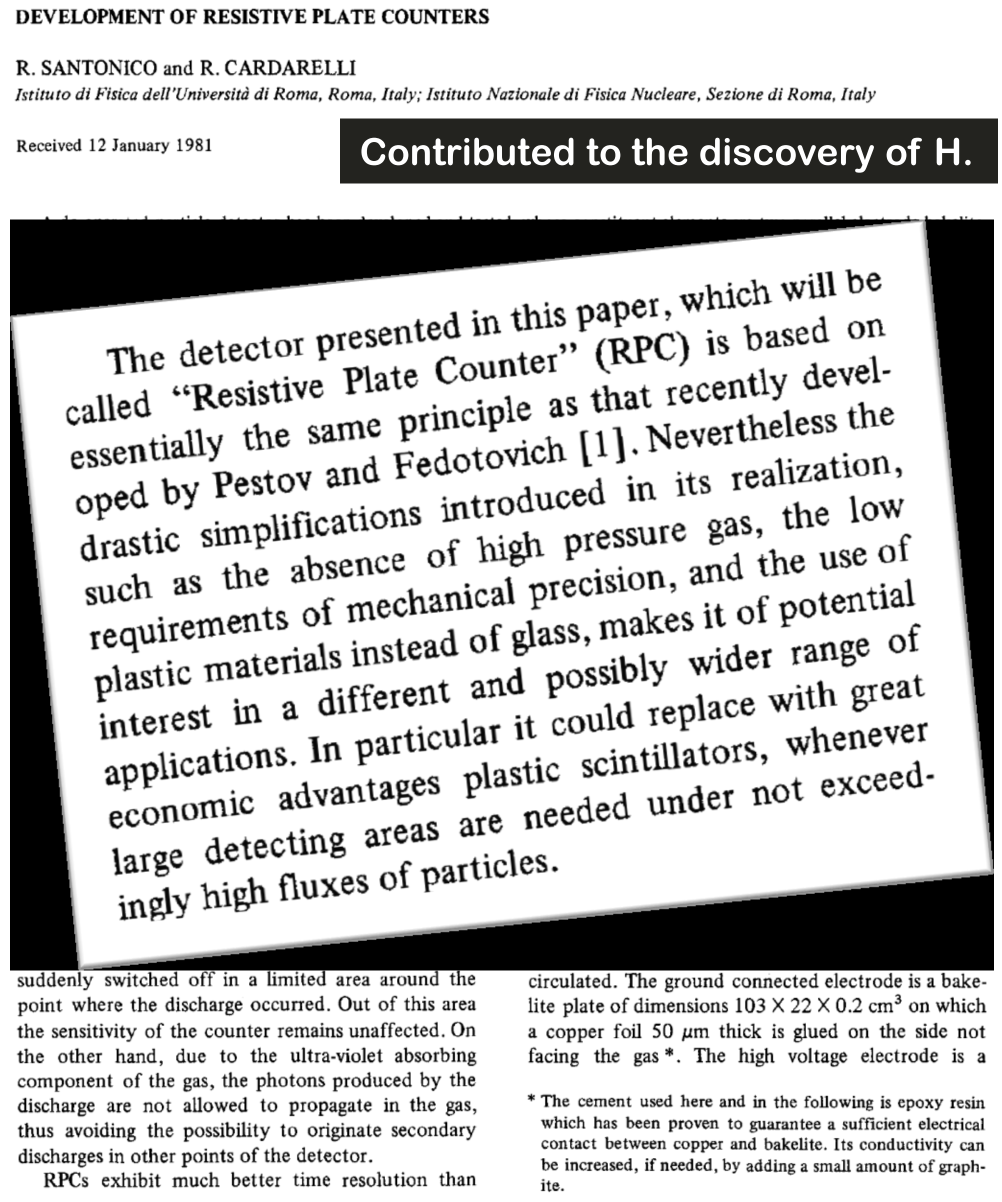
Resistive Plate Chamber (1981)

Keuffel, J.W.;
Parallel-Plate Counters
Rev. Sci. Inst. **20** (1949) 202

THIN GAP (100 μm) AND HIGH PRESSURES (~10 bar)
HIGH RESISTIVITY ELECTRODE
(PESTOV GLASS, $10^9\ \Omega$ cm

Yu.N. Pestov & G.V. Fedotovich (1978)





Contributed to the discovery of H.

DEVELOPMENT OF RESISTIVE PLATE COUNTERS

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Received 12 January 1981

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.

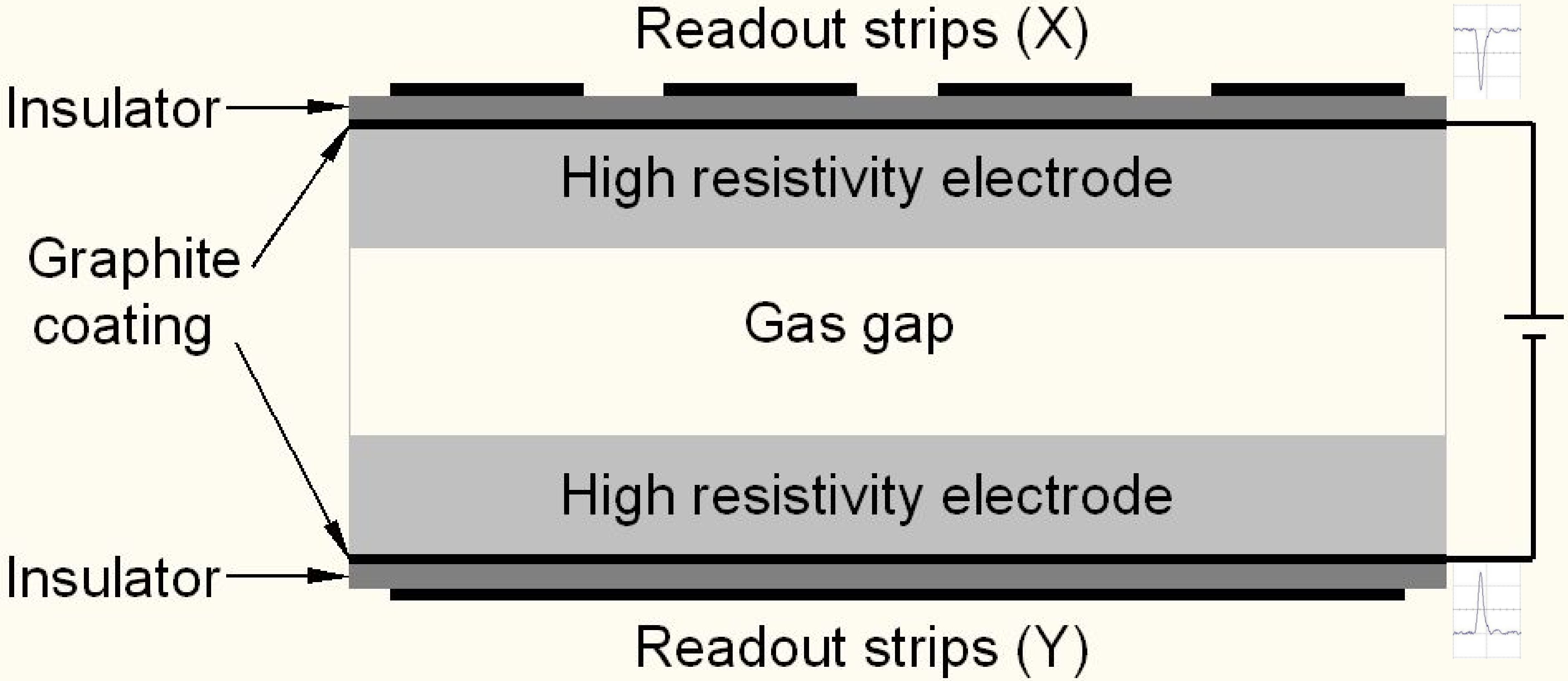
suddenly switched off in a limited area around the point where the discharge occurred. Out of this area the sensitivity of the counter remains unaffected. On the other hand, due to the ultra-violet absorbing component of the gas, the photons produced by the discharge are not allowed to propagate in the gas, thus avoiding the possibility to originate secondary discharges in other points of the detector.

RPCs exhibit much better time resolution than

circulated. The ground connected electrode is a bakelite plate of dimensions 103 × 22 × 0.2 cm^3 on which a copper foil 50 μm thick is glued on the side not facing the gas *. The high voltage electrode is a

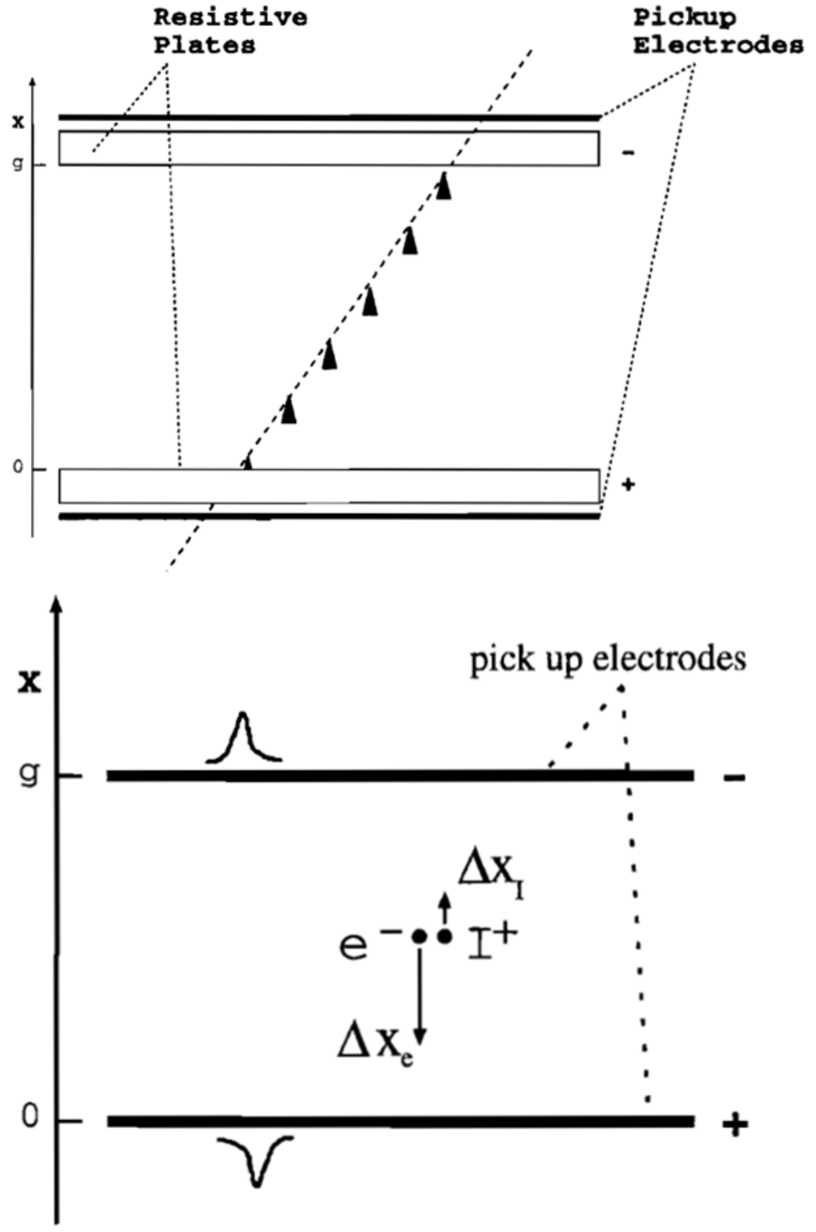
* The cement used here and in the following is epoxy resin which has been proven to guarantee a sufficient electrical contact between copper and bakelite. Its conductivity can be increased, if needed, by adding a small amount of graphite.

Schematic of a basic RPC



- Resistive materials like glass or bakelite for electrodes
- Special paint mixture (developed locally) for semi-resistive coating
- Plastic honey-comb laminations used as readout panel
- Special plastic films for insulating the readout panels from high voltages
- Two modes of operation: Avalanche (R134a:Isobutane:SF_6 ::95.5:4.2:0.3) and Streamer (R134a:Isobutane:Ar::56:7:37)

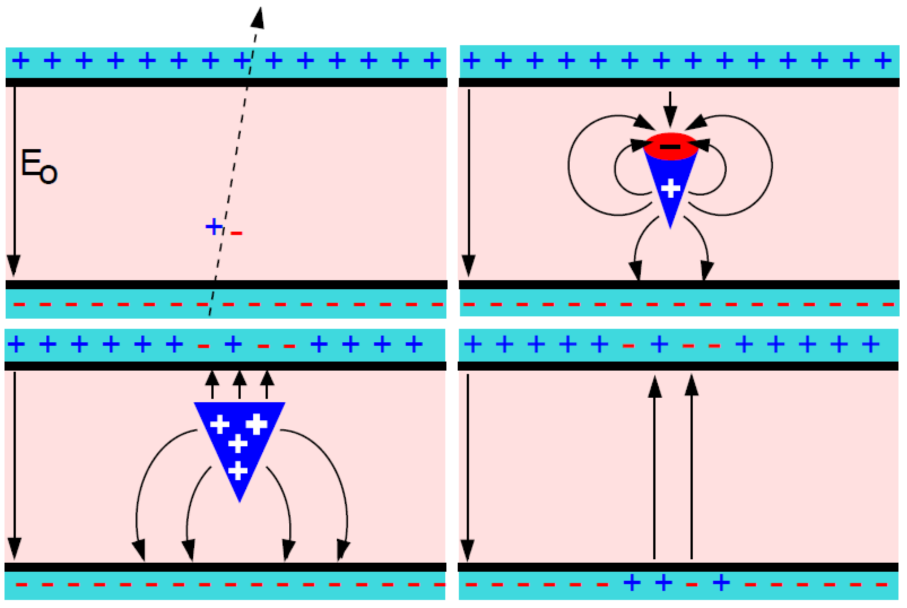
Principle of RPC operation



- Electron-ion pairs produced in the ionisation process drift in the opposite directions.
- All primary electron clusters drift towards the anode plate with velocity v and simultaneously originate avalanches.
- A cluster is eliminated as soon as it reaches the anode plate.
- The charge induced on the pickup strips is $q = (-e\Delta x_e + e\Delta x_I)/g$.
- The induced current due to a single pair is $i = dq/dt = e(v + V)/g \approx ev/g$, $V \ll v$.
- Prompt charge in RPC is dominated by the electron drift.

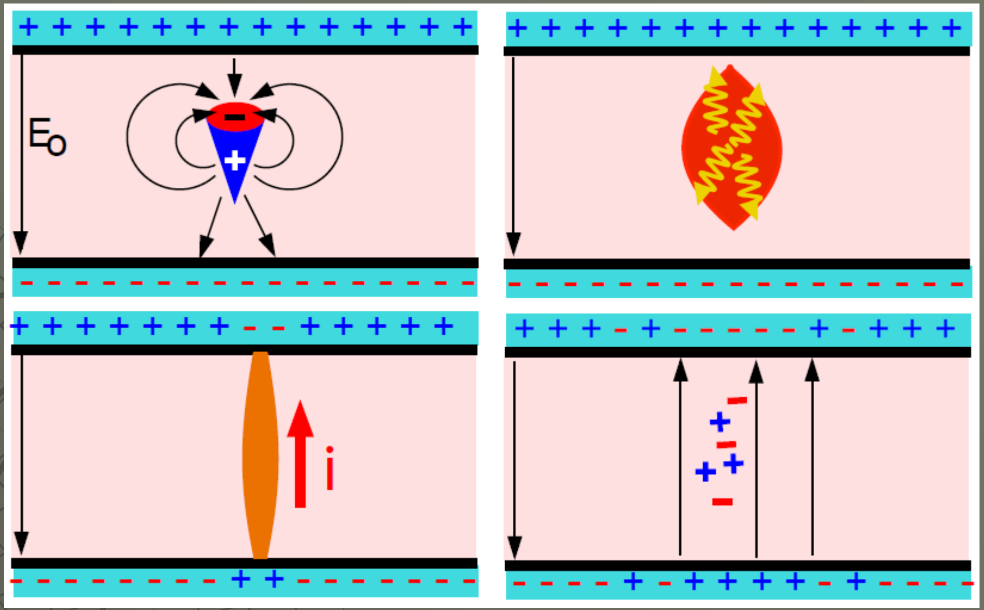
Two modes of RPC operation

Avalanche mode



- Gain of the detector $\ll 10^8$
- Charge developed ~1pC
- Needs a preamplifier
- Longer detector life
- Typical gas mixture
  R134a:iB:SF_6::94.5:4:0.5
- Moderate purity of gases is fine!
- Higher counting rate capability

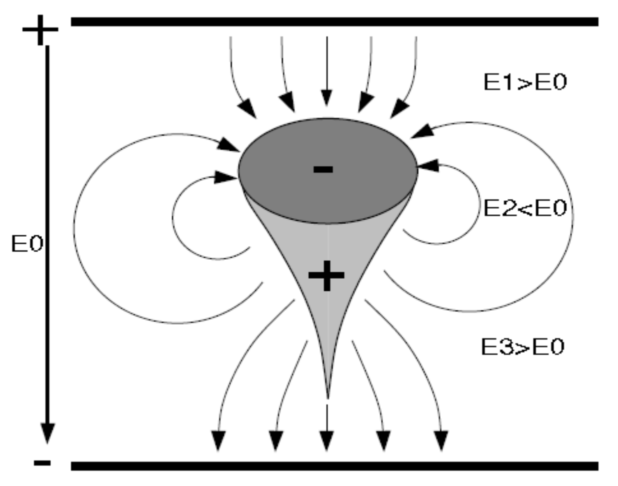
Streamer mode



- Gain of the detector $> 10^8$
- Charge developed ~100pC
- No need for a preamplier
- Relatively shorter detector life
- Typical gas mixture
  R134a:iB:Ar::62.8:30
- High purity of gases expected
- Low counting rate capability

Control of avalanche process

- Role of RPC gases in avalanche control
  - R134a is the ionising gas (83 clusters/cm, compare with Argon's 30 clusters/cm used in the streamer mode).
  - R134a also captures free electrons and localise avalanches.
    - $e^- + X \rightarrow X^- + h\nu$ (Electron attachment)
    - $X^+ + e^- \rightarrow X + h\nu$ (Recombination)
  - Isobutane to stop photon induced streamers.
  - SF_6 for preventing streamer transitions.
- Growth of the avalanche is governed by $dN/dx = \alpha N$.
- The space charge produced by the avalanche, shields (at about $\alpha x = 20$) the applied field and avoids exponential divergence.



- Townsend equation should be $dN/dx = \alpha(E)N$.

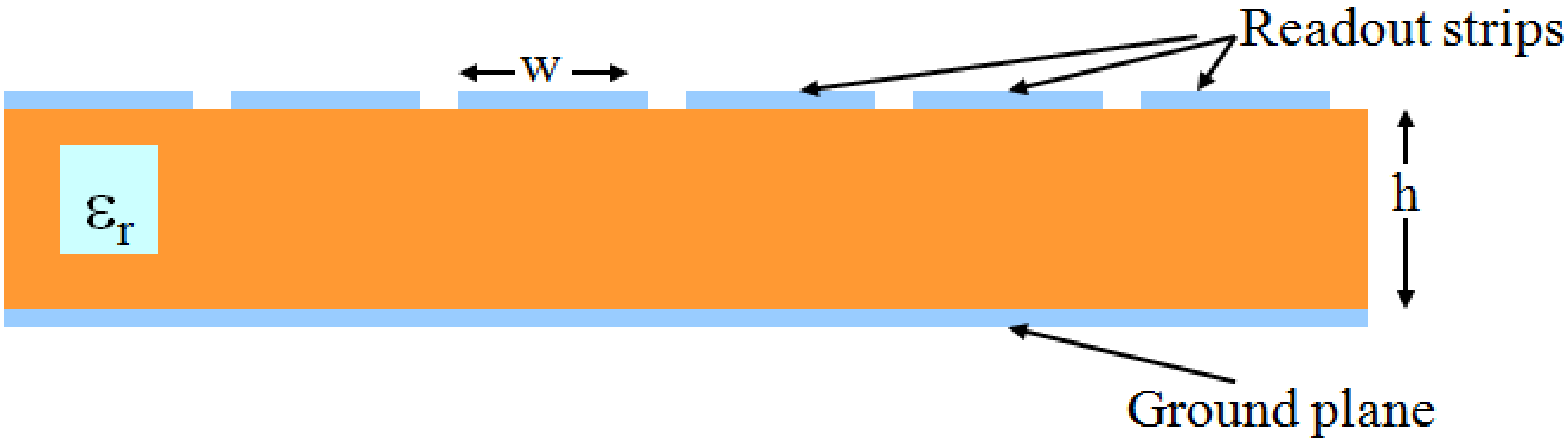
Typical expected parameters

- No. of clusters in a distance *g* follows Poisson distribution with an average of $\bar{n} = g/\lambda$
- Probability to have *n* clusters $p(n) = \frac{1}{n!}\left(\frac{g}{\lambda}\right)^{n} e^{-\frac{g}{\lambda}}$
- Number of electrons reaching the anode $n = n_0 e^{(\alpha-\beta)x}$
- Intrinsic efficiency $\in_{\max} = 1 - e^{-\bar{n}}$
- So ε_{max} depends only on gas and gap
- Intrinsic time resolution $\sigma_t = 1.28/(\alpha-\beta)v_D$
- So σ_t doesn't depend on the threshold
- Area of signal pickup spot $S = Qd \div \varepsilon V$ (→ counting rate capability)

- Gas: 96.7/3/0.3 (R134a/iB/SF_6)
- Electrode thickness: 2mm
- Gas gap: 2mm
- HV: 10.0KV (E = 50KV/cm)
- Relative permittivity (ε): 10
- Mean free path (λ): 0.104mm
- Avg. no. of electrons/cluster: 2.8
- Drift velocity (V_D) = 130mm/ns

- Townsend coefficient (α): 13.3/mm
- Attachment coefficient (β): 3.5/mm
- Total charge (q_{tot}): 200pC
- Induced charge (q_{ind}): 6pC
- Charge threshold: 0.1pC
- Efficiency (ε_{max}): 90%
- Time resolution(σ_t): 950pS
- Signal pickup spot (S) = $0.1mm^2$

Characteristic impedance of strips



$$x \equiv w/h$$

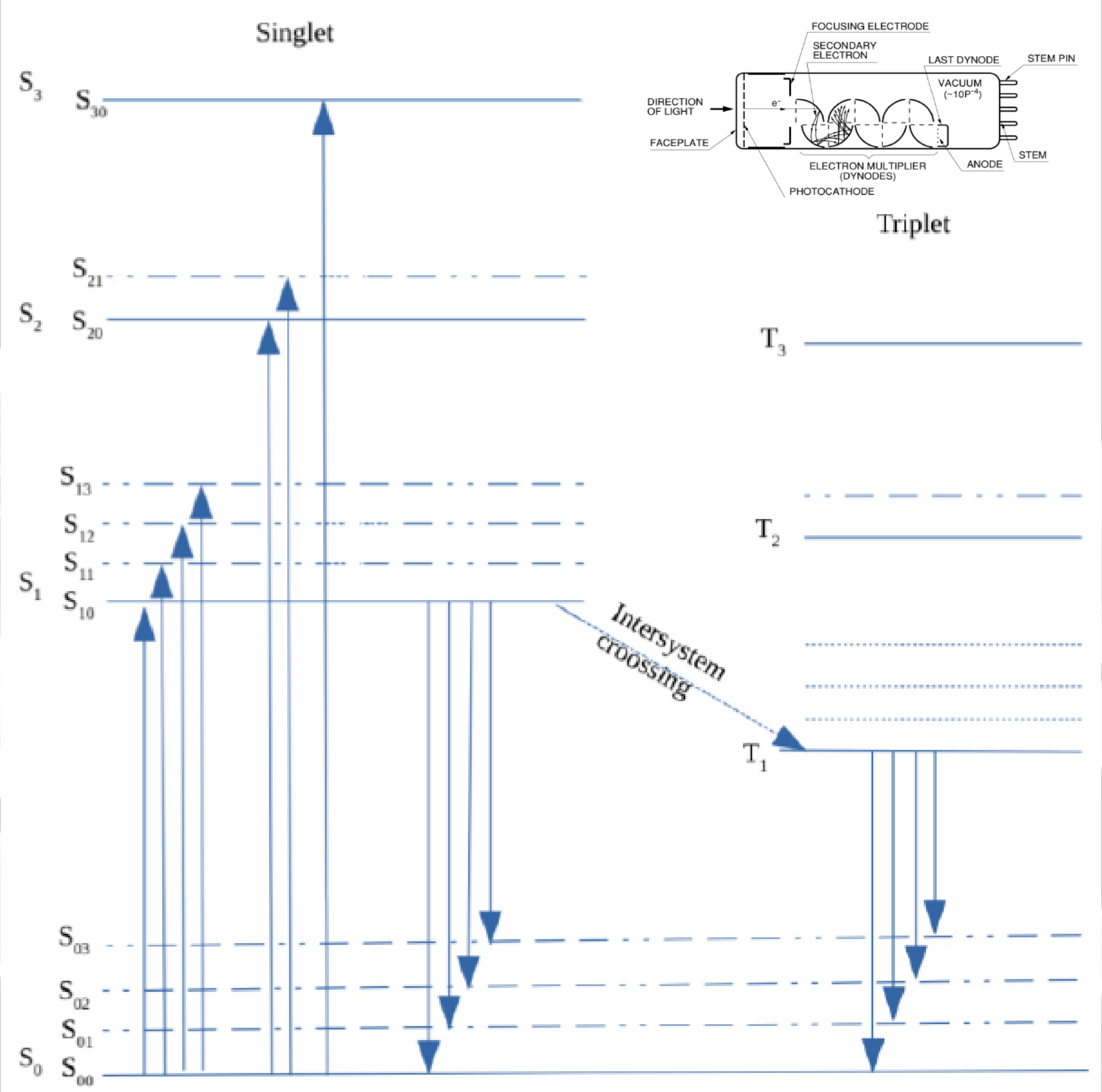
$$\varepsilon_r' = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left(1 + 10x\right)^{-\frac{1}{2}}$$

$$Z = \frac{60 \times \ln(8/x + x/4)}{\sqrt{\varepsilon_r'}} \quad : x < 1$$

Plastic honeycomb based pickup panel

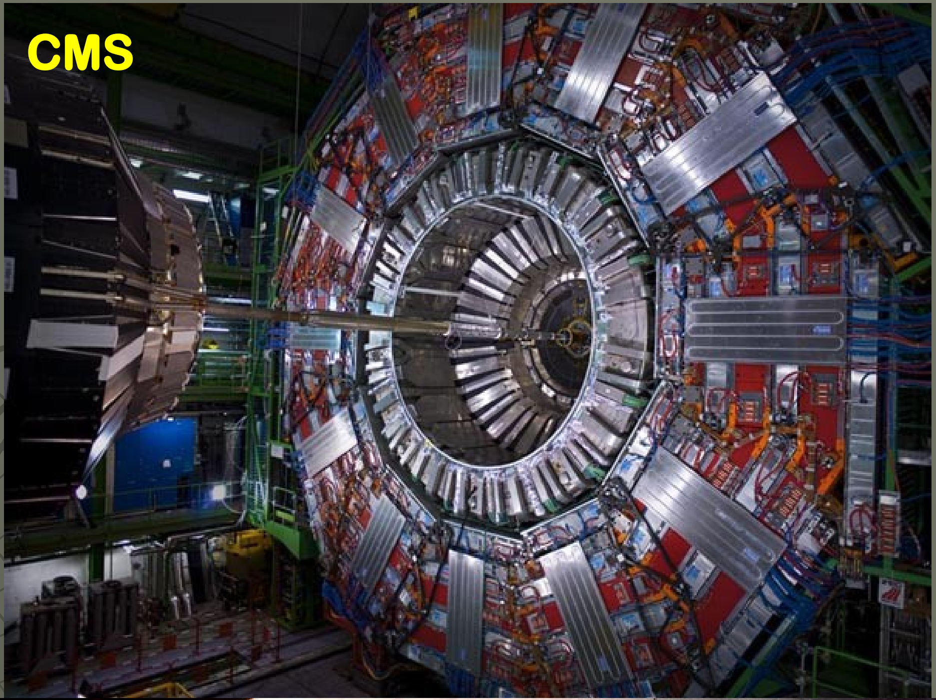
$$Z = \frac{377}{\sqrt{\varepsilon_r'}\,(x + 1.393 + 0.667\ln(x + 1.444))} \quad : x \geq 1$$

Plastic scintillators



Large scale deployment of scintillators


DZERO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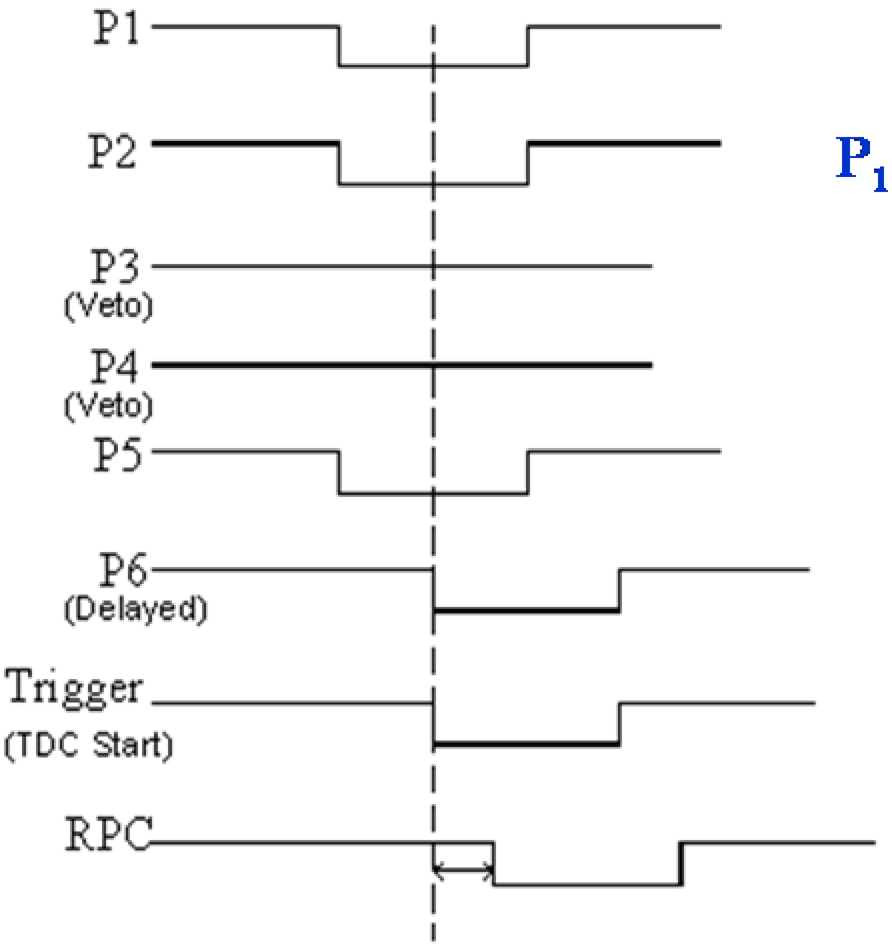
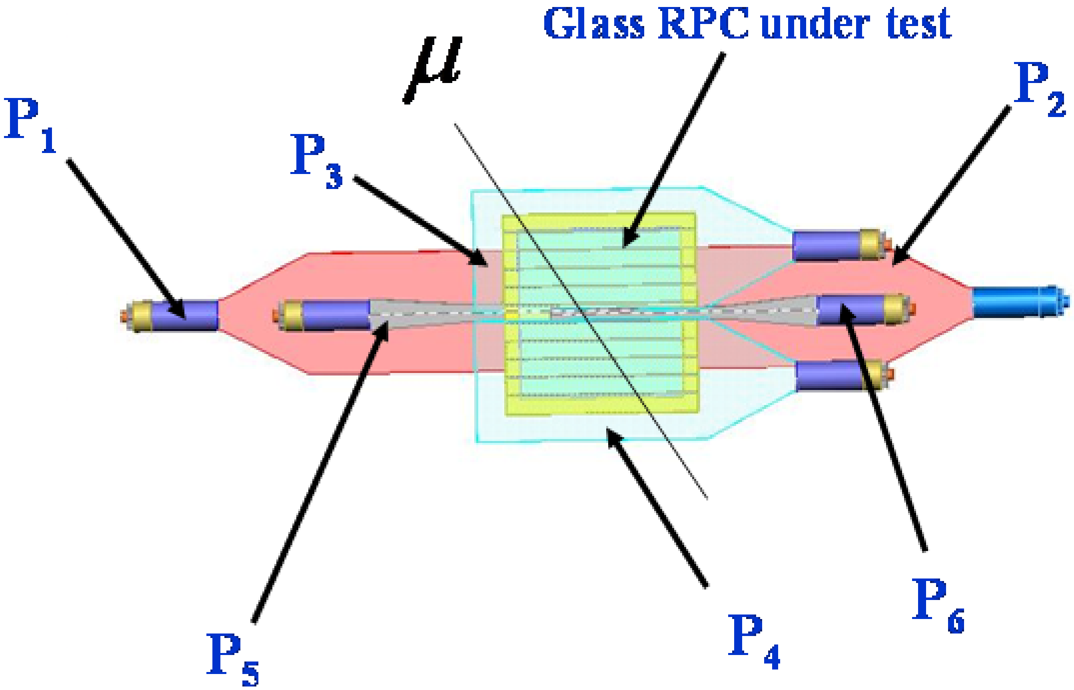
GRAPES-3


Scintillator tiles with WLS fibre readout

Coincidence scheme of a muon telescope



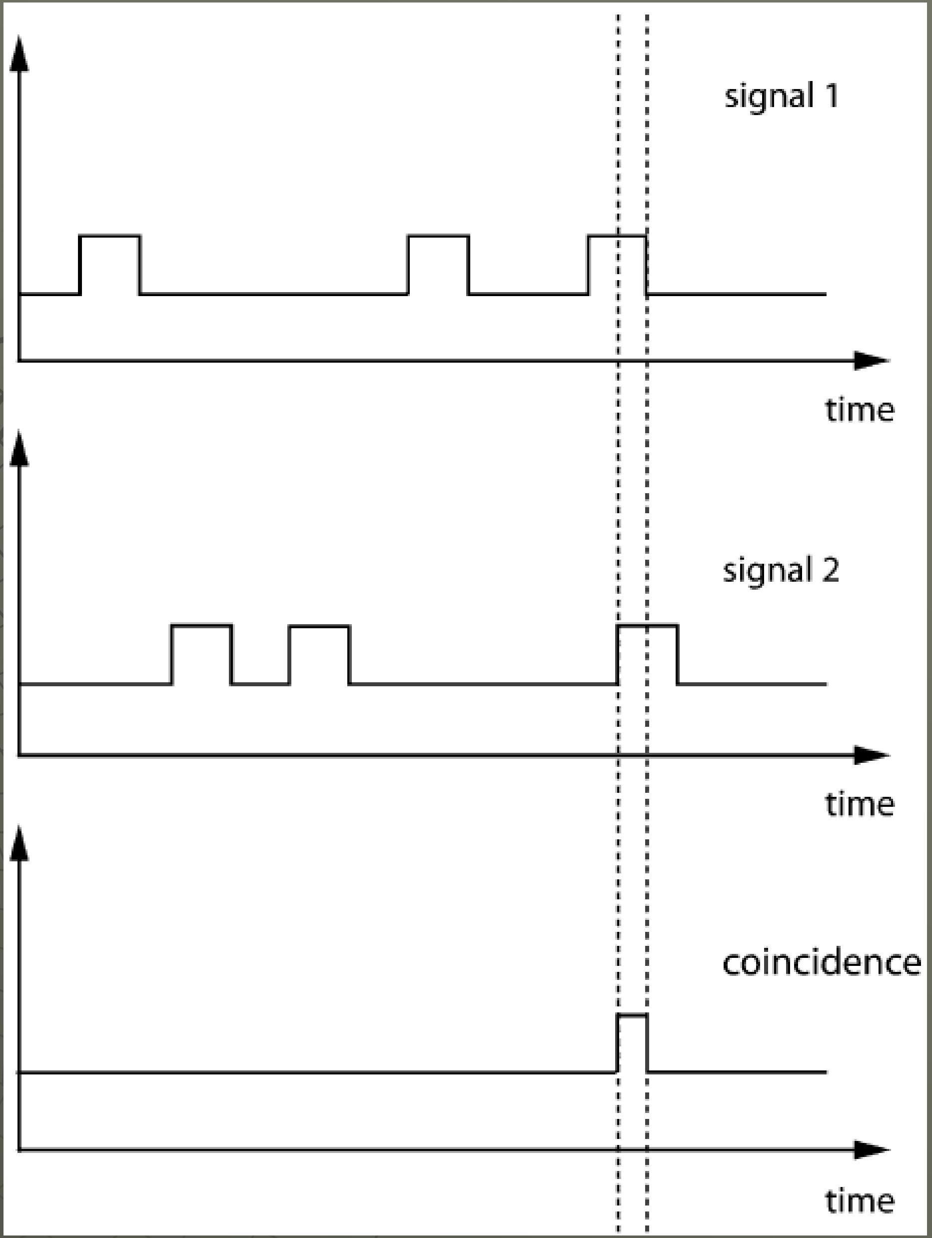


$$\textbf{Muon Trigger} = P_1 \bullet P_2 \bullet \overline{P_3} \bullet \overline{P_4} \bullet P_5 \bullet P_6$$

Coincidence of signals

- To see if an event occurred simultaneously with some other event, the electronics will look for the simultaneous presence of two logical signals within some time Window.
- In coincidence counting, one should be aware of the possibility to have random coincidences.
- These are occurrences of a coincidence caused by two unrelated events arriving by chance at the same time.
- The rate of random coincidences between two signals is proportional to the rate of each type of signal times the duration of the coincidence window:

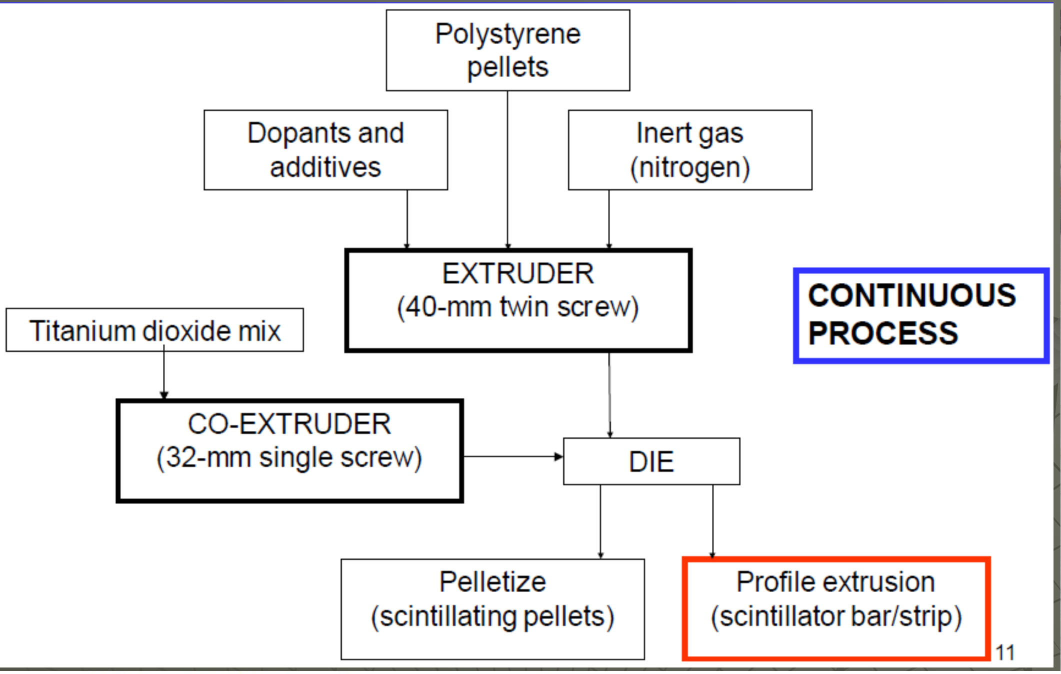
$$\frac{dN_{random}}{dt} = \frac{dN_1}{dt} \times \frac{dN_2}{dt} \times \Delta t$$



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



Polystyrene pellets

Dopants and additives

Inert gas (nitrogen)

EXTRUDER (40-mm twin screw)

Titanium dioxide mix

CO-EXTRUDER (32-mm single screw)

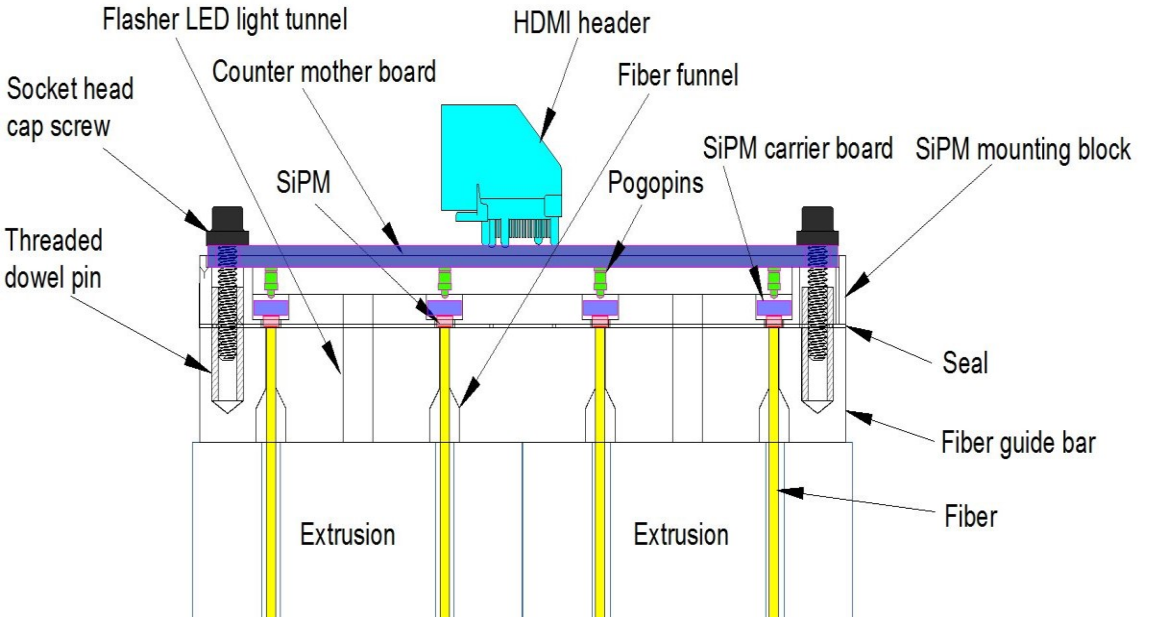
DIE

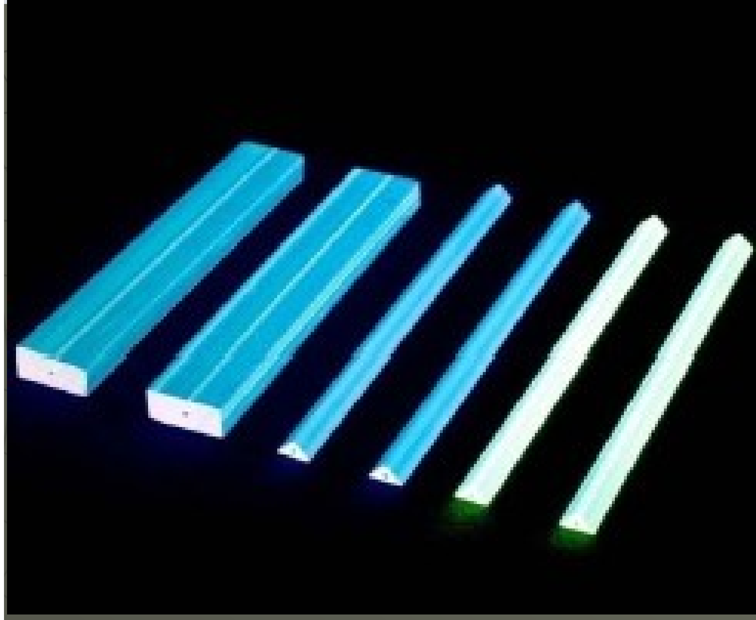
Pelletize (scintillating pellets)

Profile extrusion (scintillator bar/strip)

CONTINUOUS PROCESS

11



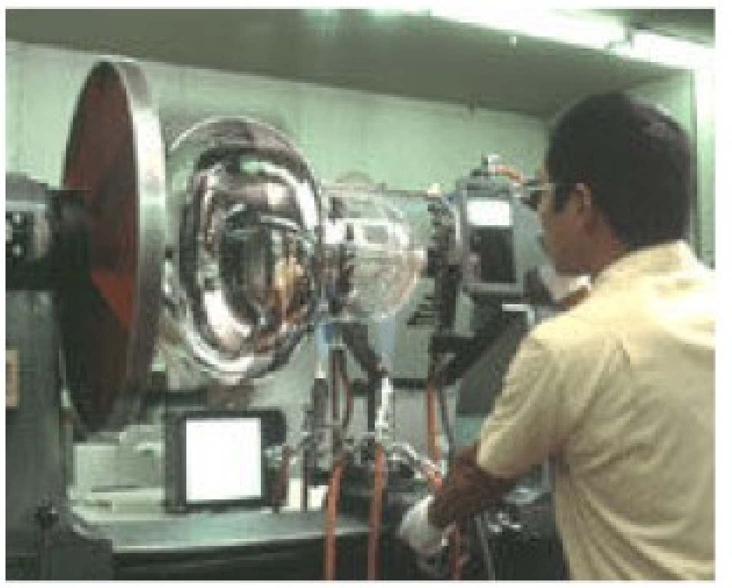


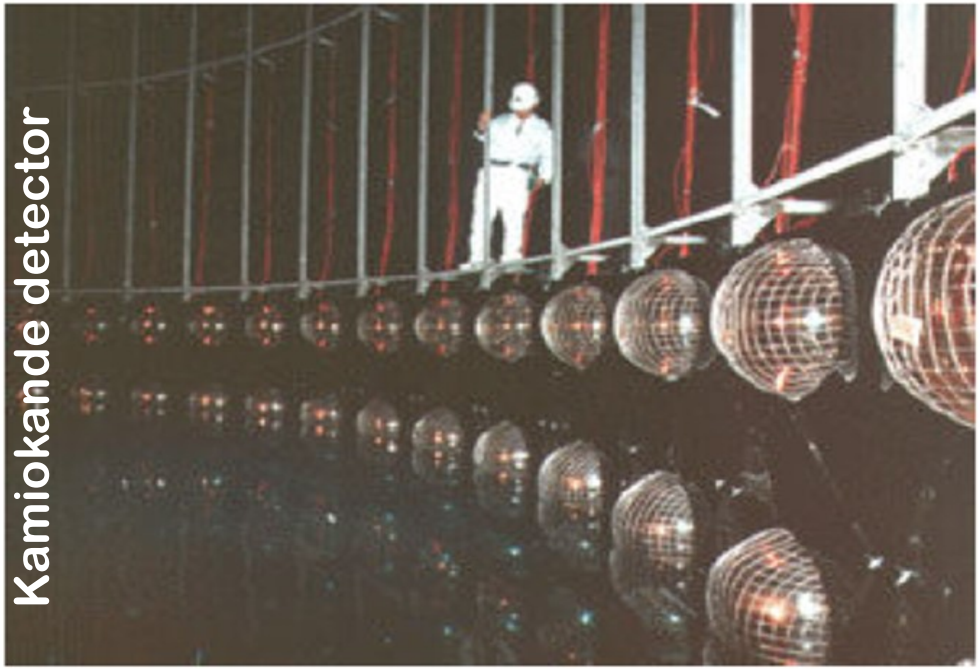
New hybrid scintillators

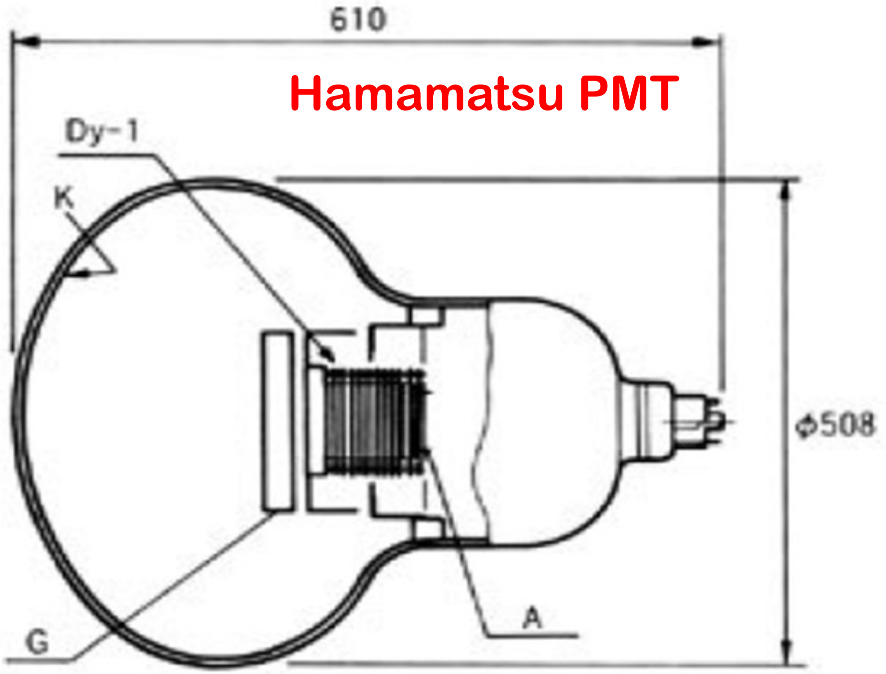
- New generation experiments require large volume, cheap scintillation materials with high light yields and short scintillation decay times.
- Extruded scintillators suffer from poorer optical quality, particulate matter and additives in polystyrene pellets.
- New single-component and multi-component 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

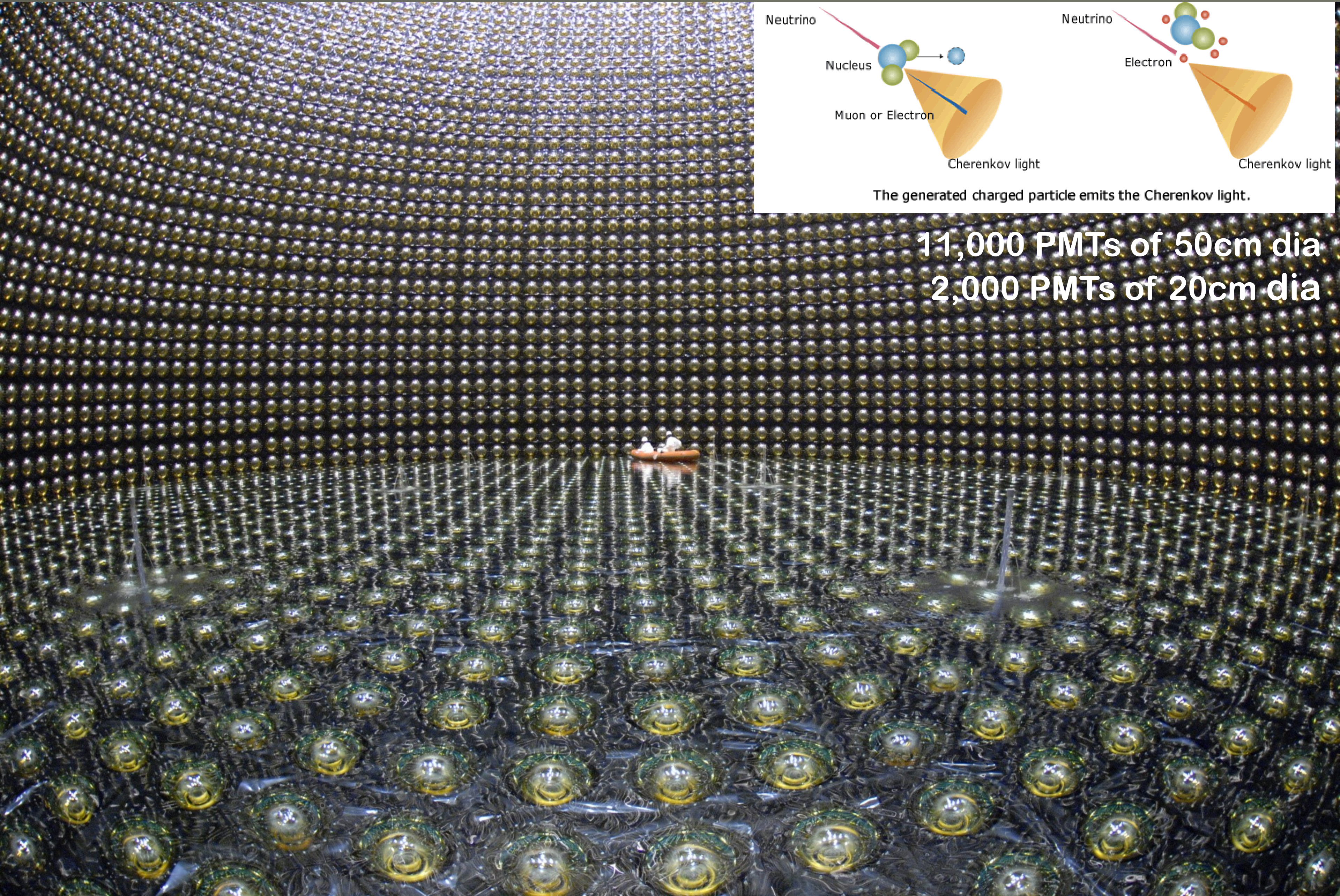
- In 1979, Masatoshi Koshiba came up with a challenging proposal to Hamamatsu's President Hiruma "Hey, could you make me a 25" PMT?"
- A number of previously acquired highly sophisticated technologies were collectively used to develop the 20" PMT.
- 50Kt water Čherenkov detector uses 11.2K PMTs.







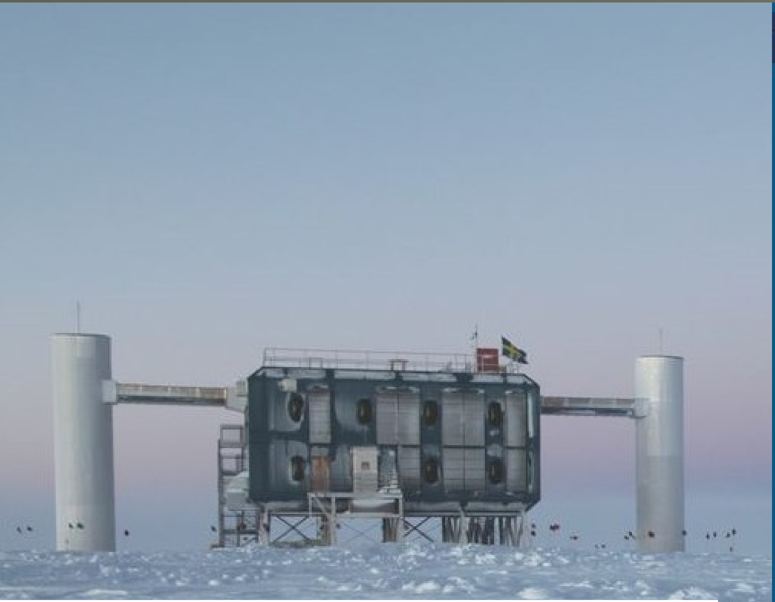
Super Kamiokande experiment

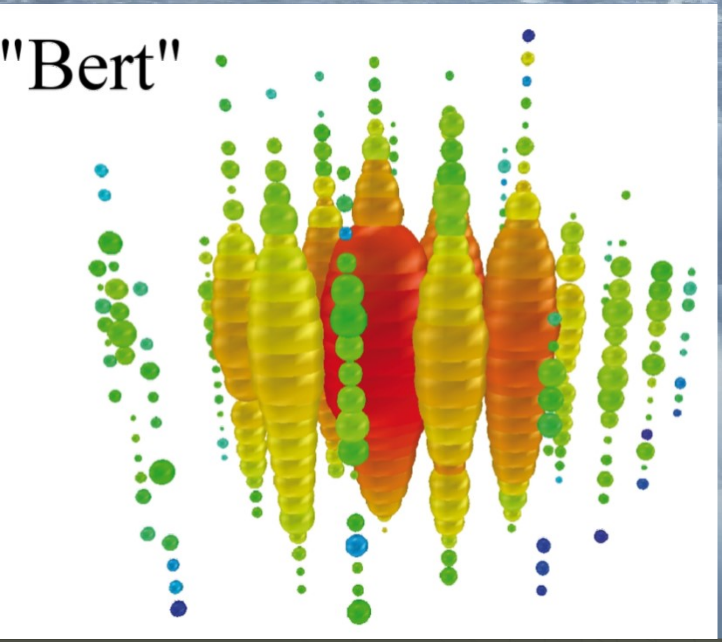


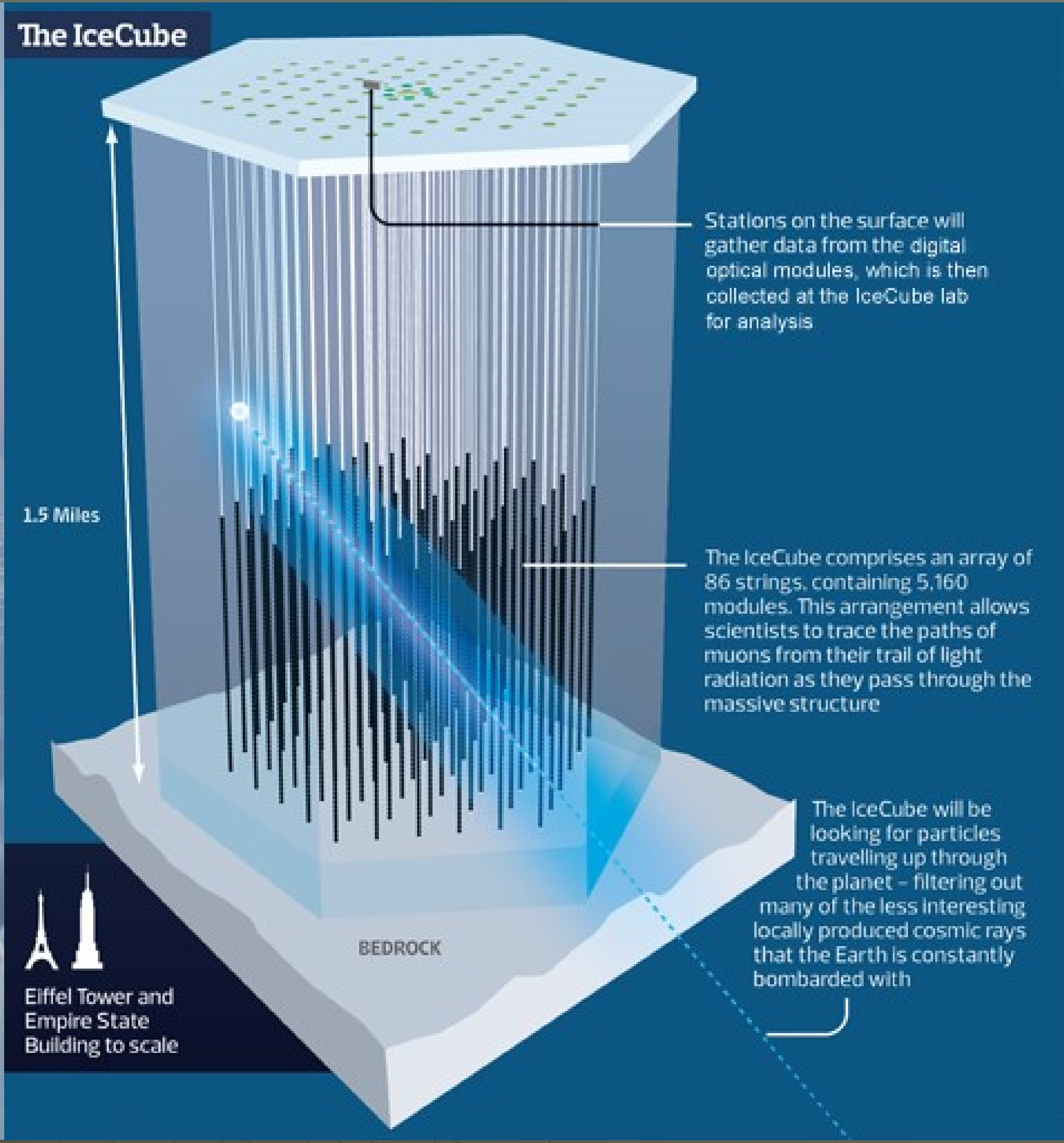
The generated charged particle emits the Cherenkov light.

11,000 PMTs of 50cm dia
2,000 PMTs of 20cm dia

The IceCube detector







Stations on the surface will gather data from the digital optical modules, which is then collected at the IceCube lab for analysis

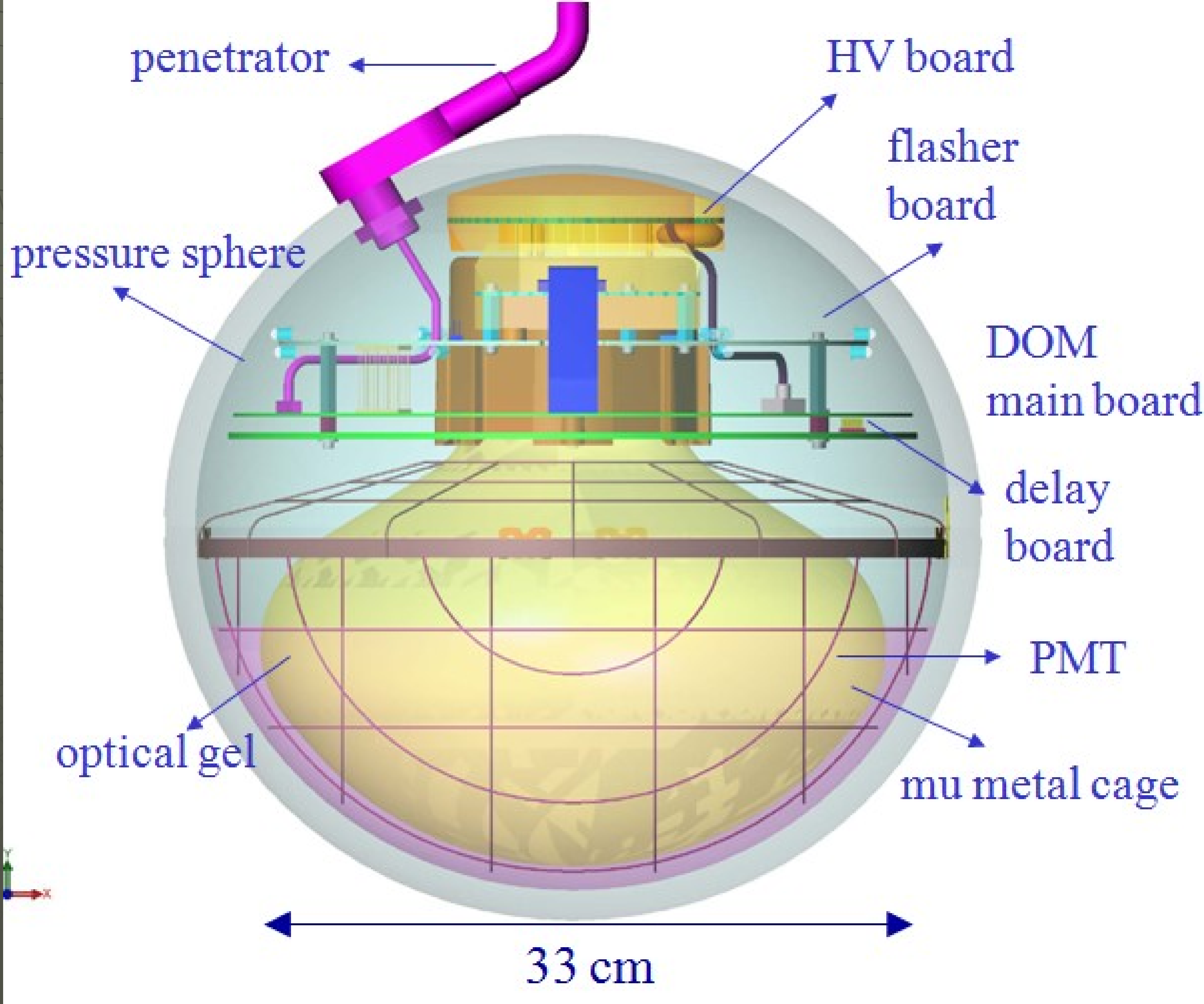
The IceCube comprises an array of 86 strings, containing 5,160 modules. This arrangement allows scientists to trace the paths of muons from their trail of light radiation as they pass through the massive structure

The IceCube will be looking for particles travelling up through the planet – filtering out many of the less interesting locally produced cosmic rays that the Earth is constantly bombarded with

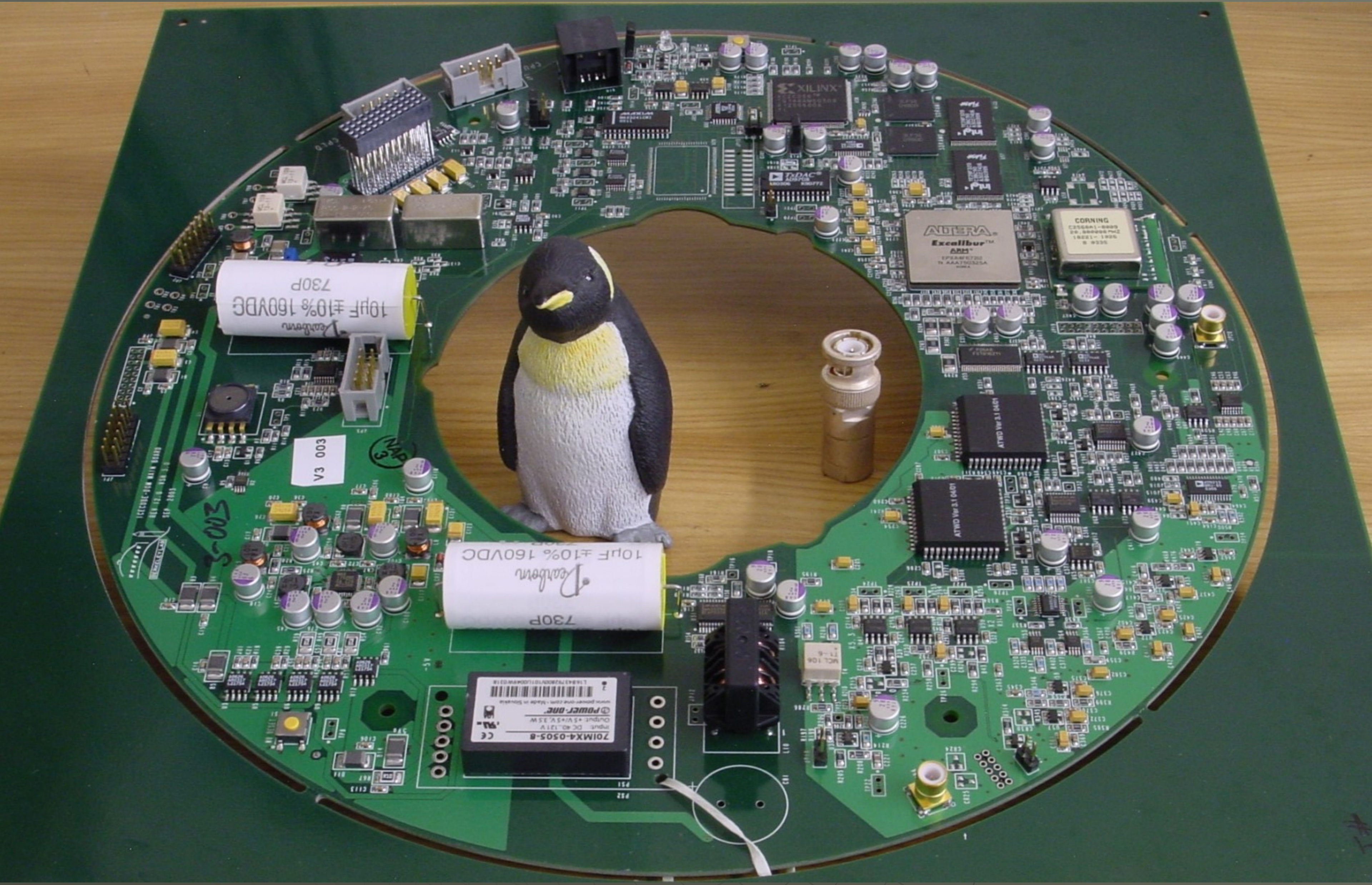
Eiffel Tower and Empire State Building to scale

Digital Optical Module (DOM)

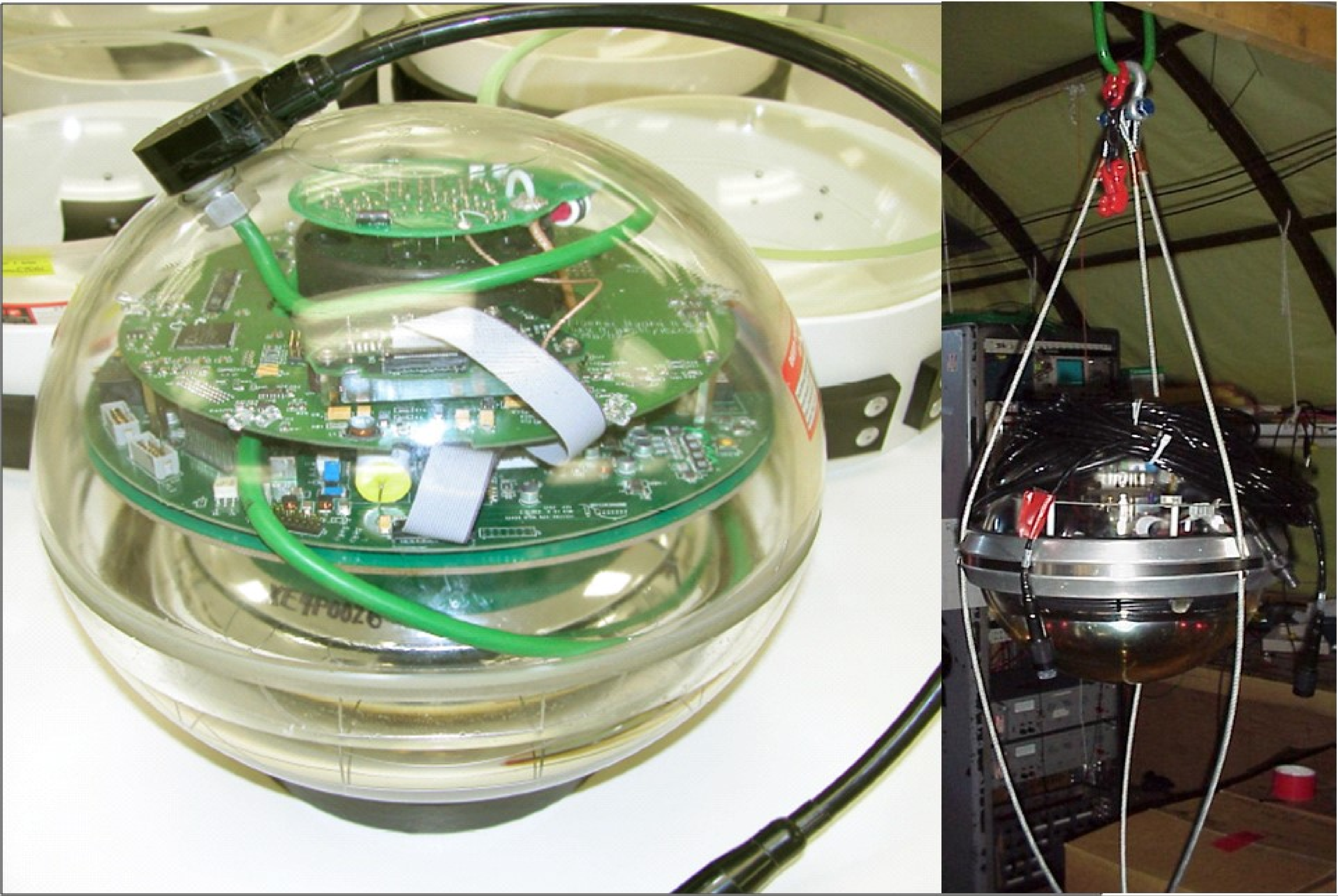
- Self-triggers on PMT pulse
- Captures waveforms with:
  - 250MHz first 500ns
  - 40MHz over 5000ns
- Dynamic range:
  - 200 PE over 15ns
  - 2000 PE over 5000ns
- Time-stamps each pulse:
  - rms < 5ns
- Dead time < 1%
- Noise rate < 1000Hz
- Calibration devices:
  - UV & blue LEDs
  - Electrical pulsers



DOM Main board



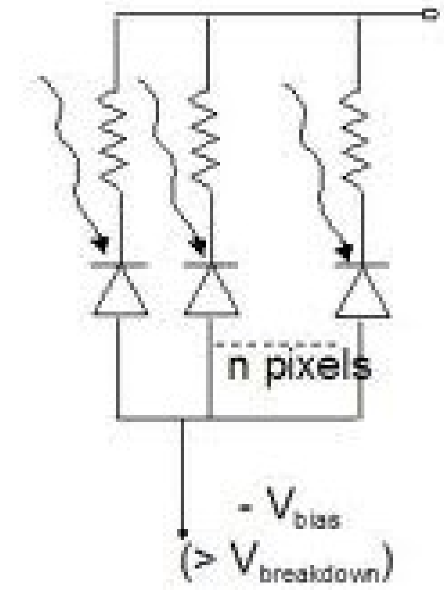
The DOM assembly

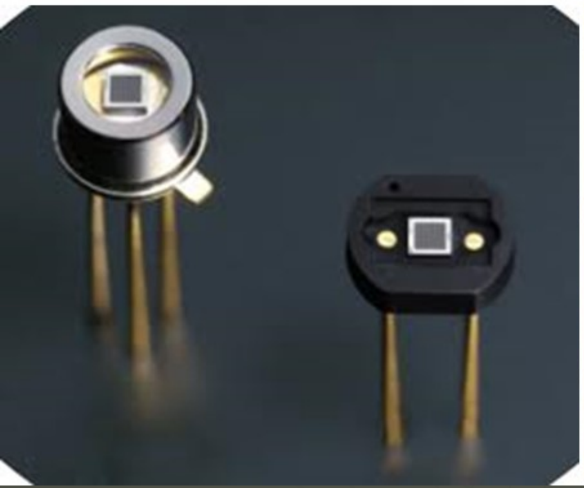


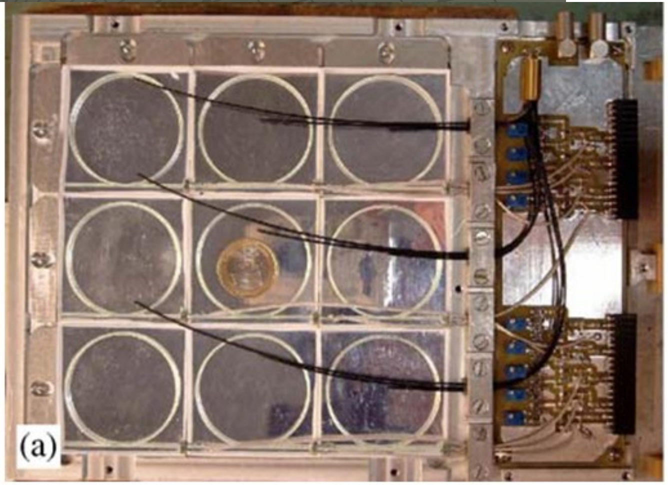
Silicon Photomultipliers

- Very small (few mm^2)
- 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

- matrix of n pixels (~1000) in parallel
- each pixel: GM-APD + $R_{quenching}$







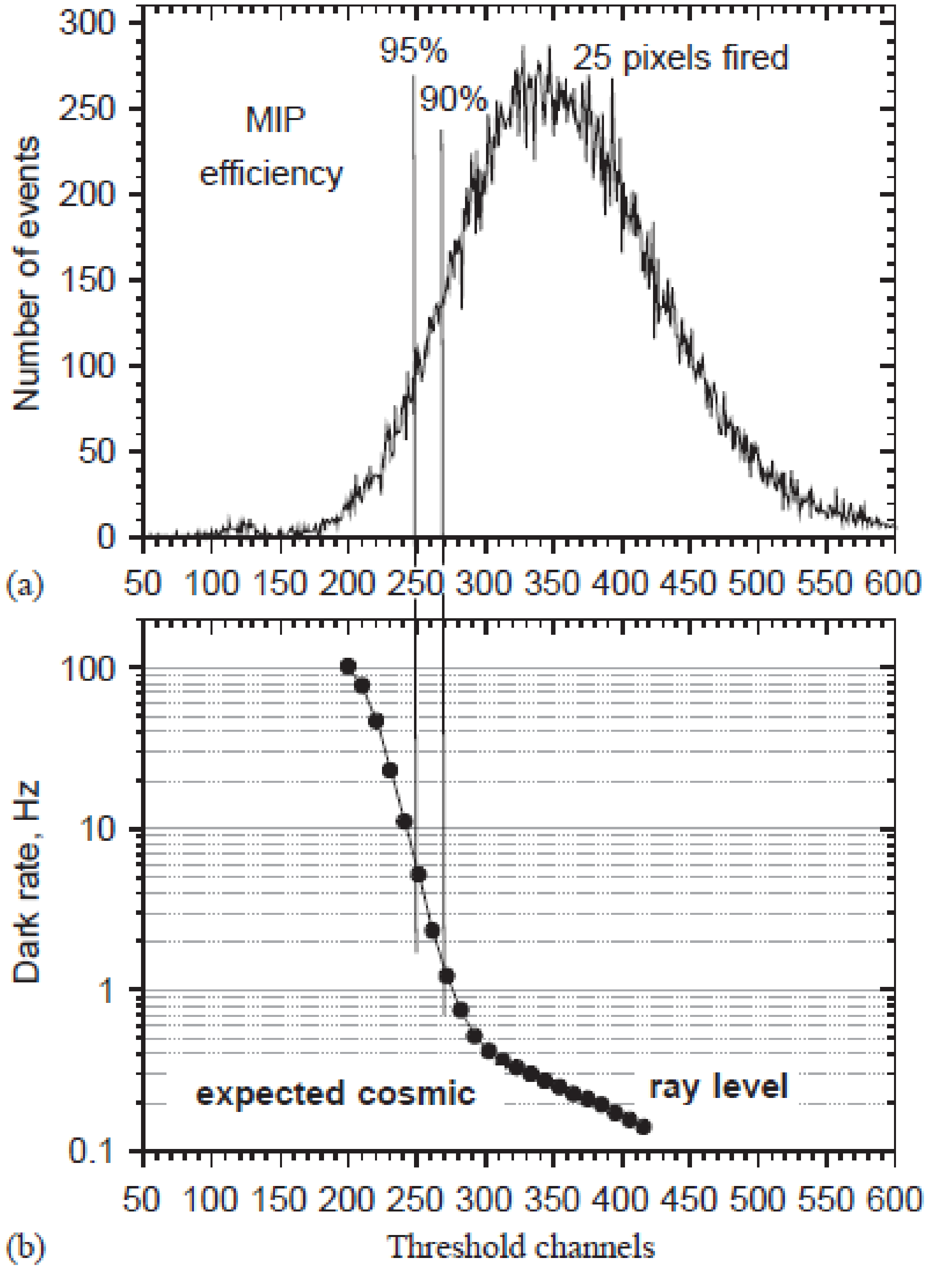
A 1-minute tutorial on SiPM

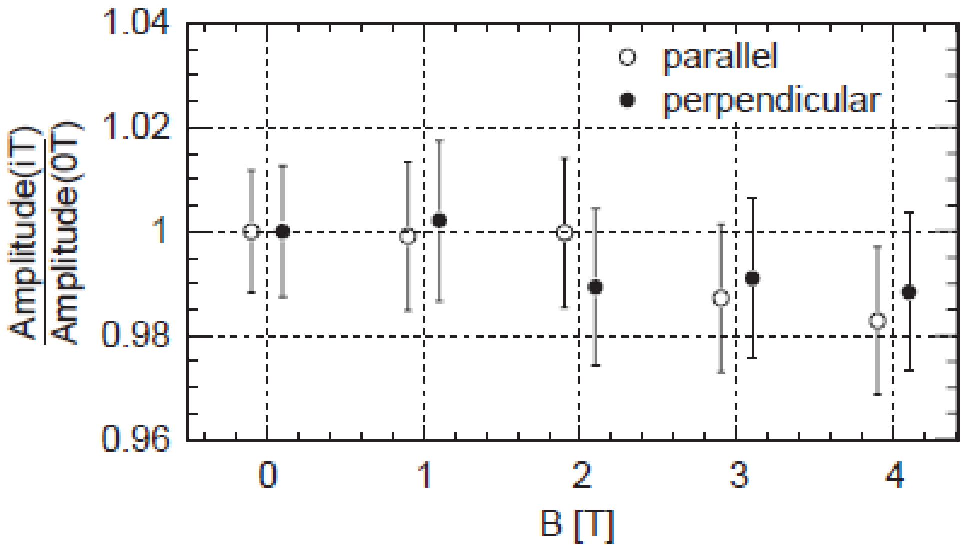
- SiPM is a pixelated avalanche photodiode operated in the limited Geiger mode.
- For example, a detector surface of 1×1mm^2 is divided into 1024 pixels.
- Operated with a reverse bias which is slightly above the breakdown voltage.
- Current flow in a pixel limited by an individual poly-silicon resistor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

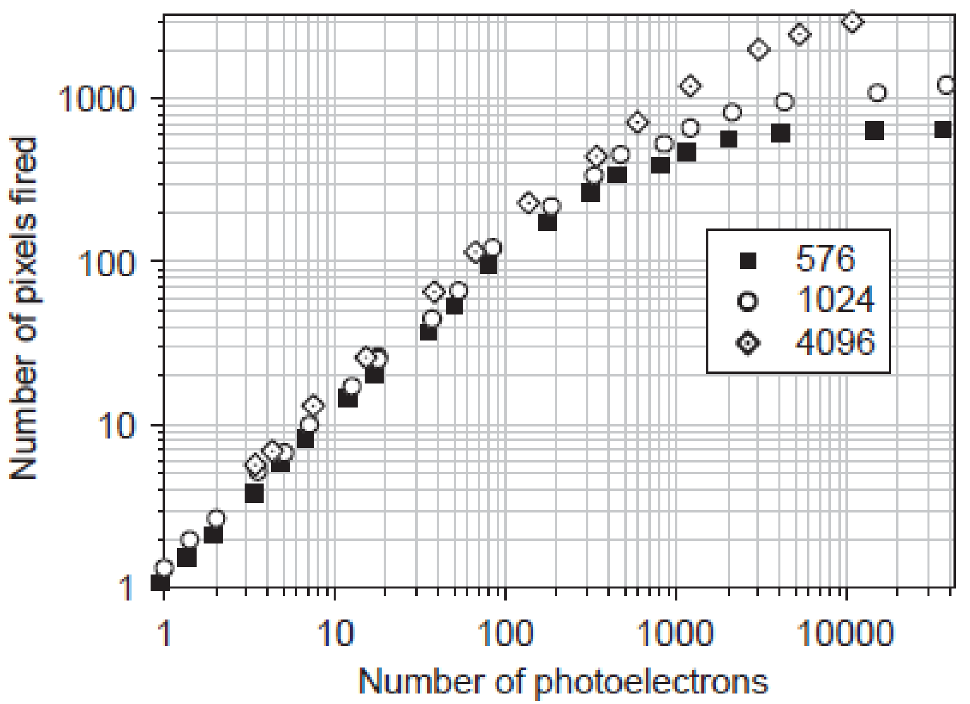
$$Q_{pixel} = C_{pixel} \times \Delta V = C_{pixel} \times (V_{bias} - V_{breakdown})$$

  where, ΔV is $\approx$ a few volts, C_{pixel} is ~50fF, yielding $Q_{pixel} \approx$ 150fC 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

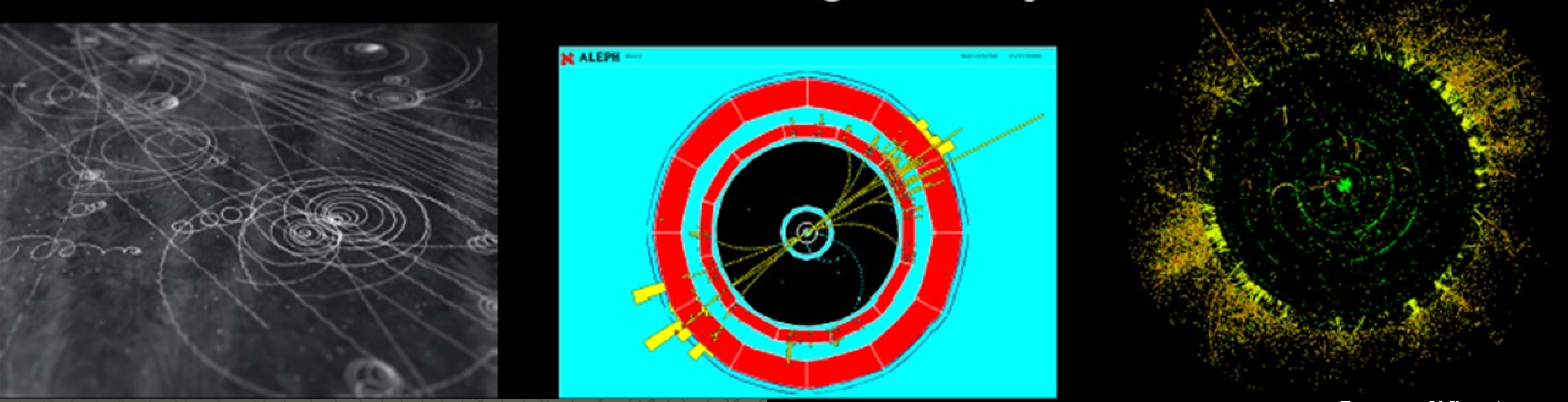




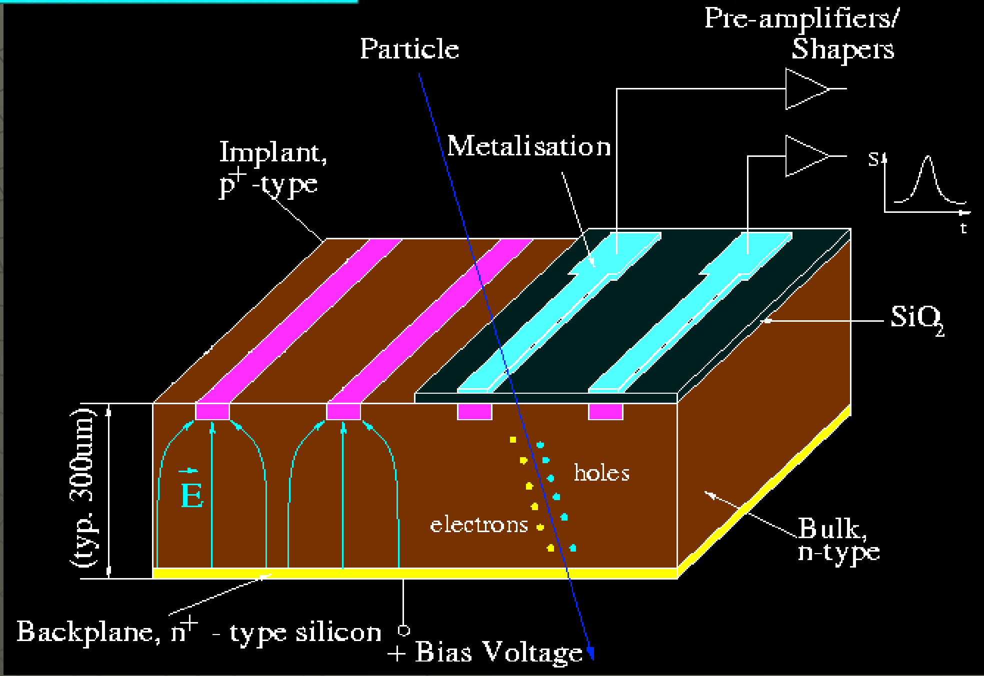


Silicon strip detectors

Silicon detectors are transforming the way we look at particles

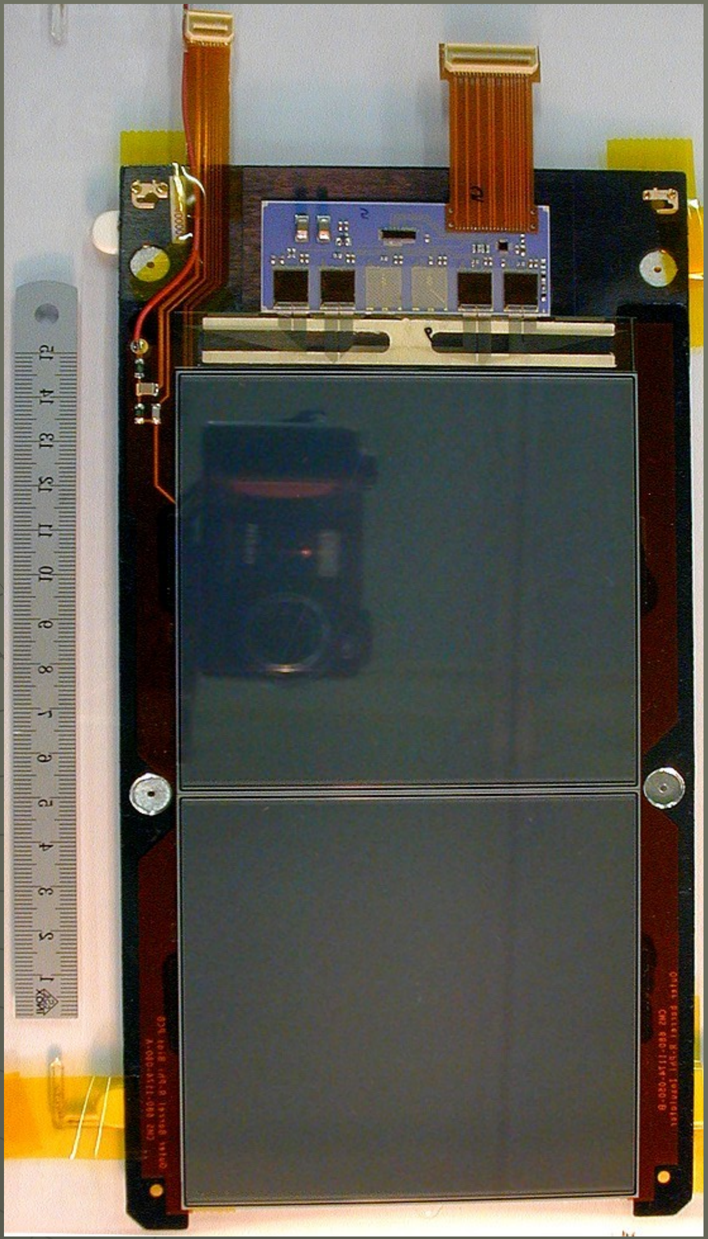


- Essentially diode with reverse bias.
- Depleted of free charge carriers.
- High resistance, only small leakage current.
- Charge deposition by ionising particle causes current.
- Use segmented electrodes (strips or pixels).
- Can localise charge deposition.
- Much better resolution than strip pitch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



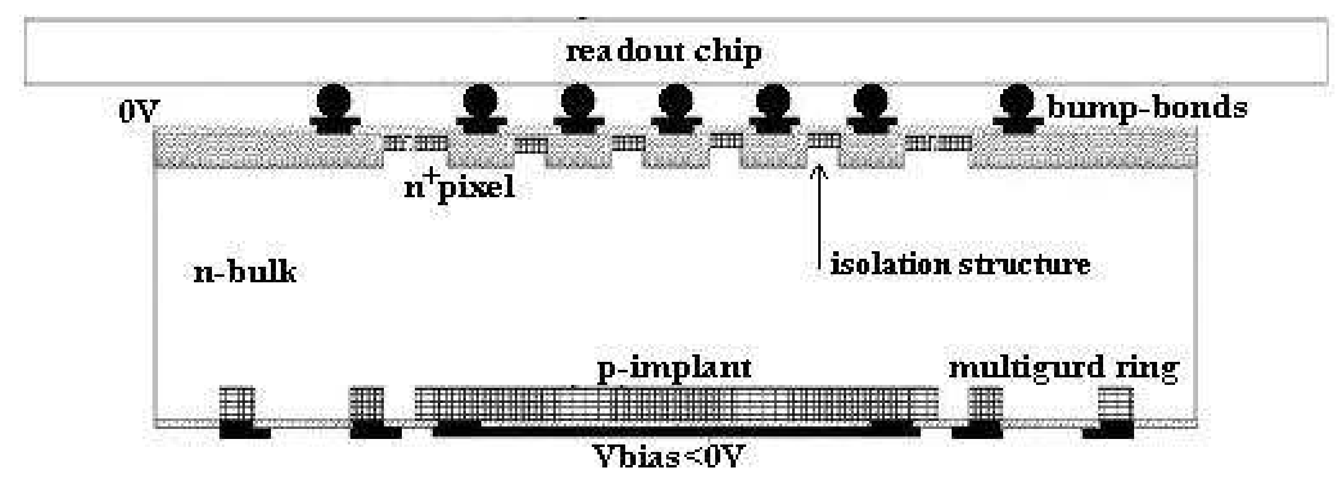
Silicon strip detectors

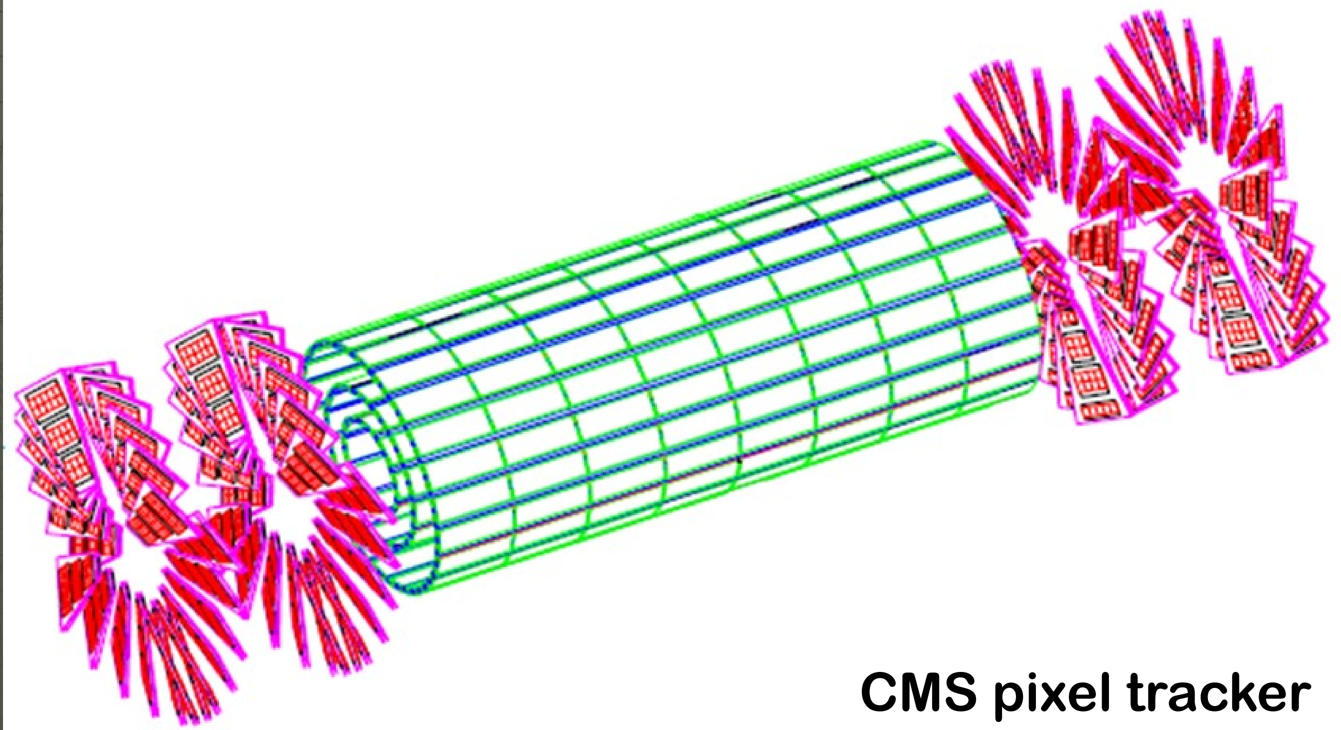
- Reading out strips is comparatively easy - just attach chips to the end.
- Readout of strip sensor, power distribution and control → hybrids.
- Custom readout chips wire bonded to electrodes on the sensor.
- Chips have amplifiers, ADCs, zero suppression, cluster finder, storage, digital communication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



Silicon 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).



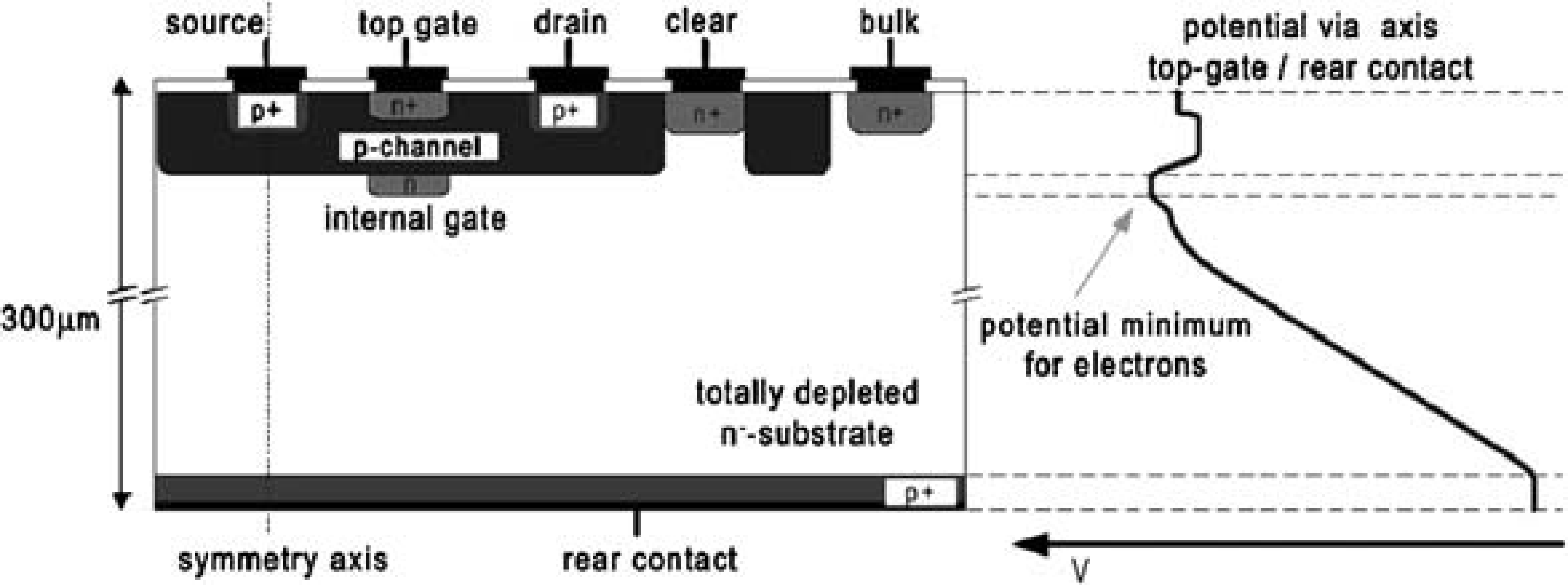


CMS pixel tracker

Integration of detectors & readout

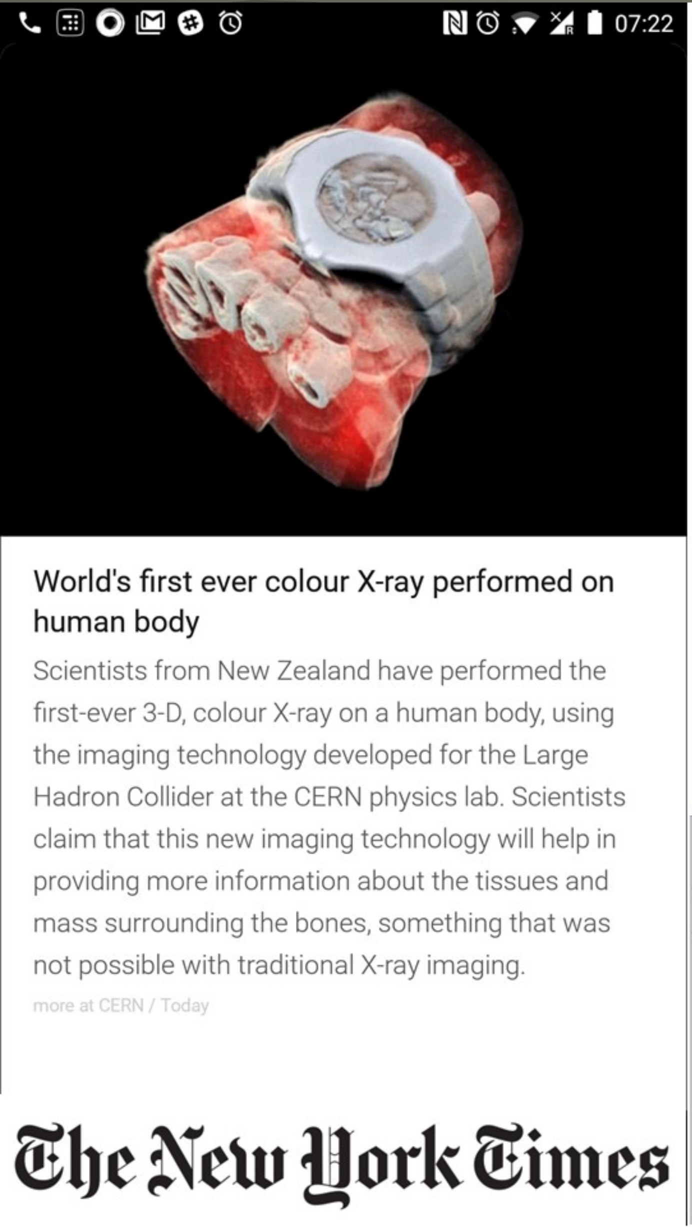
- Compatible integration of detectors and readout electronics on the same silicon substrate is of growing interest.
- As the methods of microelectronics technology have already been adapted for detector fabrication, a common technology basis for detectors and readout electronics is available.
- CMOS 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



- **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 50μm size achieved a resolution of 9.5μm and 40e- noise.
- **MAPS integrate sensors and readout electronics on the same substrate using a technology similar to the one used in visible light CMOS cameras**

Pixel sensors for medical imaging

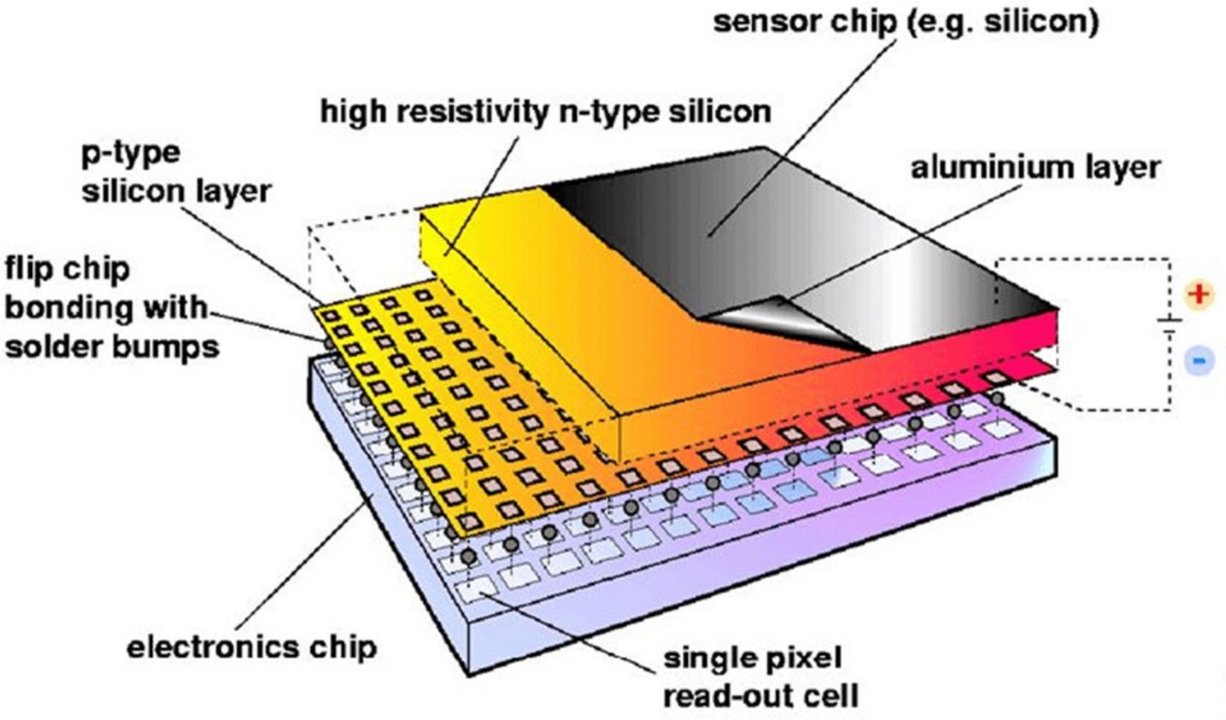


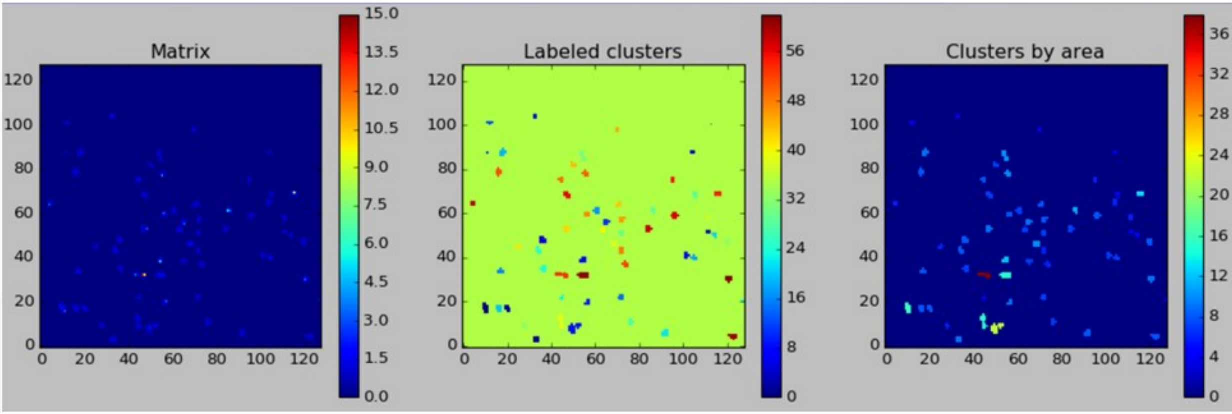
World's first ever colour X-ray performed on human body

Scientists from New Zealand have performed the first-ever 3-D, colour X-ray on a human body, using the imaging technology developed for the Large Hadron Collider at the CERN physics lab. Scientists claim that this new imaging technology will help in providing more information about the tissues and mass surrounding the bones, something that was not possible with traditional X-ray imaging.

more at CERN / Today

The New York Times





Challenges facing Si detectors

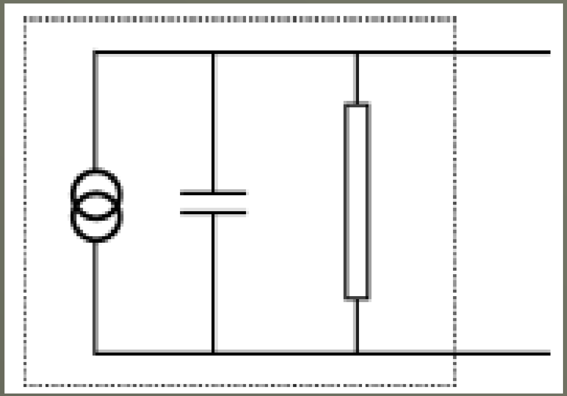
- Main issue is radiation damage.
- Silicon detectors are invariably located in the high dose region (mostly used in trackers).
- Surface damage: charge build-up, noise
- Bulk damage: displacements in crystal lattice
  - reduced charge collection efficiency (charge lost in traps).
  - changes dopant 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.

Electronic requirements for detectors

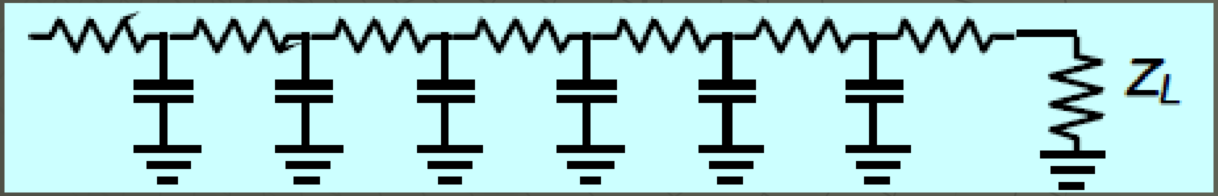
Detector	Physics	Technical
Tracking	High spatial precision Large channel count Limited energy precision Limited dynamic range	Low power ~mW/channel High radiation levels ~10Mrad
Calorimeter (EM & Hadron)	High energy resolution Large energy range Excellent linearity Very stable over time	Intermediate radiation levels ~0.5Mrad Power constraints
Muon	Very large area Moderate spatial resolution Accurate alignment & stability	Low radiation levels
Time of Flight	Discriminates between a lighter and a heavier particle of the same momentum	Time of flight between two detector planes
Neutrinos	Detected through inferred momentum conservation.	Good spatial and time resolutions
Dark matter	Principle of nuclear recoil by candidate particles	Low counting and high precision experiment

Detector equivalent circuits

- Many of the detectors can be modelled as current source associated with large internal resistance and a small capacitance.
- Capacitance of various detectors:
  - 100fF for semiconductor pixel
  - 10-20pF for gas or Si microstrip, PMT anode
  - 100pF for large area diode
  - µF for wire chamber

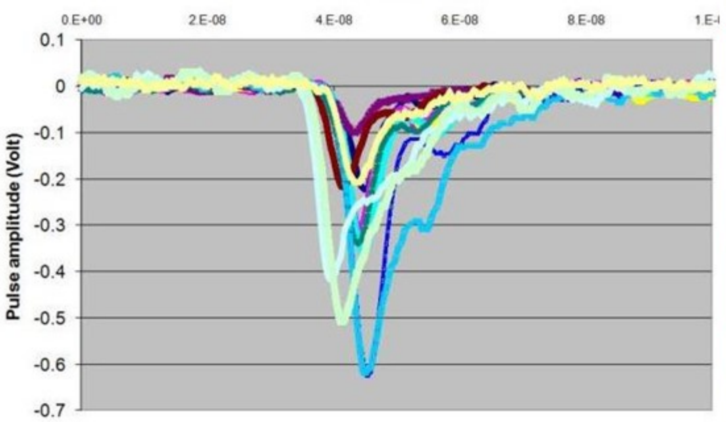


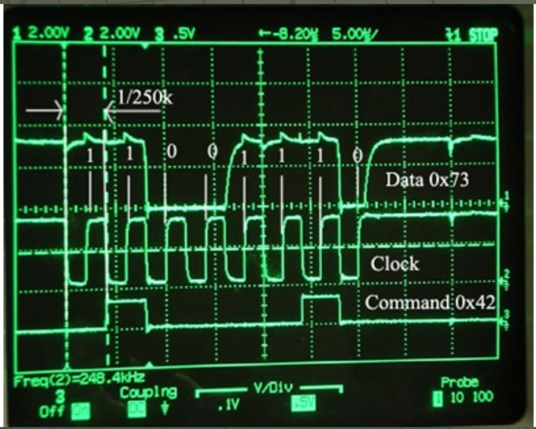
- Usually there is some resistance associated with the detector, for ex. leads or metallisation but this has little effect on signal formation or amplification
- Notable exceptions: microstrips - gas or silicon
  - The capacitance is distributed, along with the strip resistance
  - Forms a dissipative transmission line:

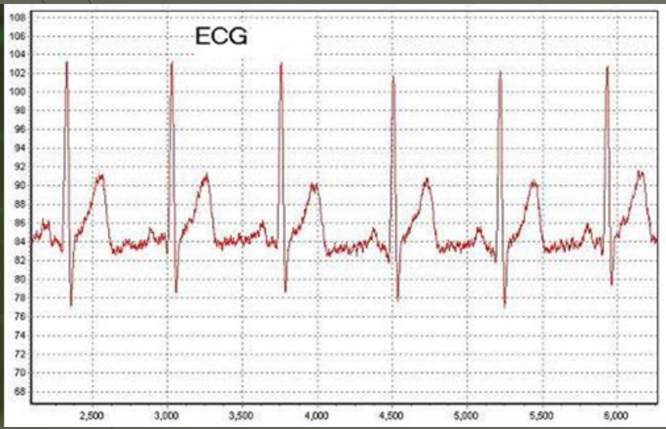


Types of Signals

- Wide range of signal types are possible
  - Depends on sensors or detectors
  - Depends on any further transformation – for example light to electrical (PMT, SiPM etc.)
- Most common types of signals
  - Short, random pulses usually of current. Pulse shape, amplitude, rise time, area etc. carry useful information - typical of radiation detectors
  - Trains of pulses, often current, usually binary - typical of communication systems
  - Continuous, usually of slowly varying quantity – for example current or voltage





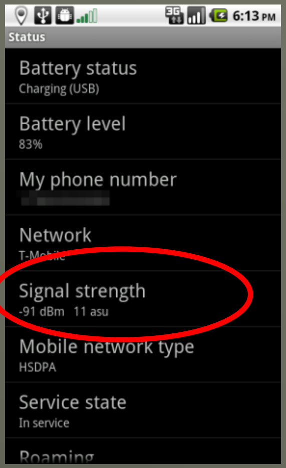


Issues on signal production

- Duration
  - Radiation: depends on transit time through detector and details of charge induction process in external circuit.
- Linearity
  - Most radiation detectors are characterised or chosen for linearity.
  - Commercial components can expect non-linearity, offset and possible saturation.
- Reproducibility
  - Many signals are temperature dependent in magnitude - mobility of charges, other effects easily possible as well.
- Ageing
  - Detector signals can change with time for many reasons.
  - Natural degradation of detector, variation in operating conditions, radiation damage, etc.
- All these issues mean that one should always be checking or calibrating measurements intended for accuracy, as best one can.

Dynamic range of signals

- In most systems, there will be a smallest measurable signal,
  - If there is noise present, it is most likely to be related to the smallest signal distinguishable from noise.
  - In the absence of any ionising radiation there is a small current, which is called the dark current or leakage current.
- and a largest measurable signal.
  - Most likely set by apparatus or instrument, eg. saturation
- Dynamic range = ratio of largest to smallest signal often expressed in dB or bits
  - For example, 8 bits = dynamic range is 256_{10} = 48dB (if the signal is voltage)
- Decibels (dB)
  - Signal magnitudes cover wide range, so frequently logarithmic scale is preferred.
  - Number of dB = $10\log_{10}(P_2/P_1)$, if power is used.
  - Often voltages are measured, then dB = $20\log_{10}(V_2/V_1)$



Status

Battery status
Charging (USB)

Battery level
83%

My phone number
[redacted]

Network
T-Mobile

Signal strength
-91 dBm 11 asu

Mobile network type
HSDPA

Service state
In service

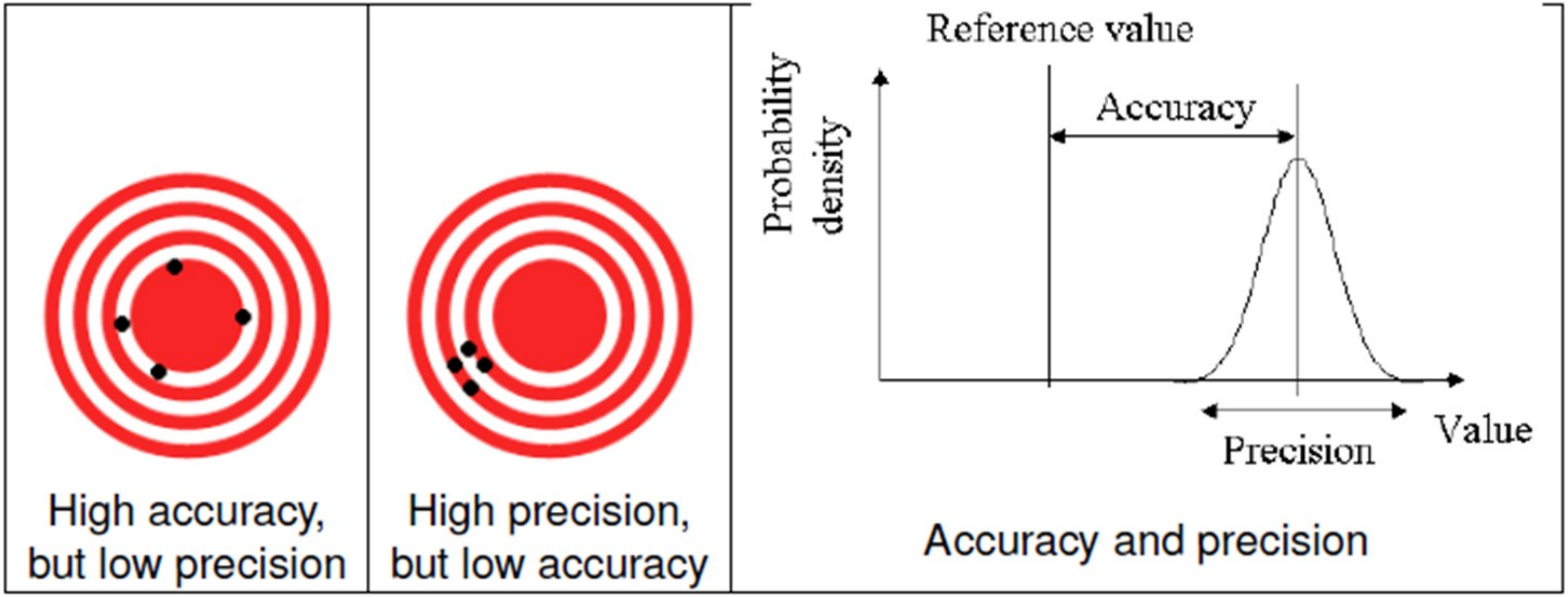
Roaming

Signal processing

- Measurement of physical parameters using sensors or detectors in the end nearly always comes down to handling some small electrical signals.
- Dealing with such small signals is one of the main challenges in designing reliable instruments or systems.
- Electronic processing of signals is done in some fashion to extract some useful information from them, usually leading to measurement of a physical parameter.

Precision and accuracy

Accuracy is the degree of conformity of a measured or calculated quantity to its actual (true) value. *Precision* is the degree to which further measurements or calculations will show the same or similar results. The results of calculations or a measurement can be accurate but not precise; precise but not accurate; neither; or both. A result is called *valid* if it is both accurate and precise.



High accuracy, but low precision

High precision, but low accuracy

Accuracy and precision

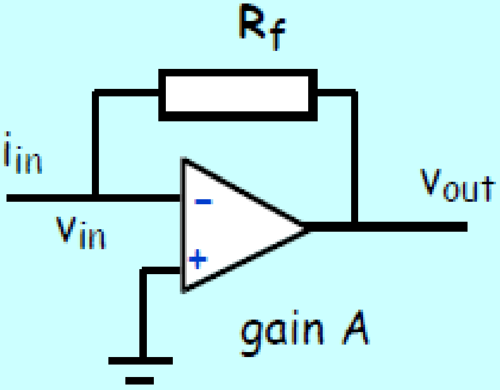
Amplifiers

- Inescapable in electronic instruments
  - amplifiers are needed for most of the detectors
  - even if not used to boost signals, amplifiers are the basis of most important functional blocks
- In many circumstances amplification, in the sense of “boosting” signals, is vital
  - signals to be measured or observed are often small
  - defined by source - or object being observed
  - and detector - it is not usually easy to get large signals
  - data have to be transferred over long distances without errors
  - safest with “large” signals ☺

Amplifiers in systems

- Amplification
  - role of a preamplifier
  - single gain stage rarely sufficient
  - add gain to avoid external noise, for ex. to transfer signals from detector
  - practical designs depend on detailed requirements
  - constraints on power, space,… cost in large systems
  - ex. ICs use limited supply voltage which may constrain dynamic range
- Noise will be an important issue in many situations
  - most noise originates at input as first stage of amplifier dominates
  - often refer to Preamplifier = input amplifier
  - may be closest to detector, subsequently transfer signal further away
- In principle, several possible choices
  - I sensitive (Used with low impedance detectors)
  - V sensitive (Conventional, most common)
  - Q sensitive (Used with semiconductor detectors)

Current sensitive amplifier



- Common configuration, eg for photodiode signals

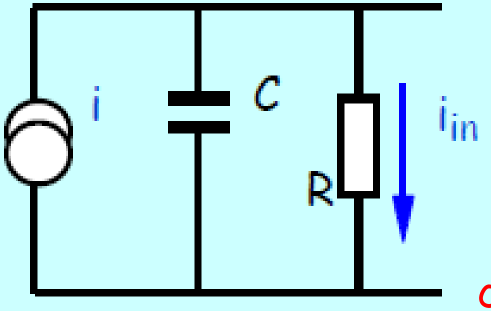
  $v_{out} = -Av_{in}$

  $v_{in} - v_{out} = i_{in}R_f$

  $v_{out} = -[A/(A+1)].i_{in}R_f \approx -i_{in}R_f$

- Input impedance

  $v_{in} = i_{in}R_f/(A+1) \qquad Z_{in} = R_f/(A+1)$



- Effect of C & R_{in} - consider in frequency domain

  $v_0 = i(1/j\omega C||R_{in})$

  $= i(\omega)R/(1 + j\omega\tau)$

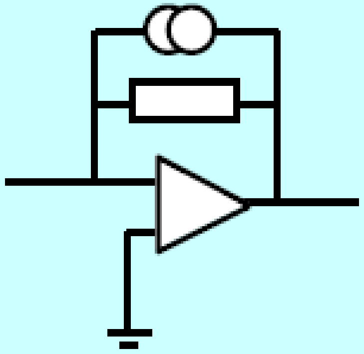
  input signal convoluted with falling exponential

  increasing R_f to gain sensitivity will increase τ

  fast pulses will follow input with some broadening

- Noise

Thermal, contact, and shot noise



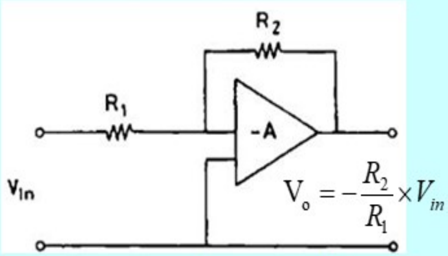
feedback resistor is a noise source

contributes current fluctuations at input ~ $1/R_f$

Voltage sensitive amplifier

- Most commonly used, simple to implement
- Many times, input signal is first manipulated, followed by a voltage amplifier

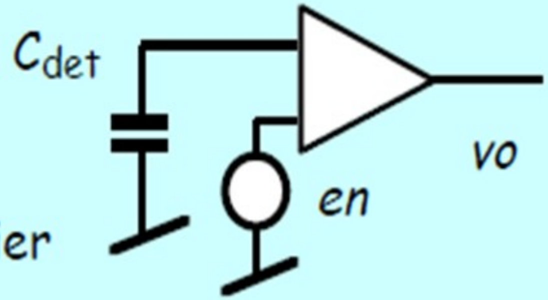
- As we have seen many sensors produce current signals but some examples produce voltages - thermistor, thermocouple,…
  - op-amp voltage amplifier ideal for these
  - especially slowly varying signals - few kHz or less



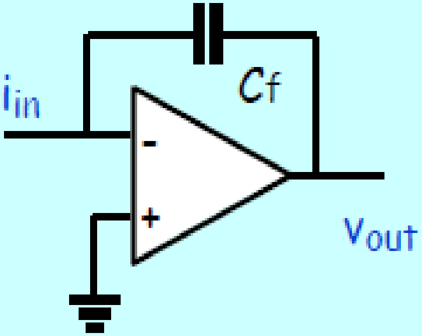
$V_o = -\frac{R_2}{R_1} \times V_{in}$

- For sensors with current signals voltage amplifier usually used for secondary stages of amplification

- Signal $V_{out} = Q_{sig}/C_{tot}$
  - *C_{tot} = total input capacitance*
  - C_{tot} will also include contributions from wiring and amplifier
  - V_{out} depends on C_{tot}
  - not desirable if C_{det} is likely to vary
    - eg with time, between similar sensors, or depending on conditions



Charge sensitive amplifier



- Ideally, simple integrator with C_f

  but need means to discharge capacitor - large R_f

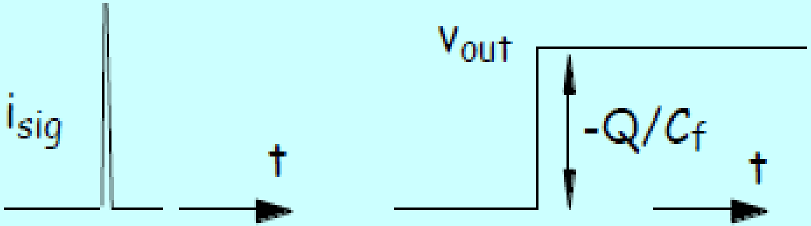
- Assume amplifier has Z_{in} very high (usual case)

  $v_{out} = -Av_{in}$

  $v_{out} - v_{in} = i_{in}/j\omega C_f$

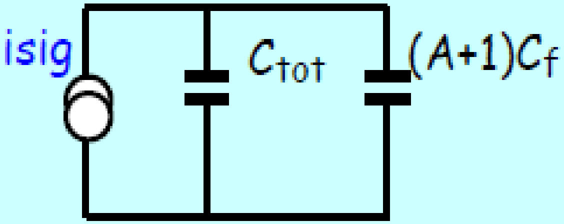
  $v_{out} = -[A/(A+1)].i_{in}/j\omega C_f \approx i_{in}/j\omega C_f$

  $\Rightarrow -Q/C_f$



- Input impedance

  $v_{in} = i_{in}/(A+1)j\omega C_f$ $C=(A+1)C_f$ at low f



so amplifier looks like large capacitor to signal source

low impedance but some charge lost

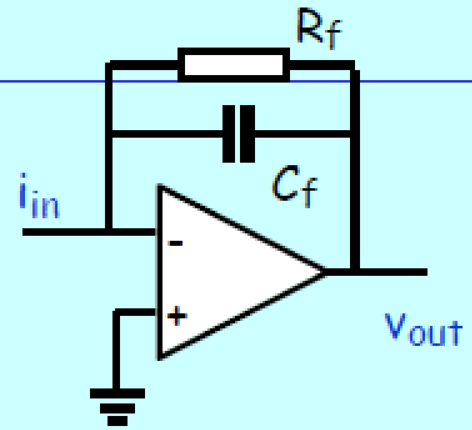
$Q_A = Q/[1 + C_{tot}/(A+1)C_f]$

e.g. $A = 10^3$ $C_f = 1pF$

$C_{tot} = 10pF$ $Q_A/Q = 0.99$

$C_{tot} = 100pF$ $Q_A/Q = 0.90$

Feedback resistance



- Must have means to discharge capacitor so add R_f

$Z_f = R_f || 1/j\omega C_f$

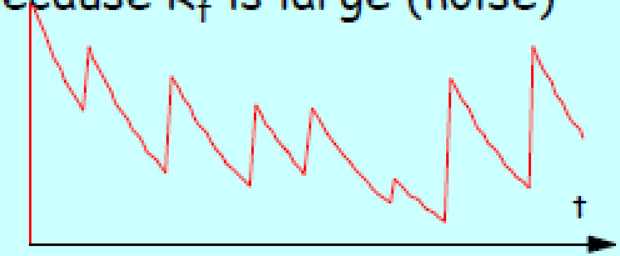
$v_{out} = -[A/(A+1)].i_{in}Z_f$

$= i(\omega)R_f/(1 + j\omega\tau_f) \qquad \tau_f = R_fC_f$

step replaced by decay with ~ $\exp(-t/R_fC_f)$ τ is long because R_f is large (noise)

easiest way to limit pulse pileup - differentiate

ie add high pass filter



- Pole-zero cancellation

exponential decay + differentiation => unwanted baseline undershoot

introduce canceling network

$v_0 = 1/(1 + j\omega\tau_f)$

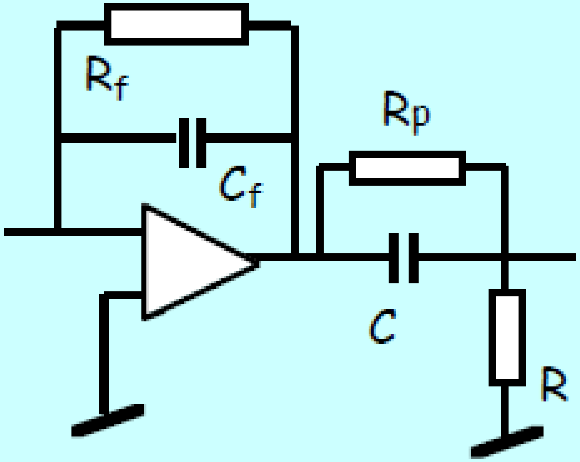
$v_1 = 1/(1 + j\omega\tau_f)(1 + j\omega\tau_1)$

$\tau_1 = RC < \tau_f$

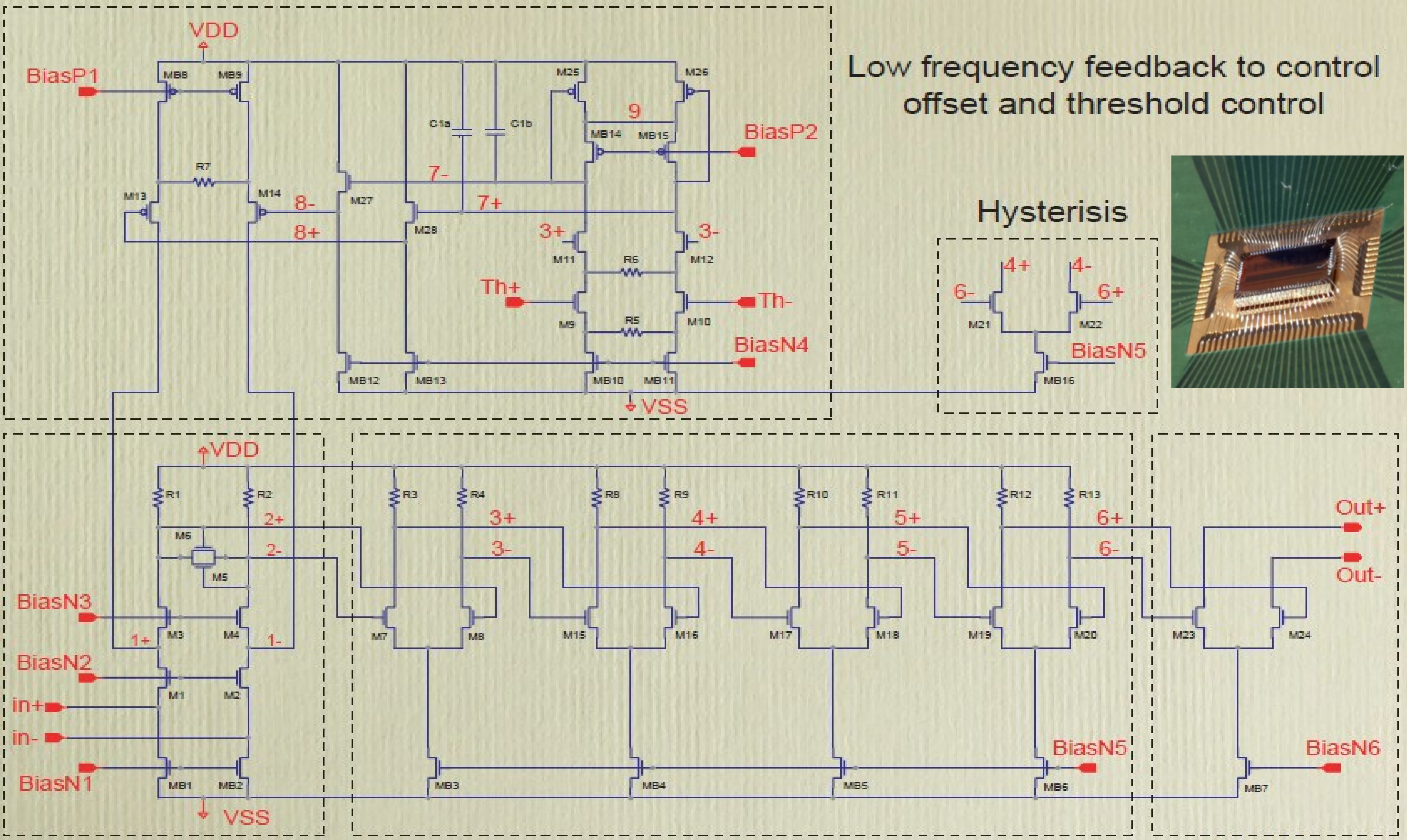
add resistor R_p so $R_pC = \tau_f$

then

$v_1' = 1/(1 + j\omega\tau_3)$ with $\tau_3 = (R||R_p)C < \tau_f$



Typical modern amplifier ASIC



Low frequency feedback to control offset and threshold control

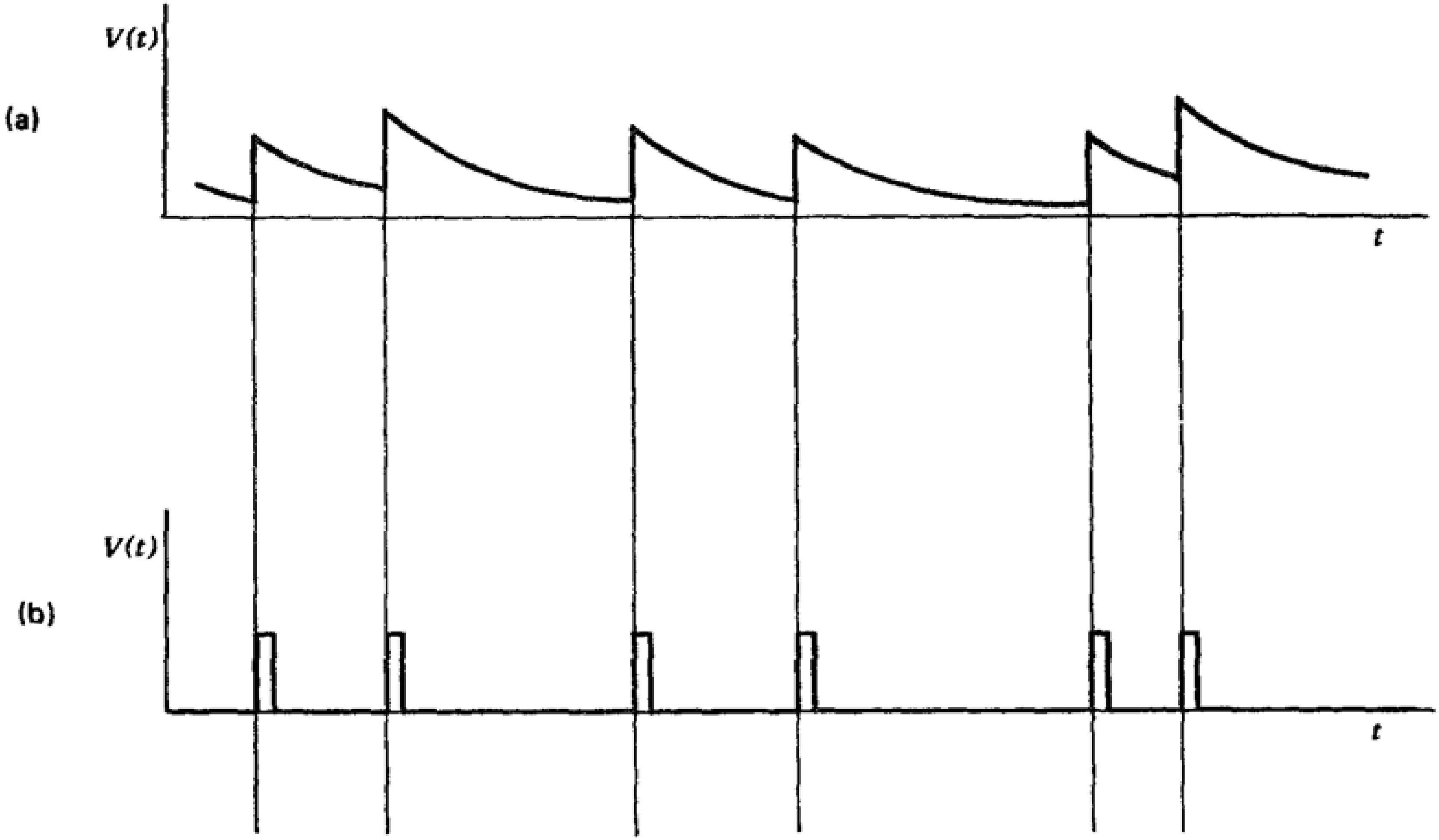
Hysterisis

Input stage

4 stage high-bandwidth amplifier

LVDS
output driver

Need for pulse shaping



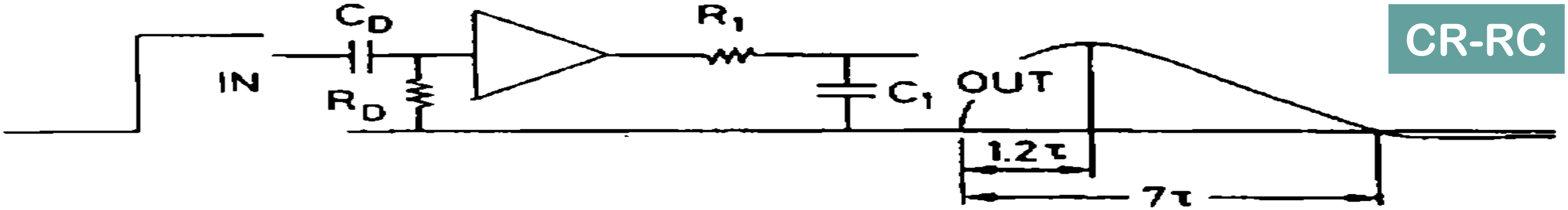
The pulses with long tails shown in part (*a*) illustrate the apparent variation in amplitude due to pulse pile-up. These effects can greatly be reduced by shaping the pulses as in part (*b*).

Pulse shaping

- Amplifiers must preserve the information of interest
  - If timing is required: fast response
  - If pulse height is required: strict proportionality, limit bandwidth
- Preamplifier pulse
  - Exponential with long tail
  - Pulse pileup: Reduce counting rate or reshape
- Optimization of signal-to-noise ratio
  - For a given noise spectrum, there exists an optimum pulse shape to improve the signal-to-noise ratio
  - For ex: Tail pulses in presence of typical noise spectra are not ideal
  - Triangular or Gaussian – symmetric pulse shapes are ideal
- Fast amplifiers: No or very little shaping
- What to do in case you need good timing and pulse height information?

CR-RC pulse shapers

CR-RC



$$\tau = R_D C_D = R_1 C_1$$

Pole-Zero Cancellation

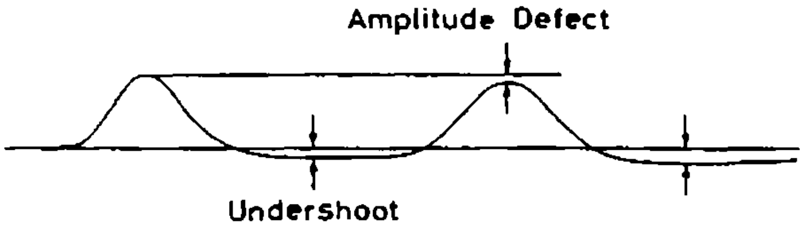


Fig. 14.6. Amplitude defect arising from undershoot in CR-RC pulse shaping

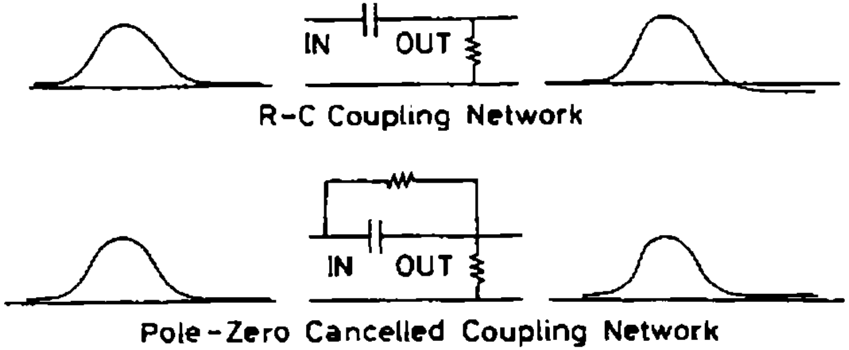
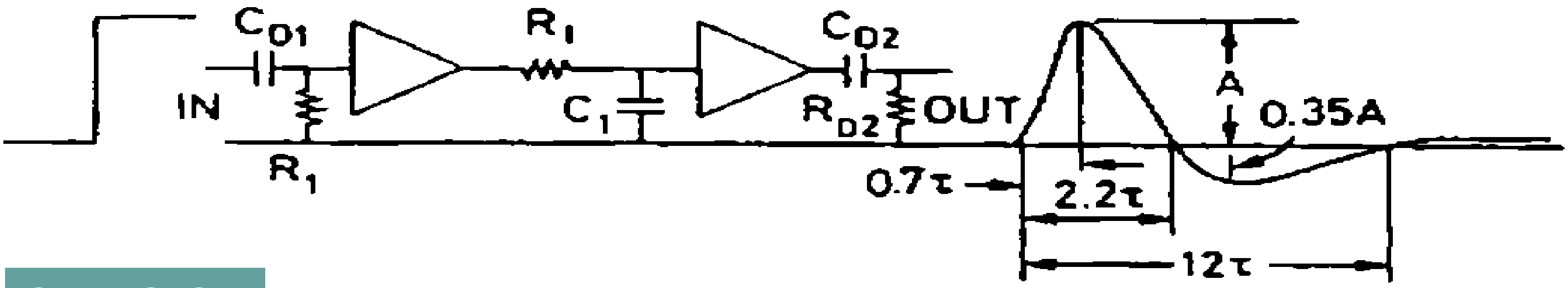


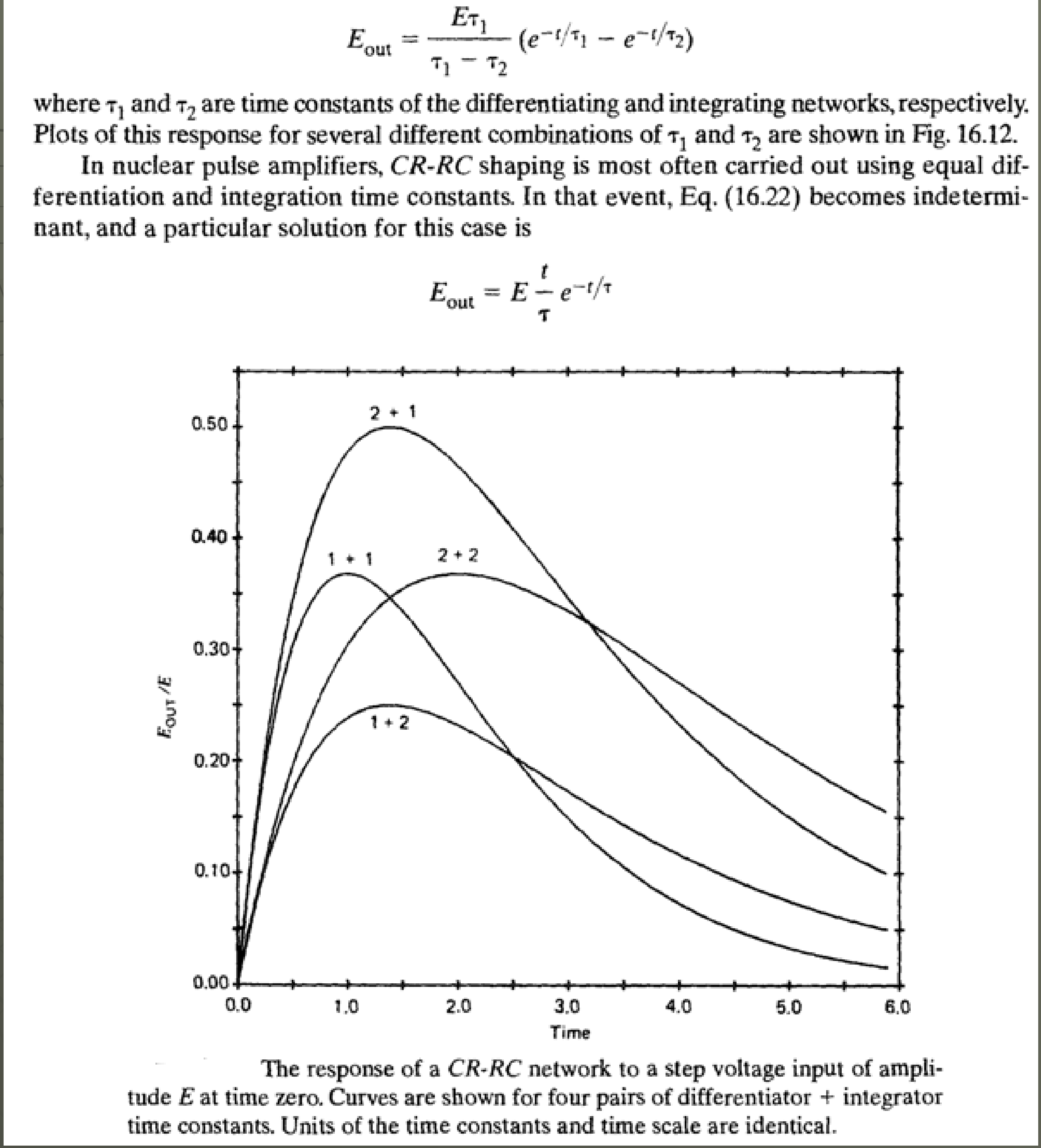
Fig. 14.7. Pole-zero cancellation circuit (from *Ortec* catalog [14.1])



CR-RC-CR

$$\tau = R_{D1} C_{D1} = R_1 C_1 = R_{D2} C_{D2}$$

Response of CR-RC shaper



$$E_{\text{out}} = \frac{E\tau_1}{\tau_1 - \tau_2}\left(e^{-t/\tau_1} - e^{-t/\tau_2}\right)$$

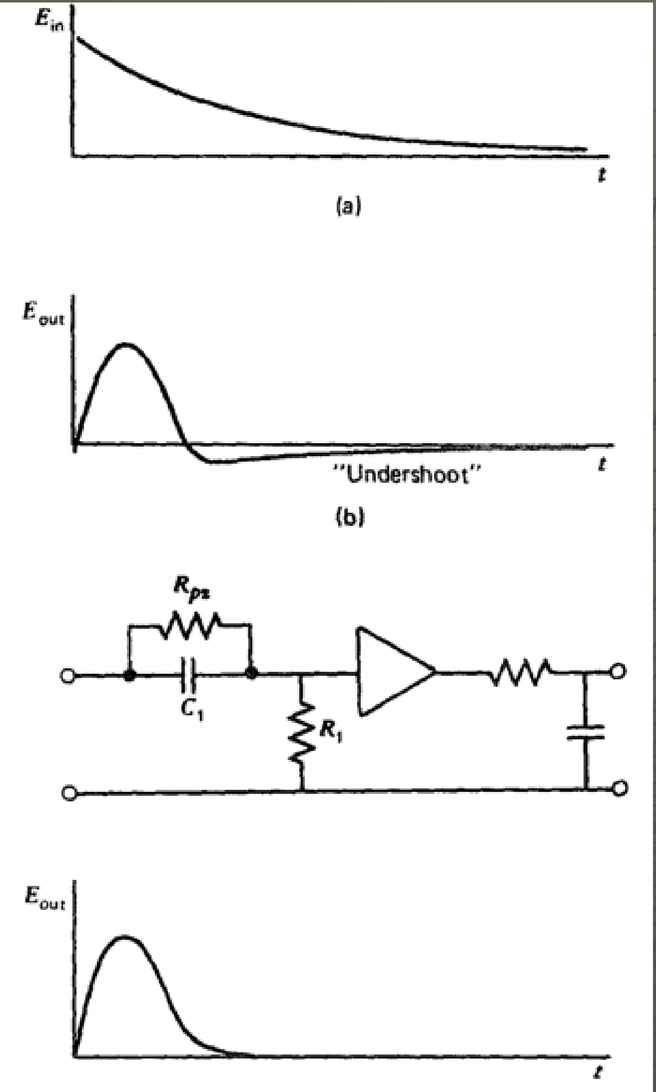
where τ_1 and τ_2 are time constants of the differentiating and integrating networks, respectively. Plots of this response for several different combinations of τ_1 and τ_2 are shown in Fig. 16.12.

In nuclear pulse amplifiers, *CR-RC* shaping is most often carried out using equal differentiation and integration time constants. In that event, Eq. (16.22) becomes indeterminant, and a particular solution for this case is

$$E_{\text{out}} = E\,\frac{t}{\tau}\,e^{-t/\tau}$$

The response of a *CR-RC* network to a step voltage input of amplitude *E* at time zero. Curves are shown for four pairs of differentiator + integrator time constants. Units of the time constants and time scale are identical.

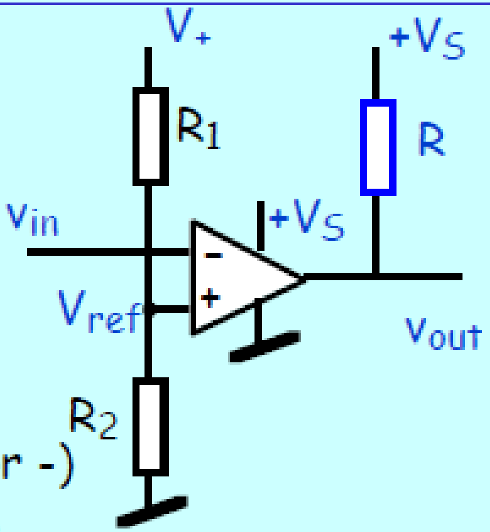
Pole-zero cancellation



- Poles and Zeros of a transfer function are the frequencies for which the value of the denominator and numerator of transfer function becomes zero respectively.
- The values of the poles and the zeros of a system determine whether the system is stable, and how well the system performs.
- Physically realizable control systems must have a number of poles greater than or equal to the number of zeros.

Application of pole-zero cancellation to eliminate the undershoot (*b*) normally generated by a *CR-RC* shaping network for an input step with finite decay time. By adding an appropriate resistance R_{pz} to the differentiator stage, a waveform without undershoot (*c*) can be obtained.

Comparators/Discriminators



- Frequently need to compare a signal with a reference
  - eg temperature control, light detection, DVM,...
  - basis of analogue to digital conversion -> 1 bit
- Comparator
  - high gain differential amplifier,
    - difference between inputs sends output to saturation (+ or -)
  - could be op-amp - without feedback - or purpose designed IC
  - Sometimes ICs designed with open-collector output so add pull-up R to supply
    - also available with latch (memory) function
- NB
  - no negative feedback so $v_- \neq v_+$
  - saturation voltages may not reach supply voltages - check specs
  - speed of transition
- Potential problem
  - multiple transitions as signal changes near threshold

Hysteresis

- Add positive feedback (Schmitt trigger)

  V_{ref} changes as $v_{out} \rightarrow +V_S$

  ie threshold falls once transition is made

  preventing immediate fall

  positive feedback speeds transition

  $v_{out} = A(V_{ref} - v_{-})$

  $V_{ref} > v_{-} \Rightarrow v_{out} = V_s \quad V_{ref} = V_{high}$

  $V_{ref} < v_{-} \Rightarrow v_{out} = 0V \quad V_{ref} = V_{low}$

  here, signal => logical "1": $v_{out} = 0V$

- Output depends on history

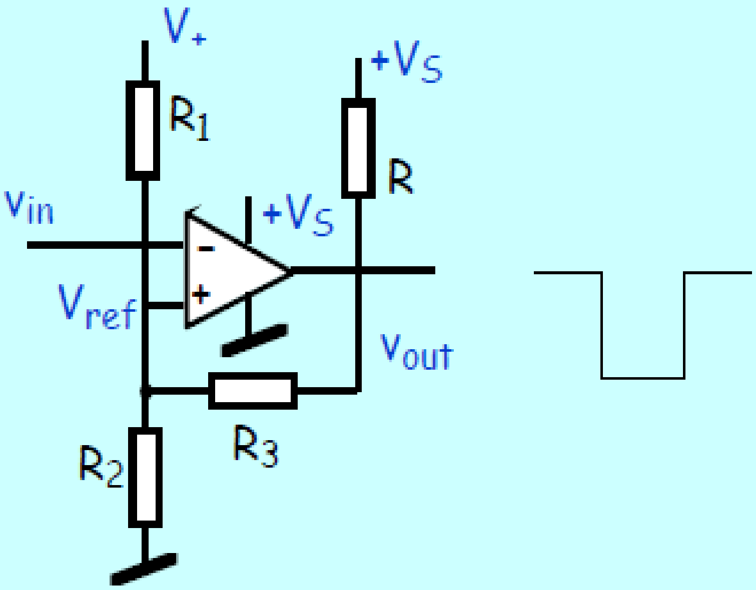
  eg $V_{+} = 10V$, $V_S = +5V, 0V$

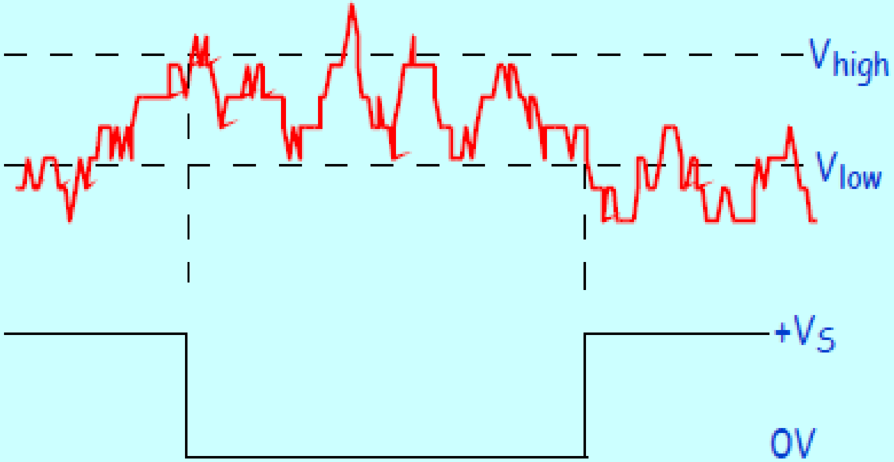
  $R_1 = 10k\Omega$, $R_2 = 10k\Omega$, $R_3 = 100k\Omega$

  $V_{out} = 0V$, $V_{ref} = 4.76V$

  $V_{out} = 5V$, $V_{ref} = 5V$

  hysteresis = $\Delta V_{ref} = 0.24V$



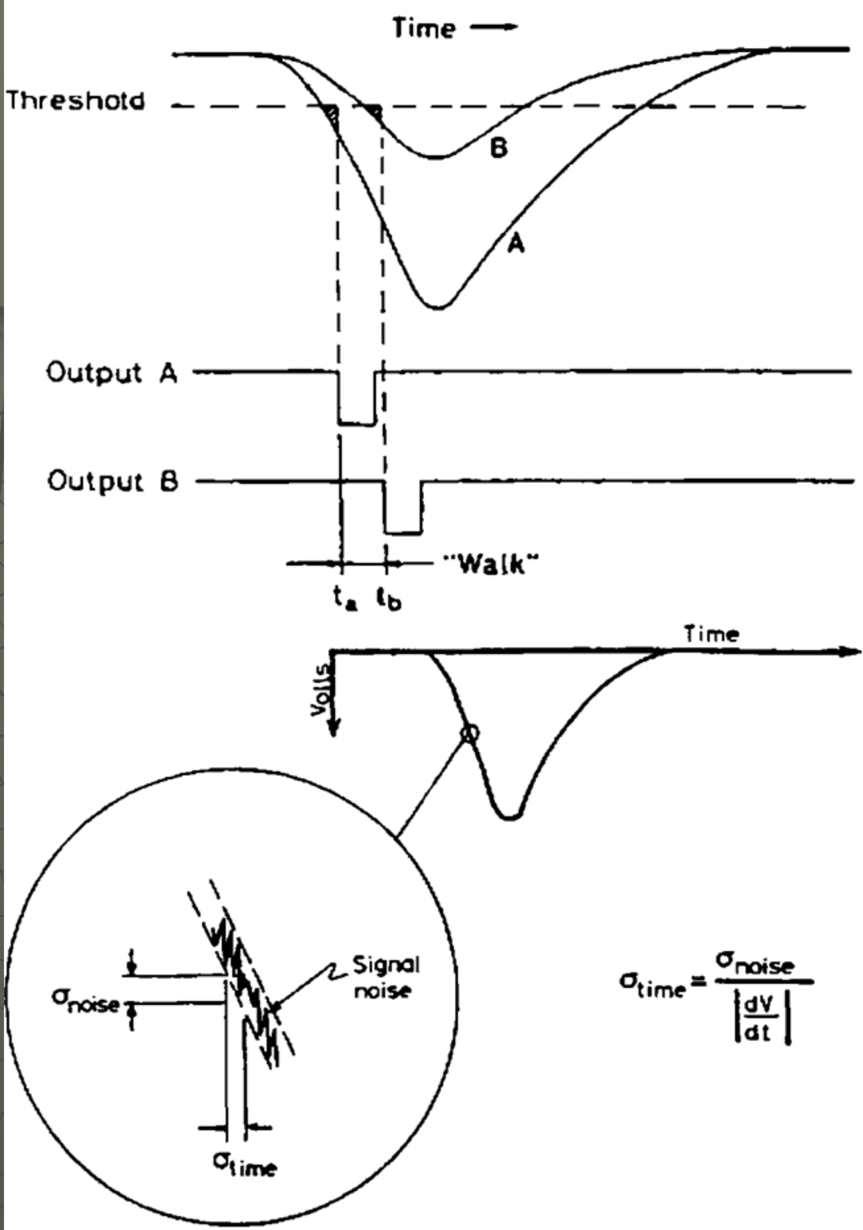


Considerations for discriminators

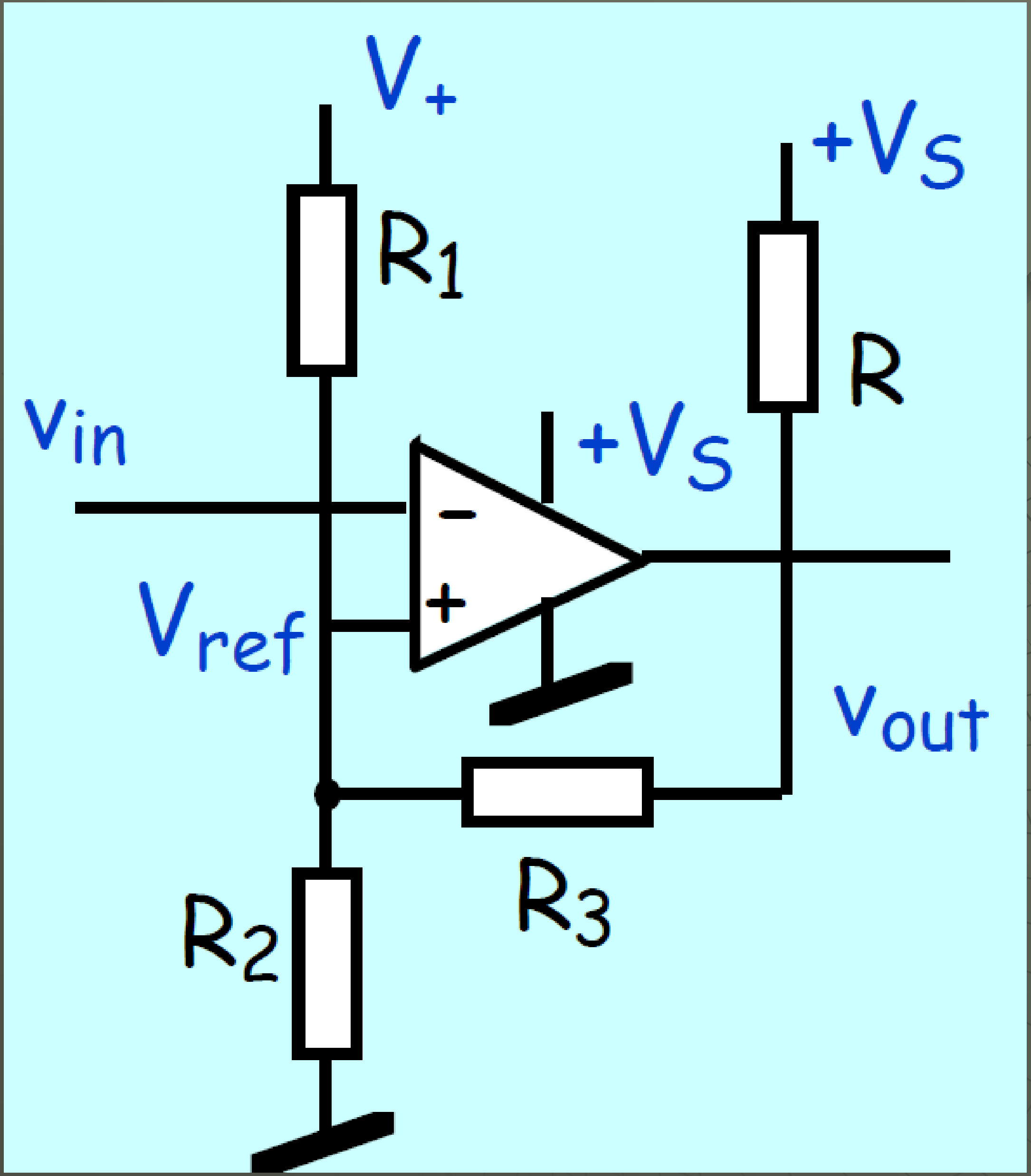
- Two common problems
  - Walk
  - Jitter
- Time-Pickoff methods
  - Leading edge triggering
  - Fast zero-crossing triggering
  - Constant fraction triggering
  - Amplitude and risetime compensated triggering

Two common problems

- Walk (due to variations in the amplitude and rise time, finite amount of charge required to trigger the discriminator)
- Jitter (due to intrinsic detection process – variations in the number of charges generated, their transit times and multiplication factor etc.)

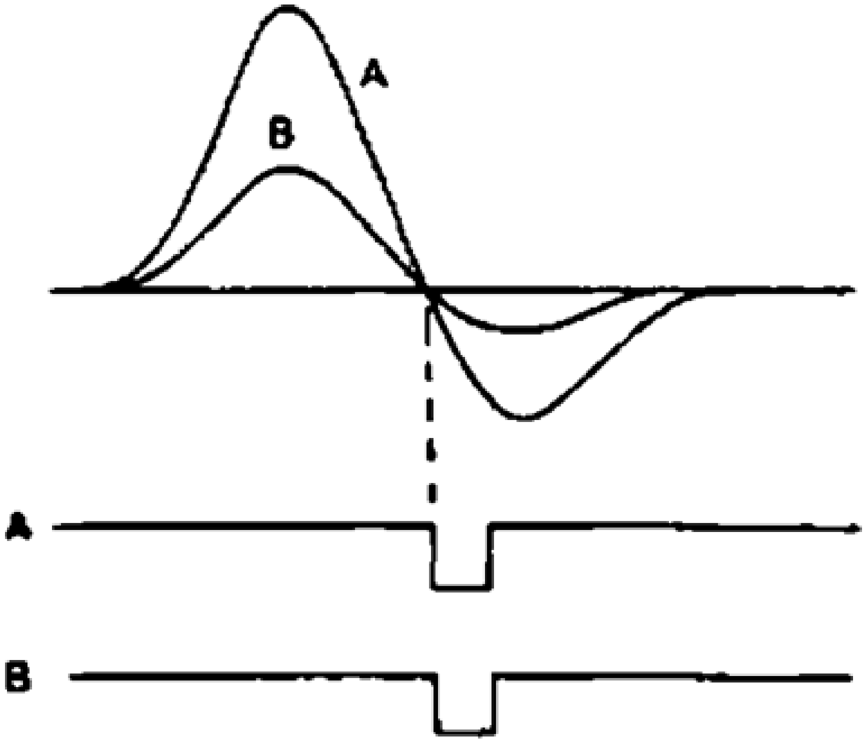


Leading edge discriminators

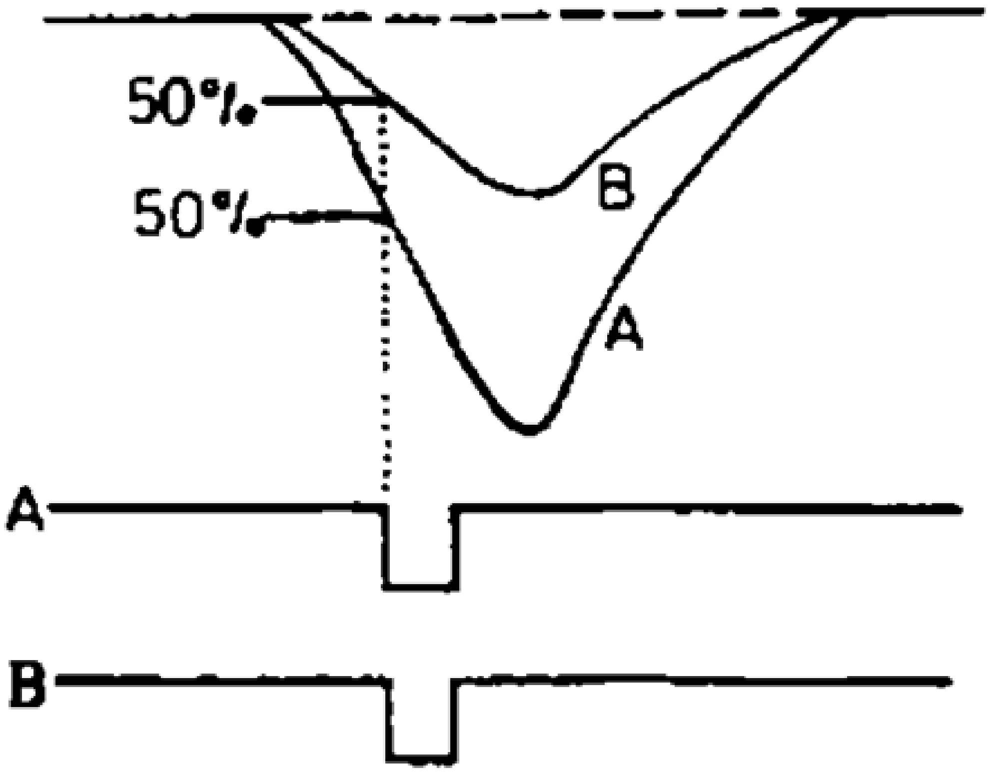


- Fine with if input amplitudes restricted to small range.
- For example:
  - With 1 to 1.2 range, resolution is about 400ps.
  - But at 1 to 10 range, the walk effect increases to ±10ns.
- That will need off-line corrections for time-walk using charge or time-over-threshold (TOT) measurements.

Zero-crossing and Constant fraction



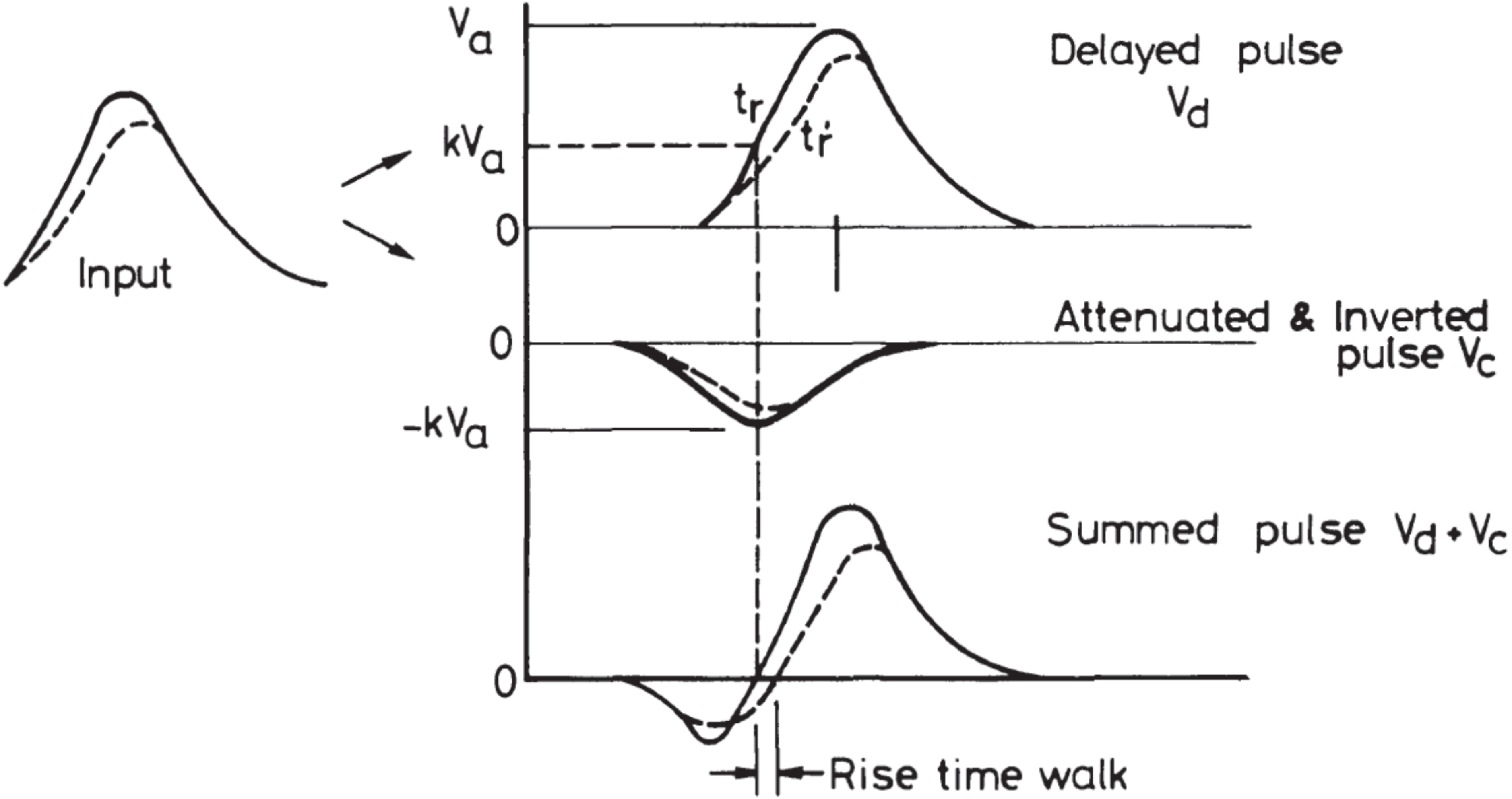
Zero-crossing timing. Variations in the cross-over point are known as *zero-crossing walk*



Constant fraction discrimination

In case of Zero-crossing triggering, timing resolution improves to 400ps, if amplitude range is 1 to 1.2 and to 600ps, even if the amplitude range is 1 to 10.

Constant fraction triggering



Unlike the zero cross-over technique, the CFT method does not require a bipolar pulse at the input. The efficiency of this technique is, nevertheless, very high yielding walk as little as ±20ps over an amplitude range of 100 to 1.

Analogue to Digital Conversion

- Converts electrical input (voltage/charge) into numeric value
- Parameters and requirements
  - Resolution
    - the granularity of the digital values
  - Integral Non-Linearity
    - proportionality of output to input
  - Differential Non-Linearity
    - uniformity of digitisation increments
  - Conversion time
    - how much time to convert signal to digital value
  - Count-rate performance
    - how quickly a new conversion can begin after a previous event
  - Stability
    - how much values change with time

Analog-to-Digital Converters (ADCs)

- Peak-sensing
  - Maximum of the voltage signal is digitised
  - Ex: Signal of the PMT in voltage mode (slow signals, already integrated)
- Charge sensitive
  - Total integrated current digitised
  - Ex: Signal of the PMT in the current mode (fast signals)
- Time of integration or the time period over which the ADC seeks a maximum is determined by the width of the gate signal

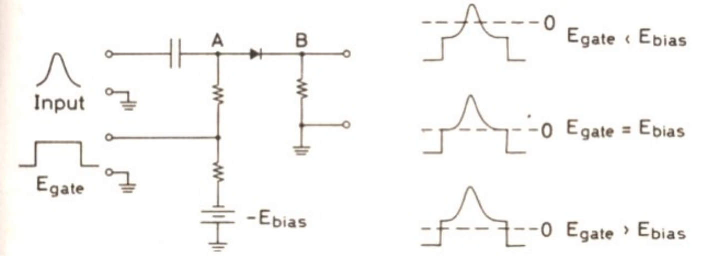
Types of ADCs

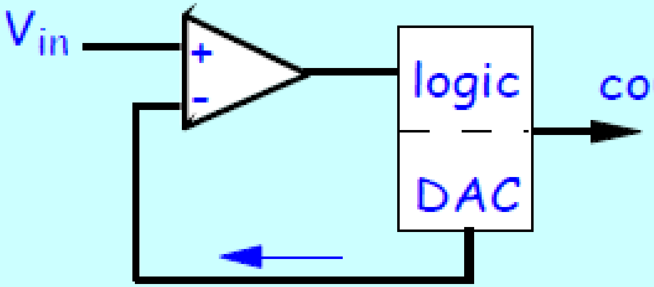
- Successive approximation
- Ramp or Wilkinson
- Sigma-delta ADC
- Flash or parallel
- Hybrid (Wilkinson + successive approximation)
- Tracking ADC
- Parallel ripple ADC
- Variable threshold flash ADC
- …

Successive approximation ADC

- analogous to binary search

```
generate $V_{ref} = \Delta V \times (2^{N-1}, 2^{N-2}, \dots 2^0)$ in N steps
set bit = 1
if $V_{in} > V_{ref}$
    leave
else bit = 0
```



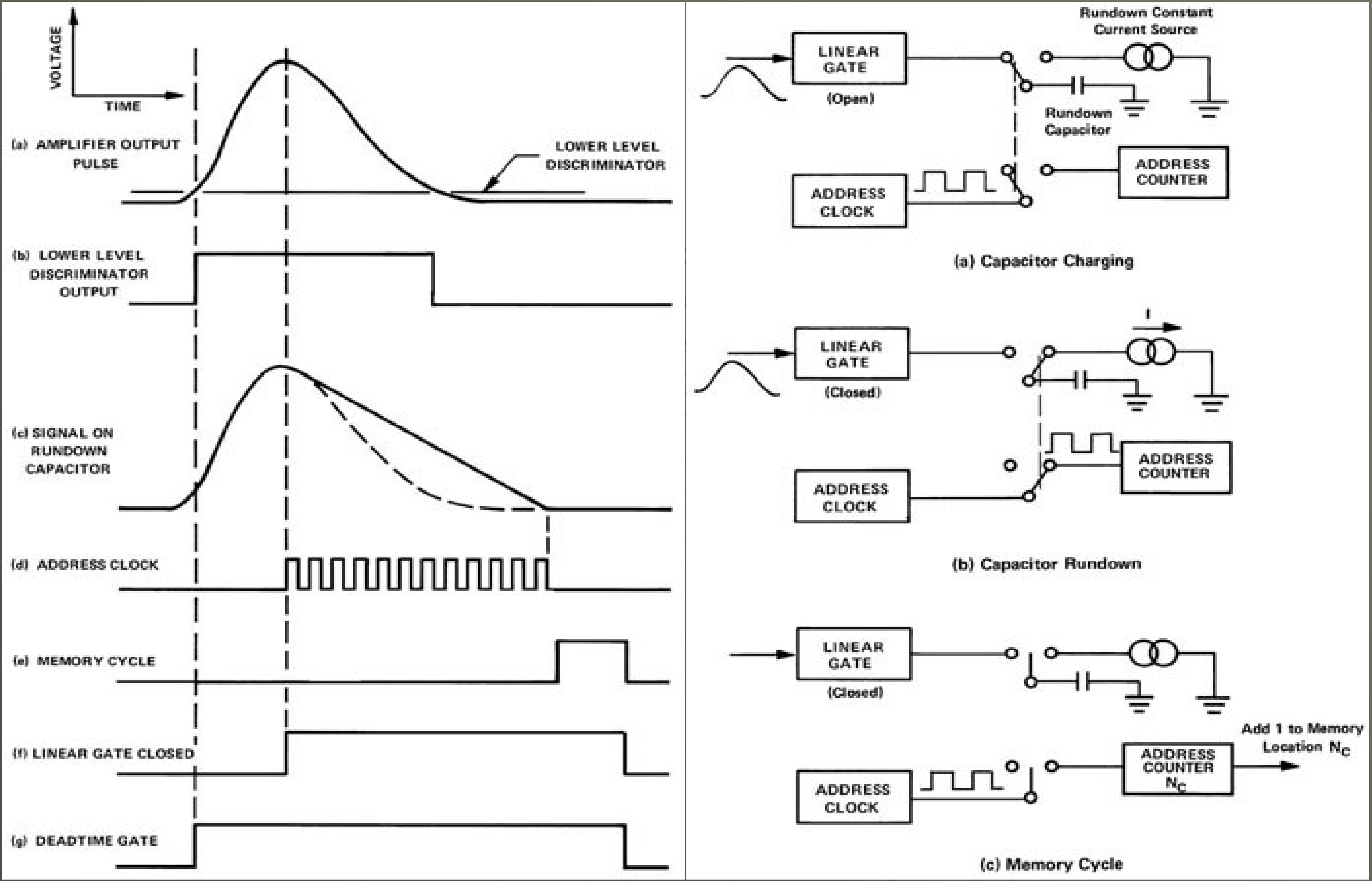


DAC = digital to analogue converter

ie number -> voltage

- Pros
  - speed ~ μsec
  - high resolution
- Cons
  - DNL 10-20%
    - *very precise resistors required with DAC for V_{ref}*

Ramp or Wilkinson ADC



(a) Capacitor Charging

(b) Capacitor Rundown

(c) Memory Cycle

Sigma-delta ADC

- Digitise the signal with 1-bit resolution at a high sampling rate (MHz).

  useful for high resolution conversion of low-frequency signals, to 20bits

  low-distortion conversion of audio signals

  good linearity and high accuracy.

- Operation - At t = 0, assume V_{ref} = 0

  V_{out} high

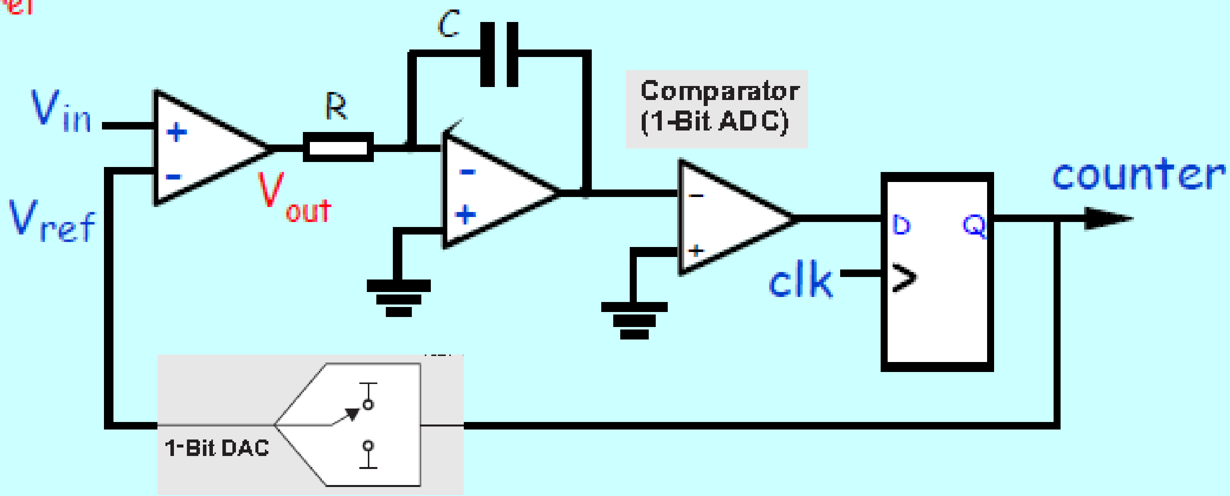
  integrator charges -ve

  at rate ~ V_{in}

  comparator flips

  counter goes low

  clock increments... etc,...



V_{in} = 0 => output = 000000...

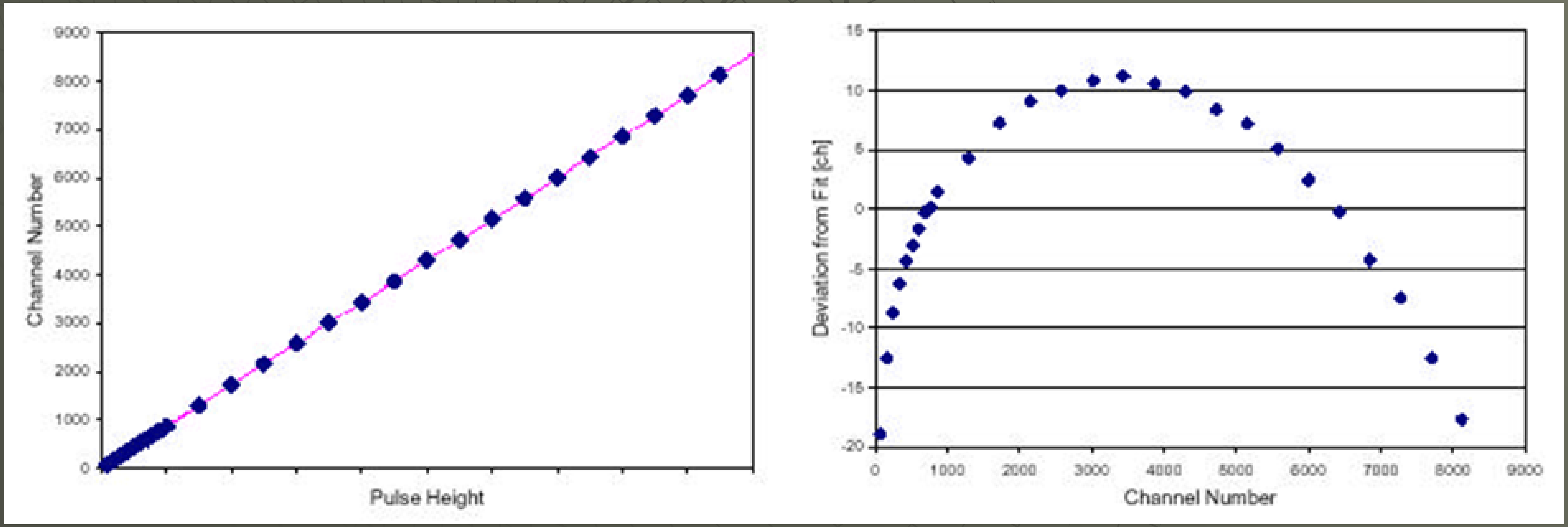
V_{in} = (1/2)V_{in}(max) => output = 101010...

V_{in} = V_{in}(max) => output = 111111...

the higher the input voltage, the more 1's at the serial digital output.

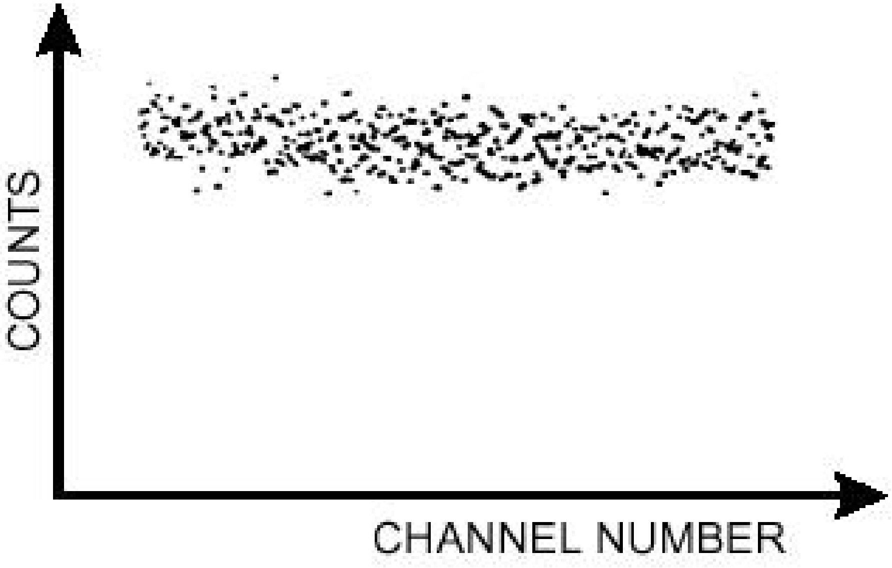
Integral non-linearity

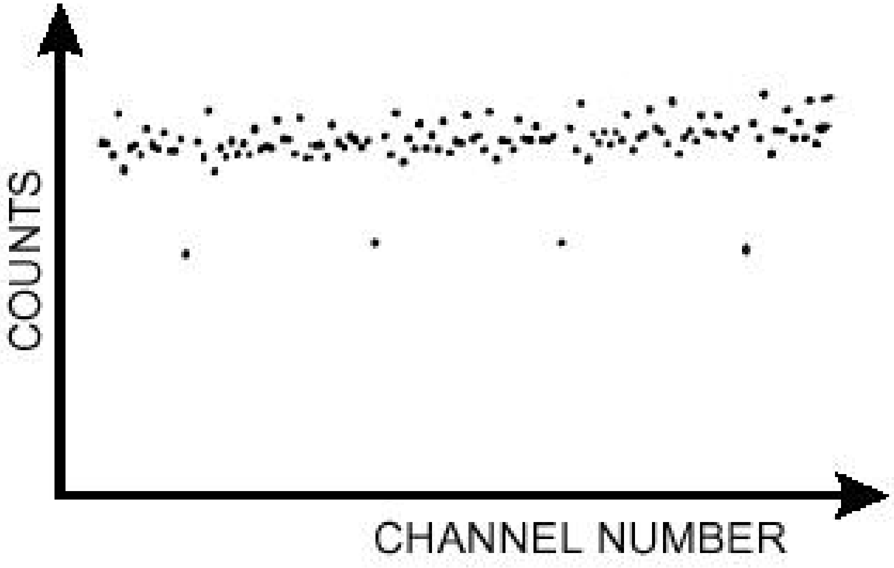
- Output value (D) should be linearly proportional to input voltage (V).
- Check with plot
- For more precise evaluation of INL fit the data to a straight line and plot only deviations.
- That is, plot D_i-D_{fit} vs nchan



Differential non-linearity

- Measures non-uniformity in channel profiles over range
    - $DNL = DV_i/\langle DV\rangle - 1$
    - DV_i = width of channel i
    - $\langle DV\rangle$ = average width
- RMS or worst case values may be quoted
    - DNL ~ 1% typical but 10^{-3} can be achieved
    - can show up systematic effects, as well as random





Resolution

- To convert an analogue value, eg voltage, to digital two parameters are required

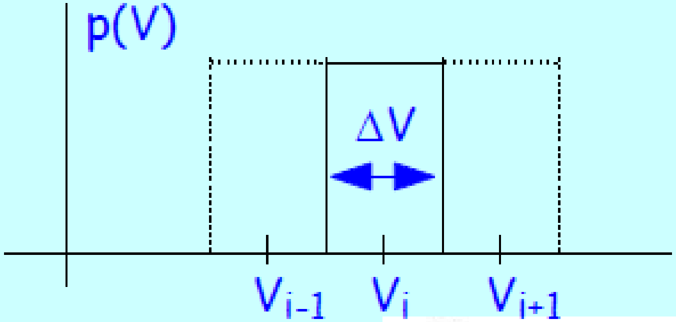
  range and number of bits

  quantum = $\Delta V = (V_{max} - V_{min}) * 2^{-N}$ referred to as 1LSB (least significant bit)

- eg 10 bits = $2^{10} = 1024$, $V_{max} - V_{min} = 1V$ => $\Delta V = 1V/1024 \approx 1mV$

- Ideal ADC behaviour

  probability vs amplitude

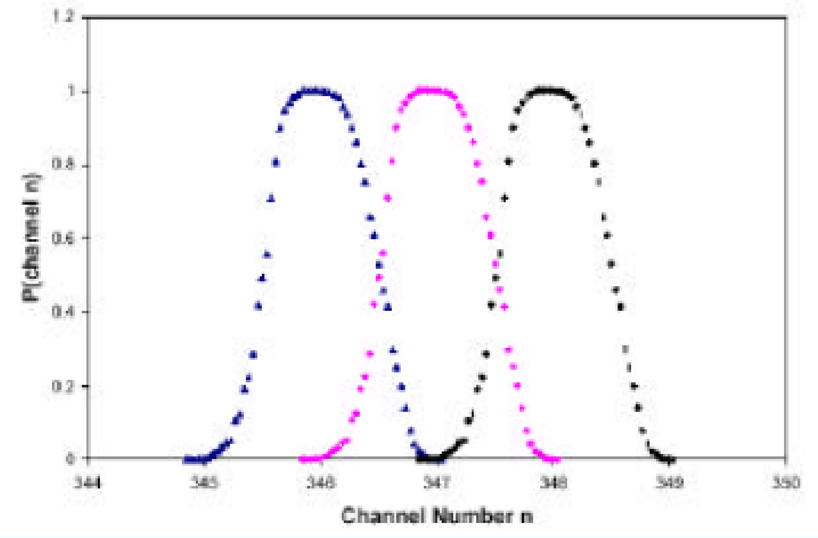


- Real ADC behaviour

  noise in digitisation process

  smears resolution

  $\sigma_{noise} < \Delta V/4$

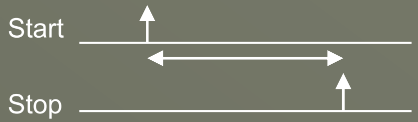


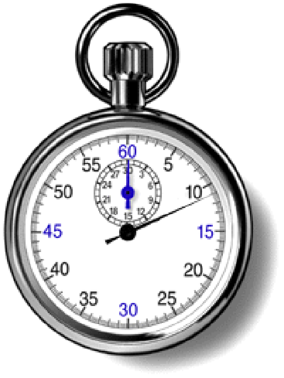
Other variables

- Conversion time
  - finite time is required for conversion and storage of values
  - may depend on signal amplitude
  - gives rise to dead time in system
  - i.e. system cannot handle another event during dead time
  - may need accounting for, or risk bias in results
- Rate effects
  - results may depend on rate of arrival of signals
  - typically lead to spectral broadening
- Stability
  - temperature effects are a typical cause of variations
- A partial solution to most of these problems is regular calibration, preferably under real operating conditions, as well as control of variables

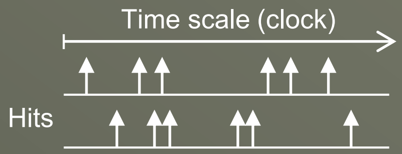
Time-to-Digital Converters

- **TDCs are used to measure time or intervals**
- **Start – Stop measurement**
  - Measurement of time interval between two events:
  - Start signal – Stop signal
  - Used to measure relatively short time intervals with high precision
  - Like a stop watch used to measure sport competitions



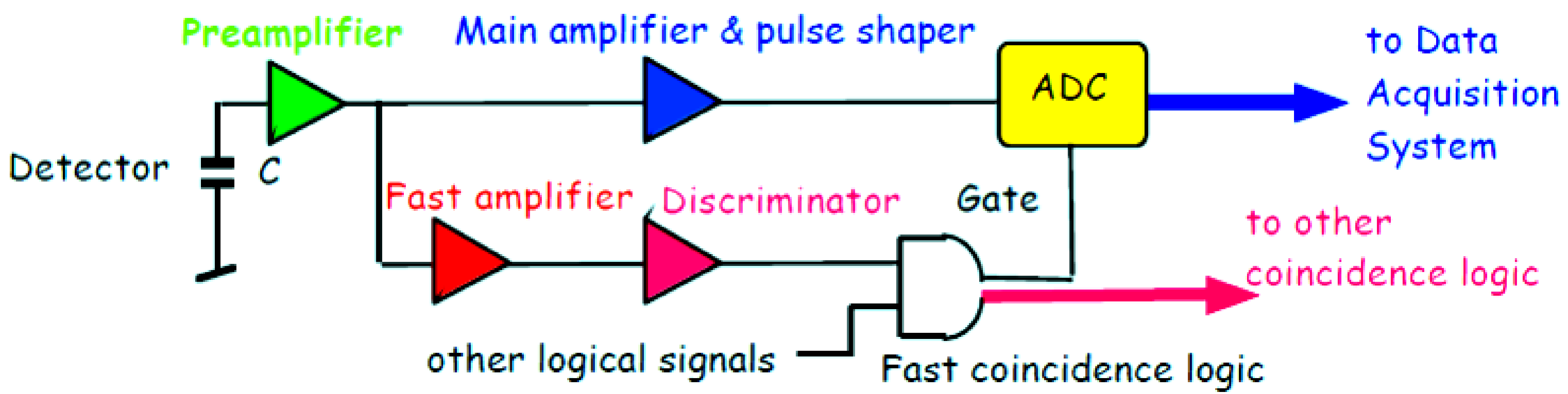


- **Time tagging**
  - Measure time of occurrence of events with a given time reference
  - Time reference (Clock)
  - Events to be measured (Hits)
  - Used to measure relative occurrence of many events on a defined time scale
  - Such a time scale will have limited range; like 12/24 hour time scale on your watch



Amplifier systems for spectroscopy

- Typical application - precise measurements of x-ray or gamma-ray energies

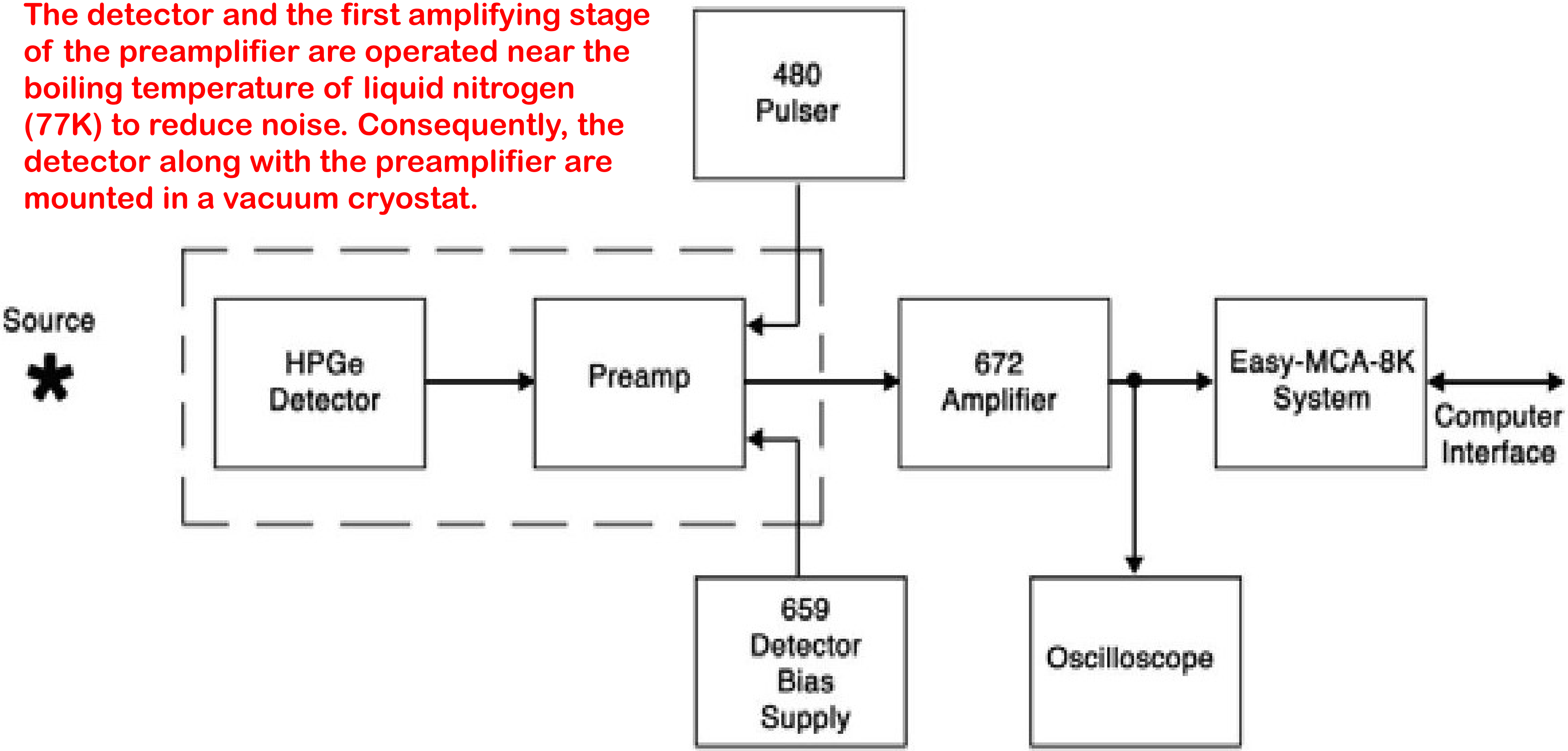


- Pre-amplifier - first stage of amplification
- Main amplifier - adds gain and provides bandwidth limiting
  - ADC - analog to digital conversion - signal amplitude to binary number
- Fast amplifier and logic
  - Start ADC ("gate") and flag interesting "events" to DAQ system
  - Most signals arrive randomly in time.
  - Other logic required to maximise chance of "good" event, ex. second detector

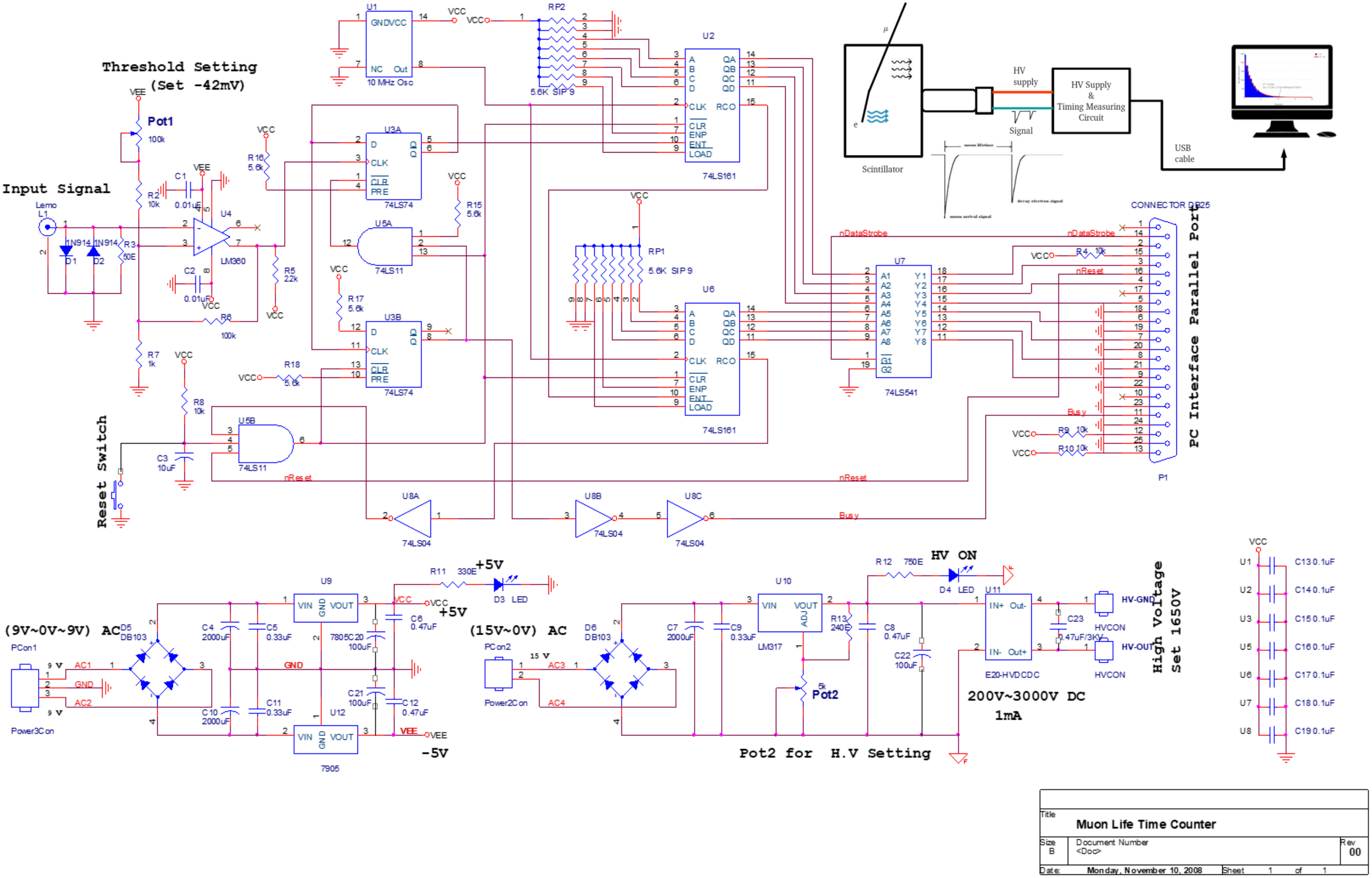
Amplifier systems for spectroscopy

- Typical application - precise measurements of x-ray or gamma-ray energies

The detector and the first amplifying stage of the preamplifier are operated near the boiling temperature of liquid nitrogen (77K) to reduce noise. Consequently, the detector along with the preamplifier are mounted in a vacuum cryostat.

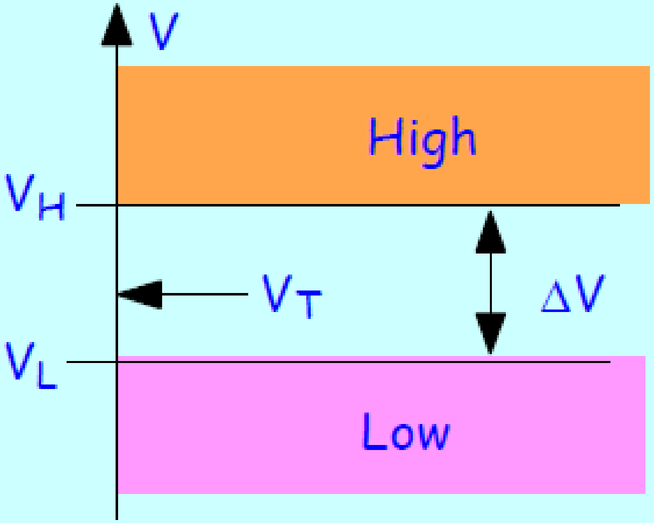


A simple circuit for a useful experiment



Basic digital logic

- bits can be represented in several ways, almost invariably voltage
  - 0/1: Low/High (voltage level) ... or High/Low
    - values and range depend on families, most common are...
- TTL (bipolar) Transistor-Transistor Logic
  - usually V_S = 0 to +5V
  - $V_T \sim 1.5V$ $\Delta V \sim 1V$
  - outputs & inputs sink/source currents
    - *not identical levels*
- CMOS - now most common
  - V_S = 0 to +5V but +12V, +3.5V and lower
  - $V_T \sim V_S/2$ $\Delta V \sim 0.4\ V_S$
  - outputs swing between supplies
- ECL Emitter Coupled Logic
  - high speed, but power hungry



designs must tolerate variations

- component manufacture
- operating temperature
- supply voltage
- loading
- noise

Integrated Circuits and VLSI

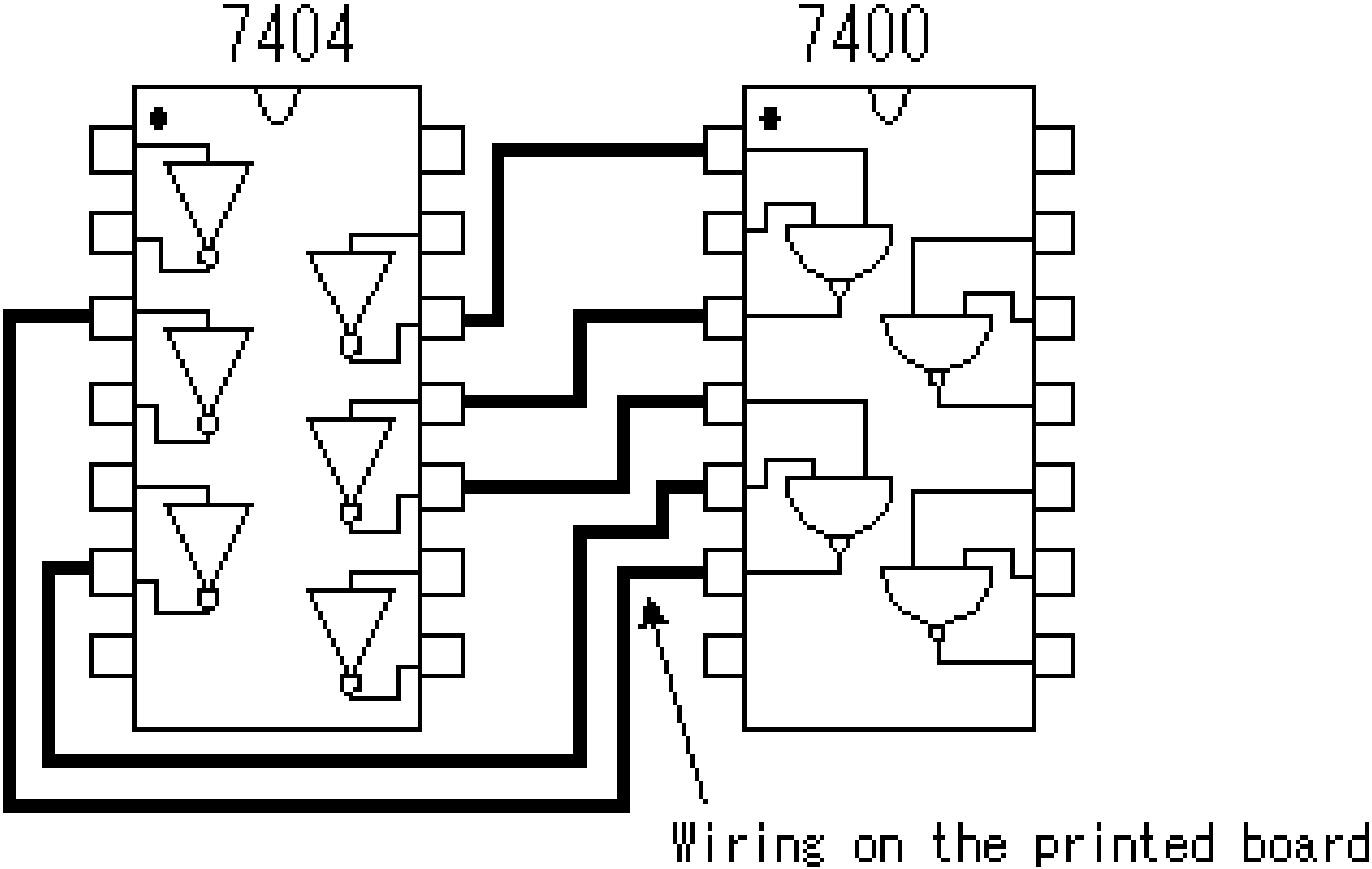
- Integrated Circuits contain many transistors fabricated on a single chip.
- They are classified as
  - <100: SSI (1963)
  - 100-3000: MSI (1970)
  - 3000-30000: LSI (1975)
  - 30000-1000000: VLSI (1980)
  - >1000000: ULSI (1990)

GSI

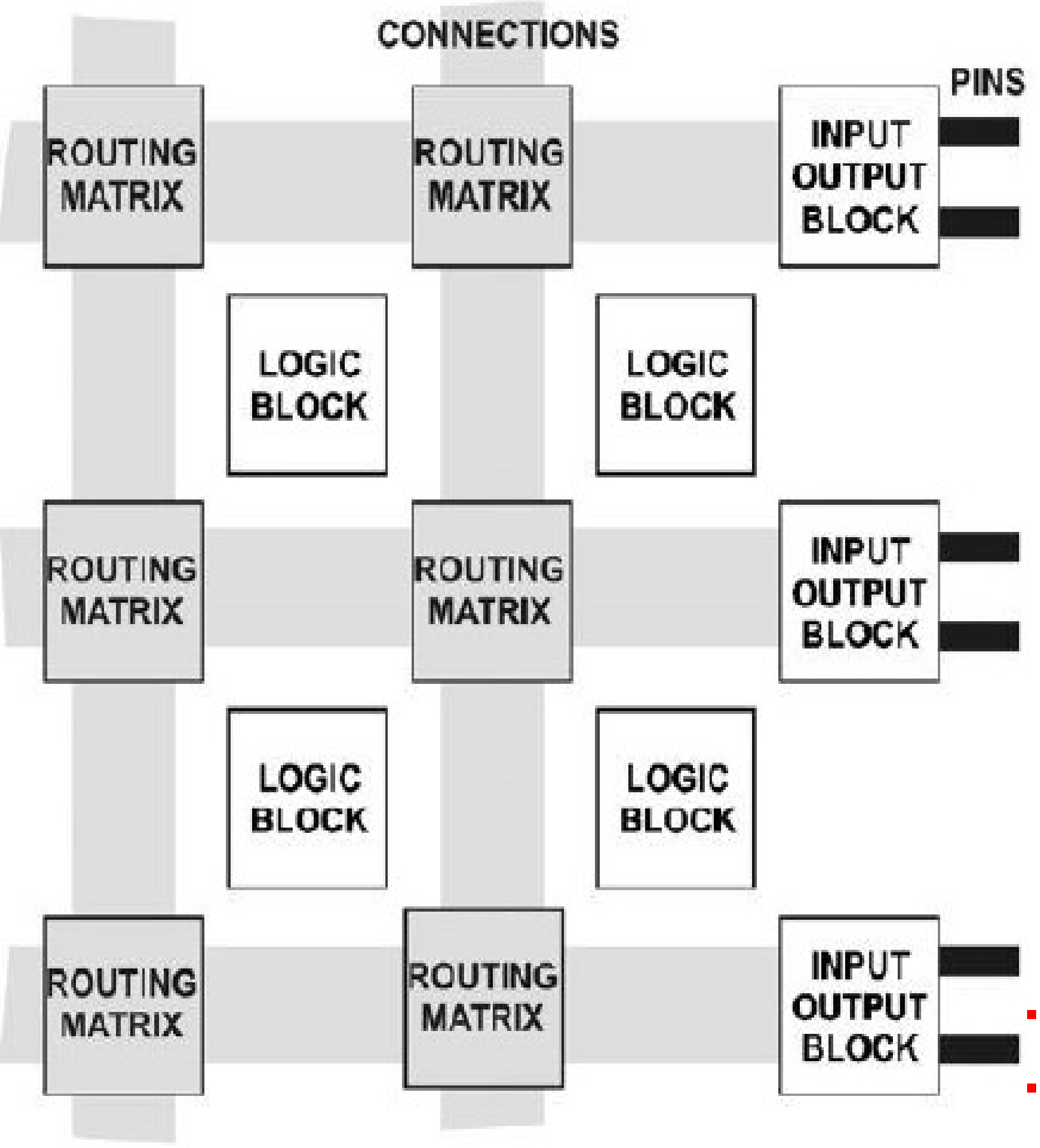
(Billion transistors)

- A VLSI (Very Large Scale Integration) system integrates millions of “electronic components” in a small area (few mm^2 to few cm^2).
- Objectives: design “efficient” VLSI systems that has:
  - Circuit speed (high)
  - Power consumption (low)
  - Design area (low)

‘Old way’ of building circuits using ICs



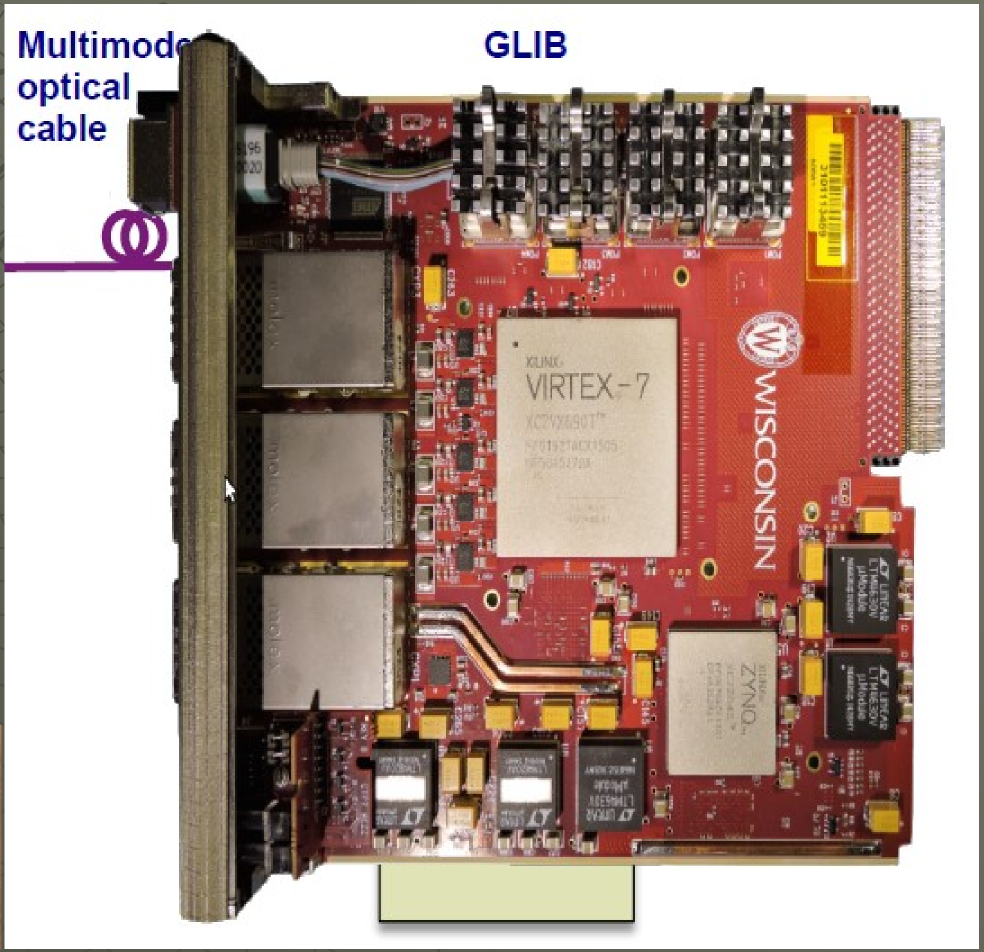
Field Programmable Gate Array (FPGA)



- Logic function implemented as look up table LUT).
- LUT may be alternately configured as RAM or shift register

Computation and communication

- Artificial Intelligence on FPGAs: A breakthrough for data acquisition in HEP experiments
- Class separation and parameter estimation
- Energy reconstruction
- Particle identification
- Particle tracking
- Event selection
- Customised hardware
  - High-end FPGAs
  - GPUs and architectures
  - TPU ASICs

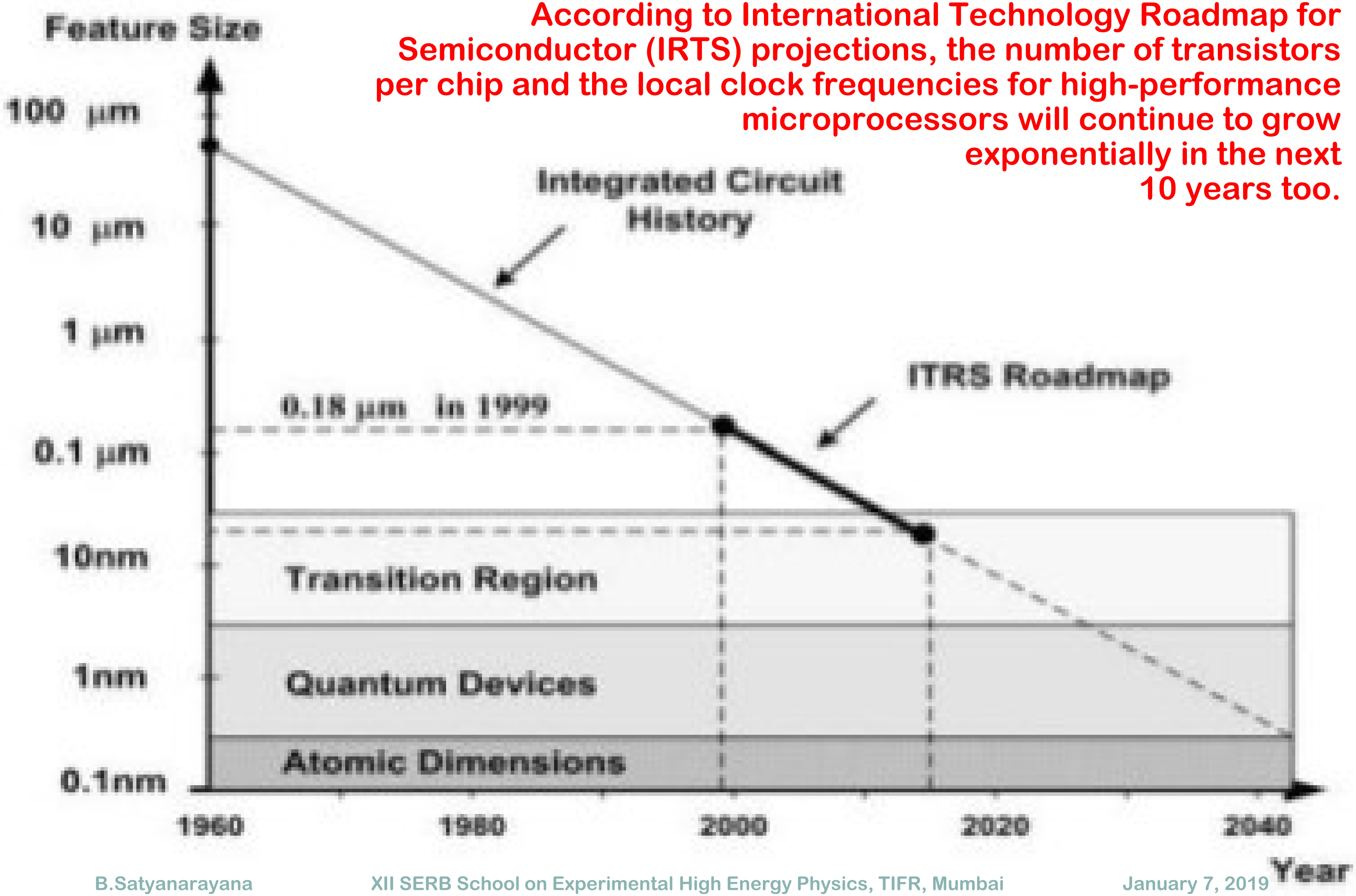


FPGA versus ASIC

Parameter	FPGA	ASIC
Circuit Design	User programmable	Fully custom
Design Flexibility	Reconfigurable	Rigid
Logic Density	Lower	Higher
Complexity	Limited	High
Speed	Lower	Higher
Power Consumption	Higher	Lower
Area	Large	Small
Development Cycle	Simpler and faster	Complicated and time-consuming
Development Cost	Lower	Extremely high
Production Cost	Effective for small-scale applications	Cheaper for large-volume designs

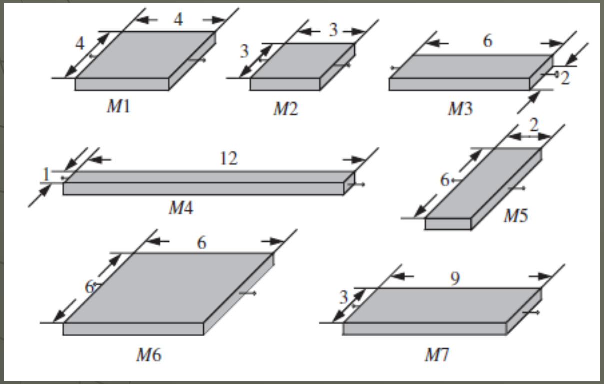
Trends in feature size

According to International Technology Roadmap for Semiconductor (IRTS) projections, the number of transistors per chip and the local clock frequencies for high-performance microprocessors will continue to grow exponentially in the next 10 years too.

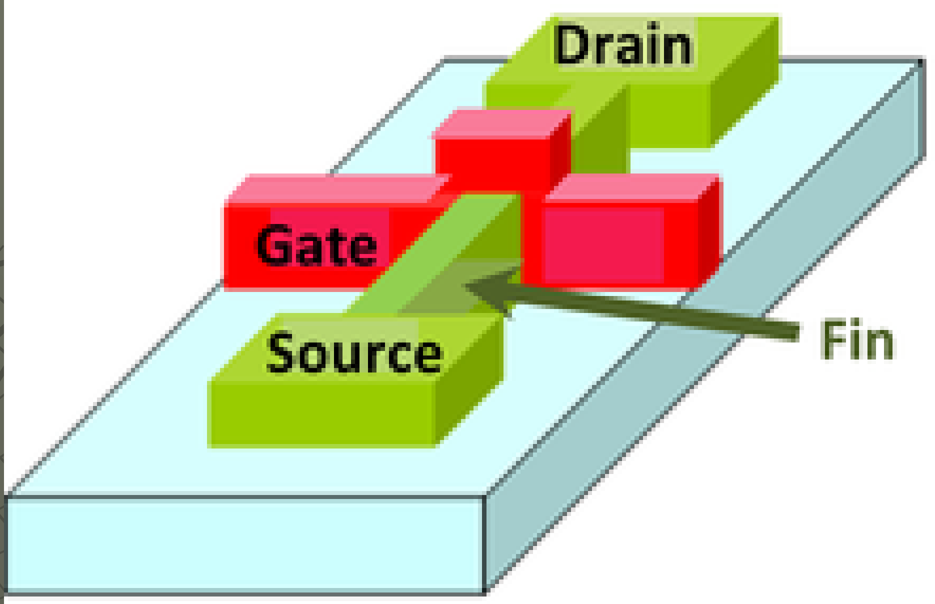


Challenges of technology scaling

- Advances in optical lithography have allowed manufacturing of on-chip structures with increasingly higher resolution.
- The area, power, and speed characteristics of transistors with a planar structure, such as MOS devices, improve with the decrease (i.e. scaling) in the lateral dimensions of the devices. Therefore, these technologies are referred as scalable.
- Generally, scalable technology has three main goals:
  - Reduce gate delay by 30%, resulting in an increase in operating frequency of about 43%.
  - Double transistor density and
  - Reduce energy per transition by about 65%, saving 50% of power, at a 43% increase in frequency.

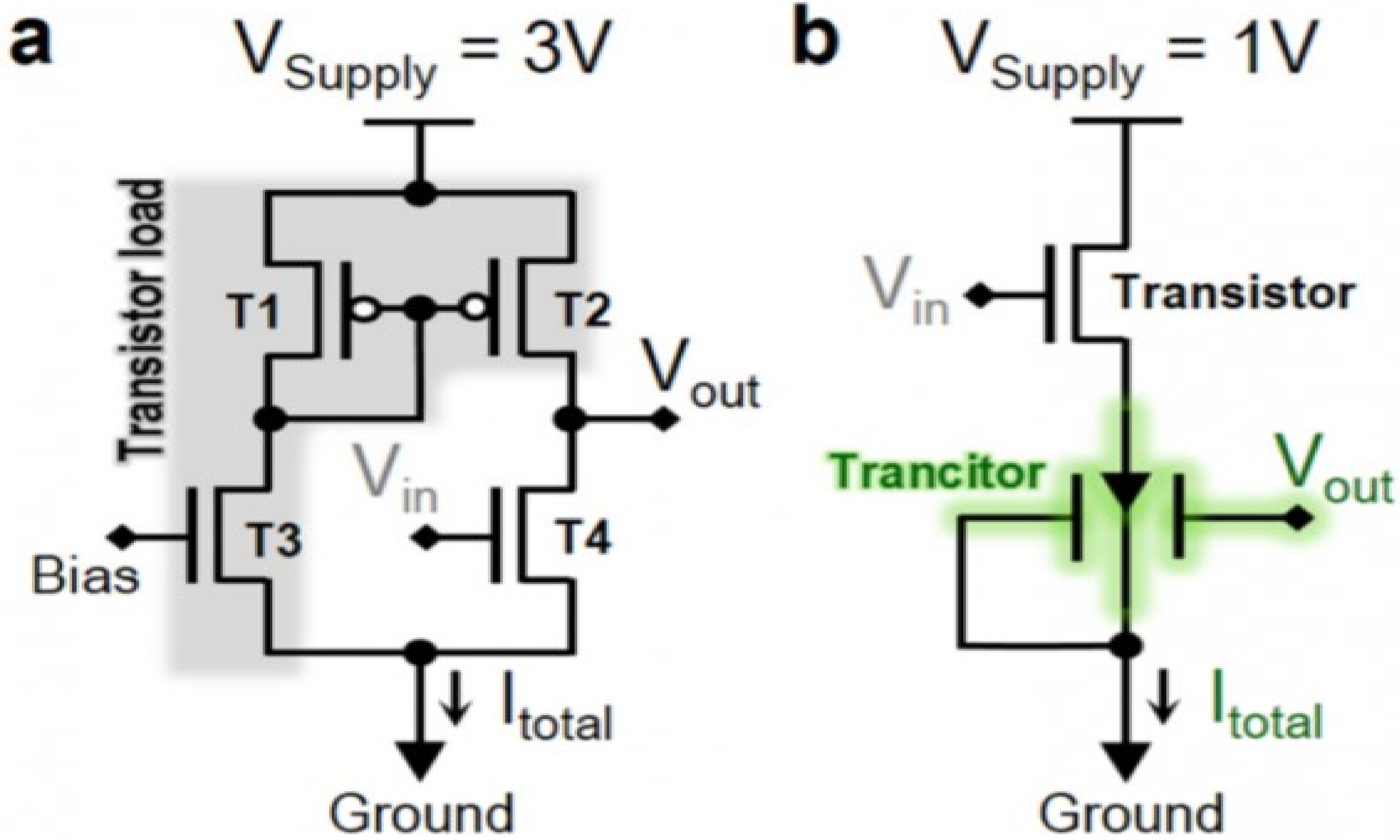


FinFET technology

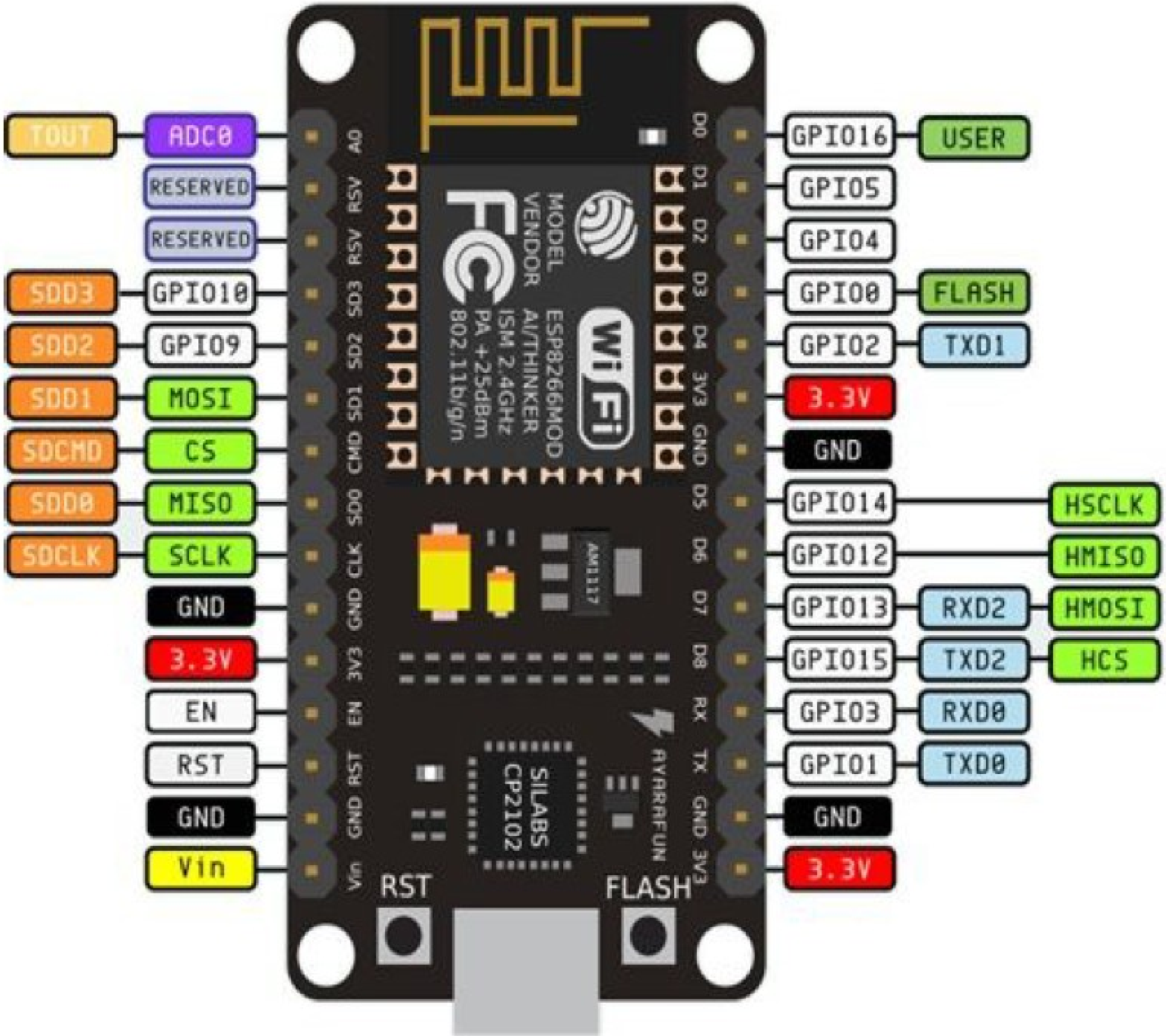


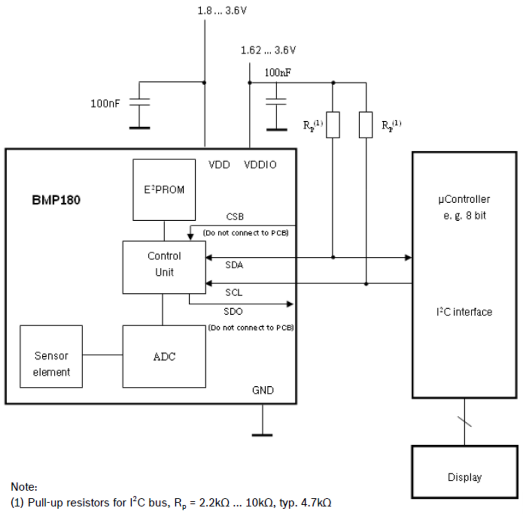
- A Fin Field-effect transistor(FinFET) is a MOSFET double-gate transistor built on substrate where the gate is placed on two, three, or four sides of the channel or wrapped around the channel, forming a double gate structure. These devices have been given the generic name "FinFETs" because the source/drain region forms fins on the silicon surface. The FinFET devices have significantly faster switching times and higher current density than the mainstream CMOS technology.
- The FinFET transistors can have gate thickness of 5nm and gate width under 50nm, are supposed to find application in sub-28nm chips. FinFET technology is being pursued by AMD, IBM, and Motorola and in academia.
- The industry's first 25nm transistor operating on just 0.7V was demonstrated in December 2002 by TSMC. The "Omega FinFET" design, named after the similarity between the Greek letter "Omega" and the shape in which the gate wraps around the source/drain structure, has a gate delay of just 0.39ps for the N-type transistor and 0.88ps for the P-type.

A missing active device: Trancitor



Smart sensors and readout

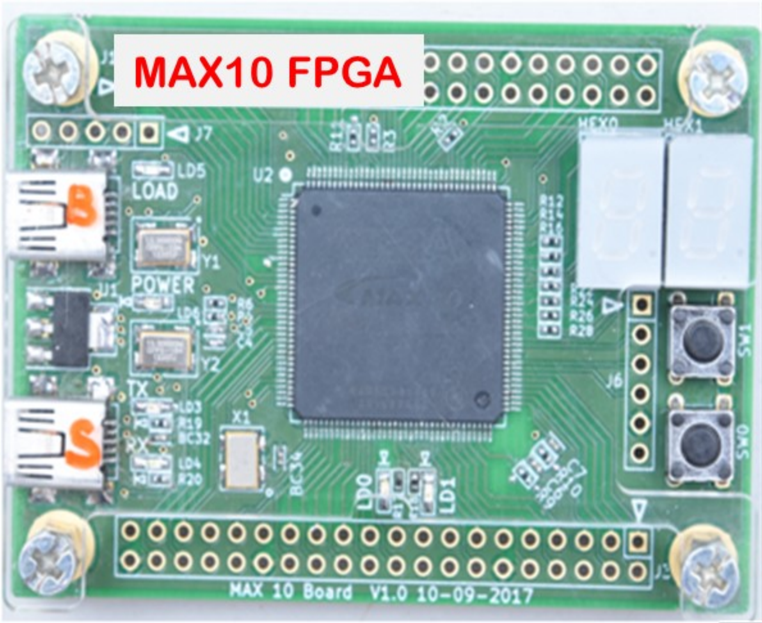


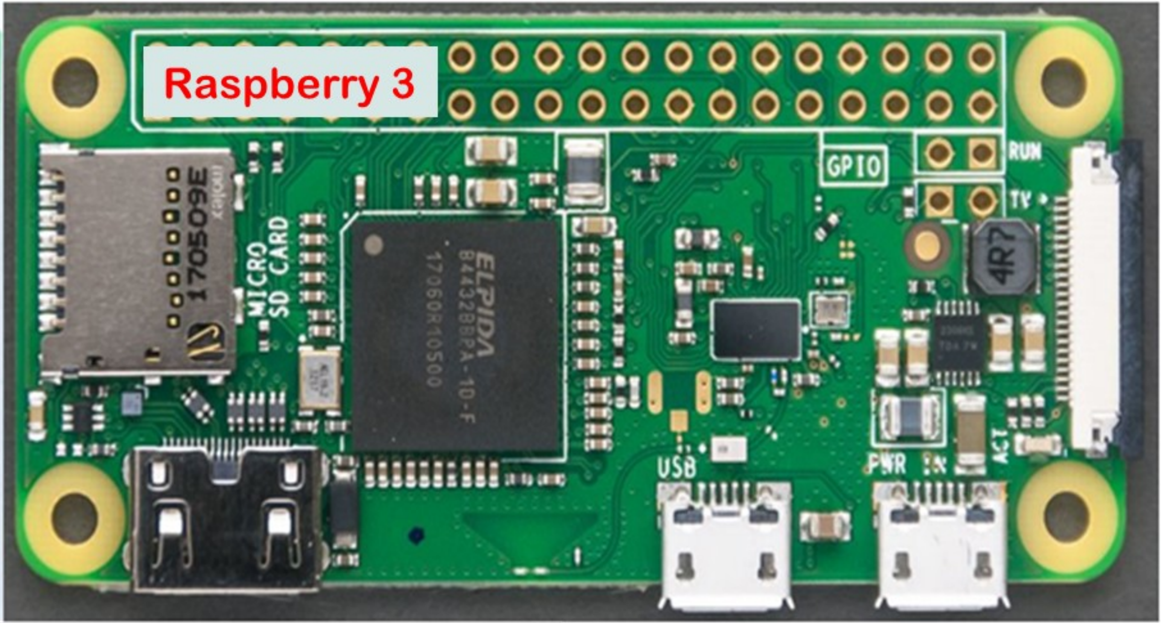


Note:
(1) Pull-up resistors for I^2C bus, R_p = 2.2kΩ ... 10kΩ, typ. 4.7kΩ

Sensors – The lifeblood of Internet of Things (IoT)

Work horses for sensor readout


MAX10 FPGA


Raspberry 3


ESP8266

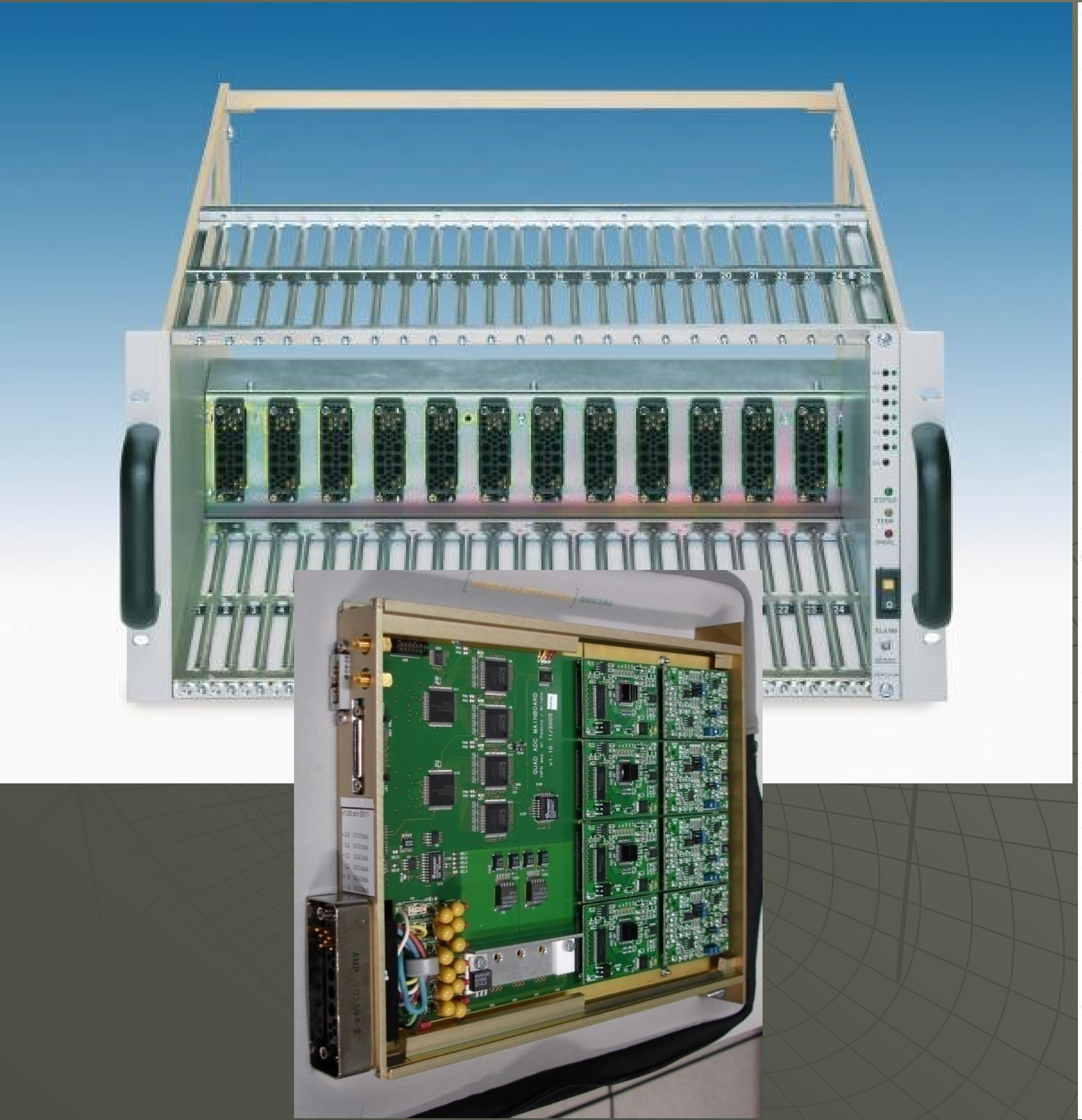

Raspberry Pi Zero

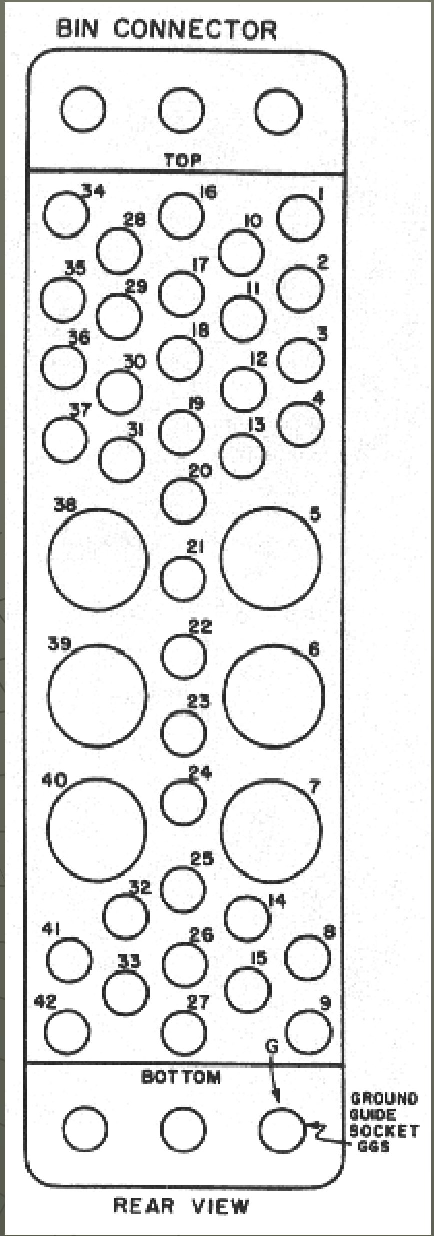

Arduino Nano

Introduction to NIM

- The NIM (Nuclear Instrumentation Methods) standard established in 1964 for the nuclear and high energy physics communities. The goal of NIM was to promote a system that allows for interchangeability of modules.
- Standard NIM modules are required to have a height of 8.75", width in multiples of 1.35". Modules with a width of 1.35" are referred to as single width modules and modules with a width of 2.7" are double width modules, etc. The NIM crate, or NIM bin, is designed for mounting in EIA 19" racks, providing slots for 12 single-width modules. The power supply, which is in general, detachable from the NIM bin, is required to deliver voltages of ±6V, ±12V and ±24V.
- The NIM standard also specifies three sets of logic levels.
  - In fast-negative logic, usually referred to as NIM logic, logic levels are defined by current ranges. Since the standard also requires 50 ohm input/out impedances, these current ranges correspond to voltages of 0V and -0.8V for logic 0 and 1 respectively. Fast-negative logic circuitry can provide NIM signal with rise times of order 1 nsec.
  - Slow-positive logic, is rarely used in fast-pulse electronics due to the slow rise times involved.
  - Specifications for ECL (emitter-coupled logic) voltage levels and interconnections have been added to the NIM subsequently.

NIM crate and power supplies

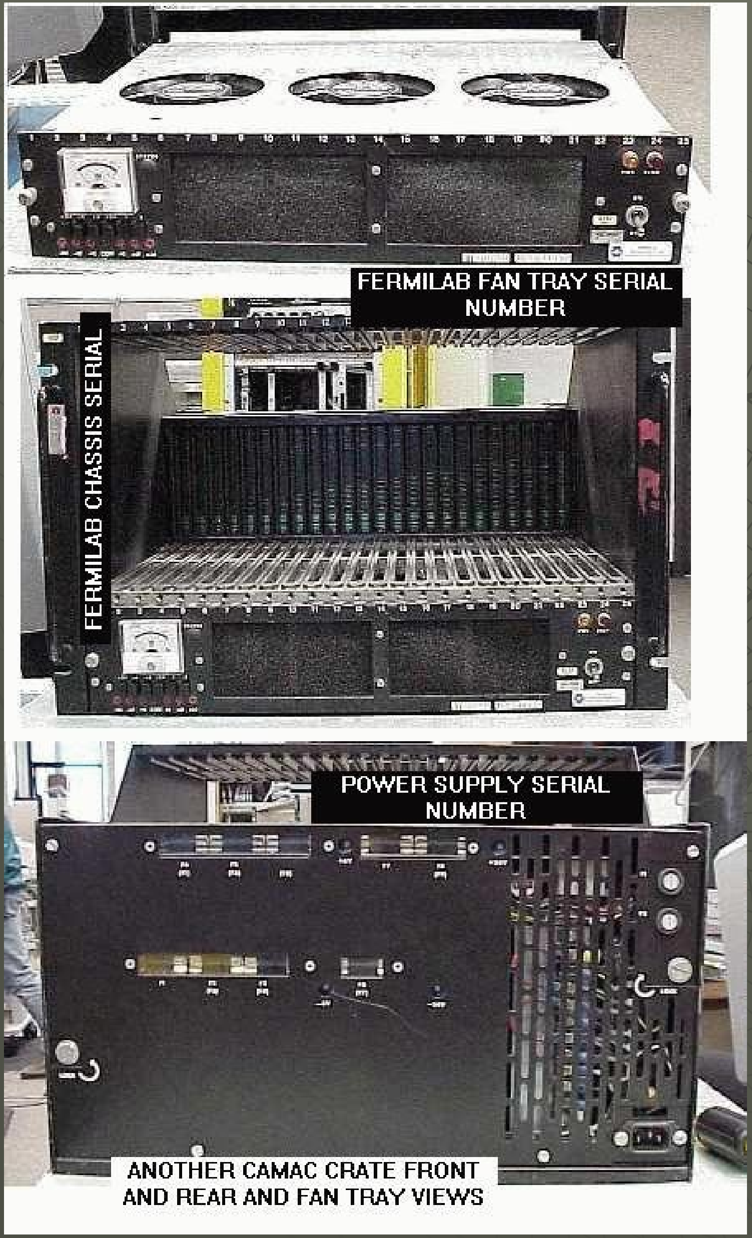




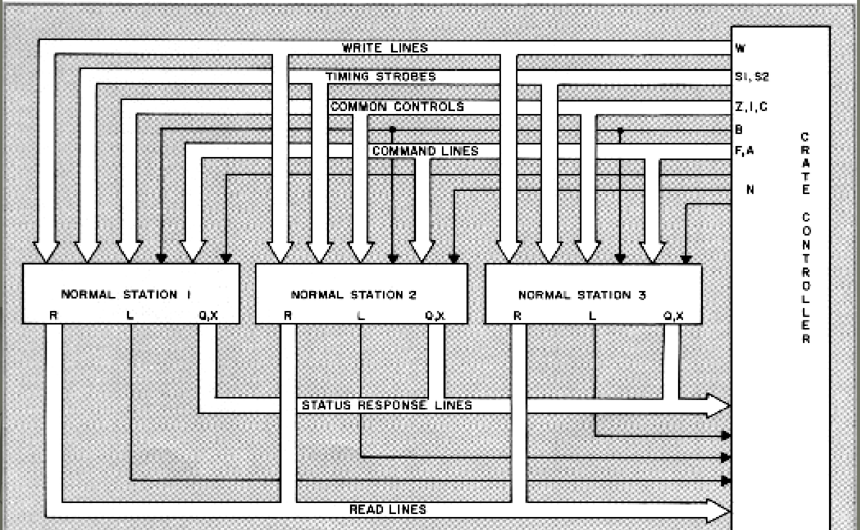
PIN	FUNCTION
1	RESERVED
2	RESERVED
3	BIN GATE
4	RESERVED
5	
6	
7	
8	+200 V D.C.
9	SPARE
* 10	+6 V
* 11	-6 V
12	RESERVED
13	SPARE
14	SPARE
15	RESERVED
* 16	+12 V
* 17	-12 V
18	SPARE
19	RESERVED
20	SPARE
21	SPARE
22	RESERVED
23	RESERVED
24	RESERVED
25	RESERVED
26	SPARE
27	SPARE
* 28	+24 V
* 29	-24 V
30	SPARE
31	SPARE
32	SPARE
33	117 V A.C. (HOT)
* 34	POWER RETURN GND
* 35	RESET
36	GATE
37	SPARE
38	
39	
40	
* 41	117 V A.C. (NEUTRAL)
* 42	HIGH QUALITY GND
G	GROUND GUIDE PIN

** Must be bussed to all bin connectors GPIB through PG12B.*

CAMAC hardware and signals

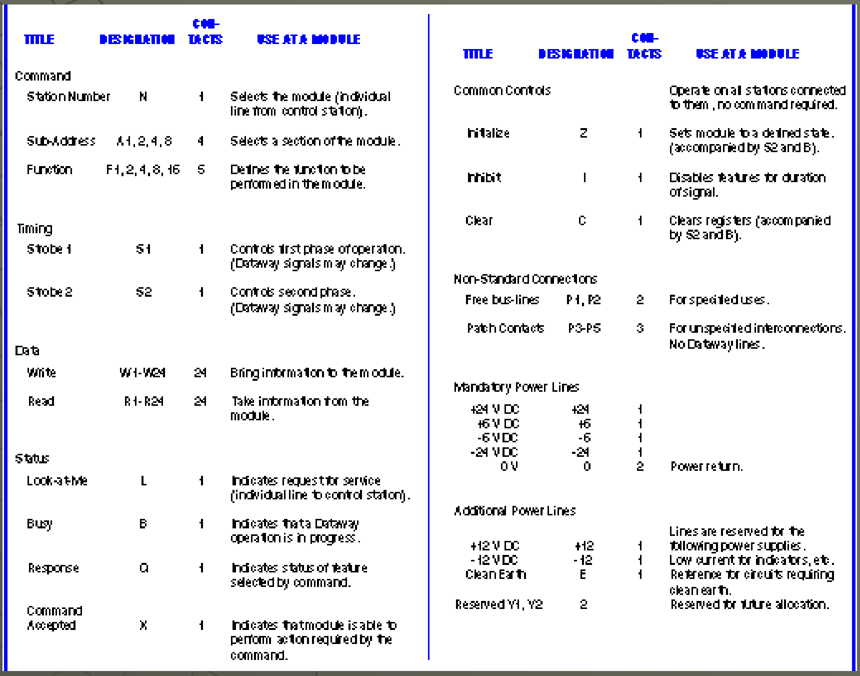


ANOTHER CAMAC CRATE FRONT AND REAR AND FAN TRAY VIEWS



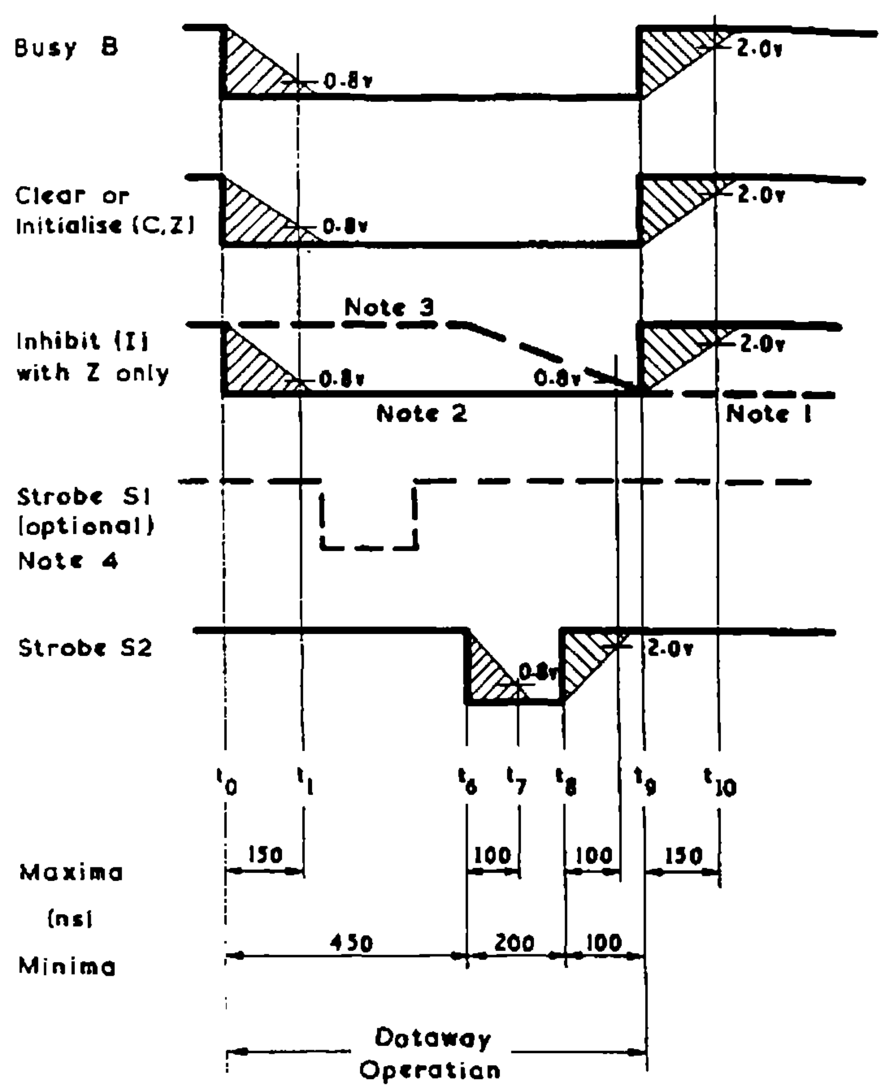
Block diagram and signal paths for 3 CAMAC modules and a Crate Controller.

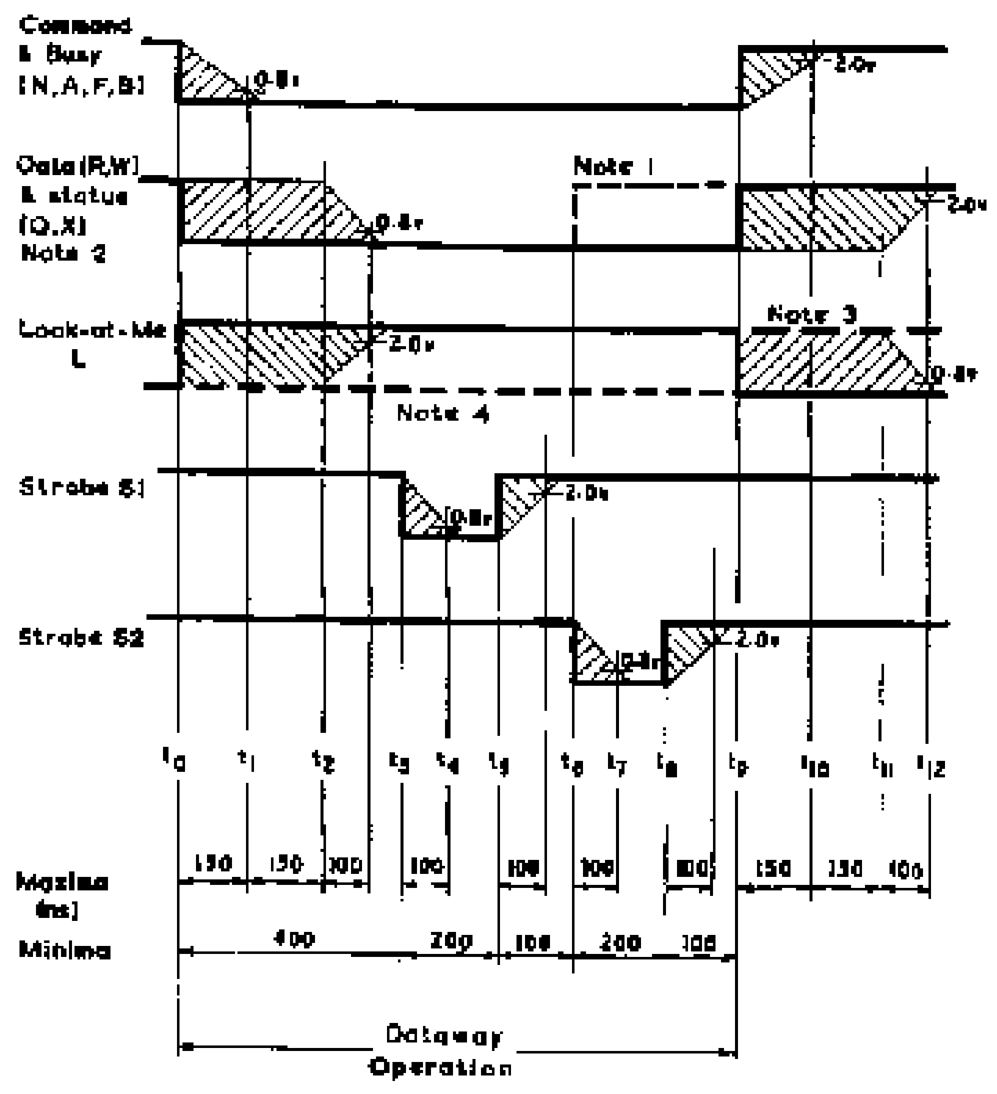
A-599



TITLE	DESIGNATION	CON-TACTS	USE AT A MODULE
Command			
Station Number	N	1	Selects the module (individual line from control station).
Sub-Address	A1, 2, 4, 8	4	Selects a section of the module.
Function	F1, 2, 4, 8, 16	5	Defines the function to be performed in the module.
Timing			
Strobe 1	S1	1	Controls first phase of operation. (Dataway signals may change.)
Strobe 2	S2	1	Controls second phase. (Dataway signals may change.)
Data			
Write	W1-W24	24	Bring information to the module.
Read	R1-R24	24	Take information from the module.
Status			
Look-at-Me	L	1	Indicates request for service (individual line to control station).
Busy	B	1	Indicates that a Dataway operation is in progress.
Response	Q	1	Indicates status of feature selected by command.
Command Accepted	X	1	Indicates that module is able to perform action required by the command.
Common Controls			Operate on all stations connected to them, no command required.
Initialize	Z	1	Sets module to a defined state. (accompanied by S2 and B).
Inhibit	I	1	Disables features for duration of signal.
Clear	C	1	Clears registers (accompanied by S2 and B).
Non-Standard Connections			
Free bus-lines	P1, P2	2	For specified uses.
Patch Contacts	P3-P5	3	For unspecified interconnections. No Dataway lines.
Mandatory Power Lines			
+24 V DC	+24	1	
+6 V DC	+6	1	
-6 V DC	-6	1	
-24 V DC	-24	1	
0 V	0	2	Power return.
Additional Power Lines			Lines are reserved for the following power supplies.
+12 V DC	+12	1	Low current for indicators, etc.
-12 V DC	-12	1	
Clean Earth	E	1	Reference for circuits requiring clean earth.
Reserved Y1, Y2	2		Reserved for future allocation.

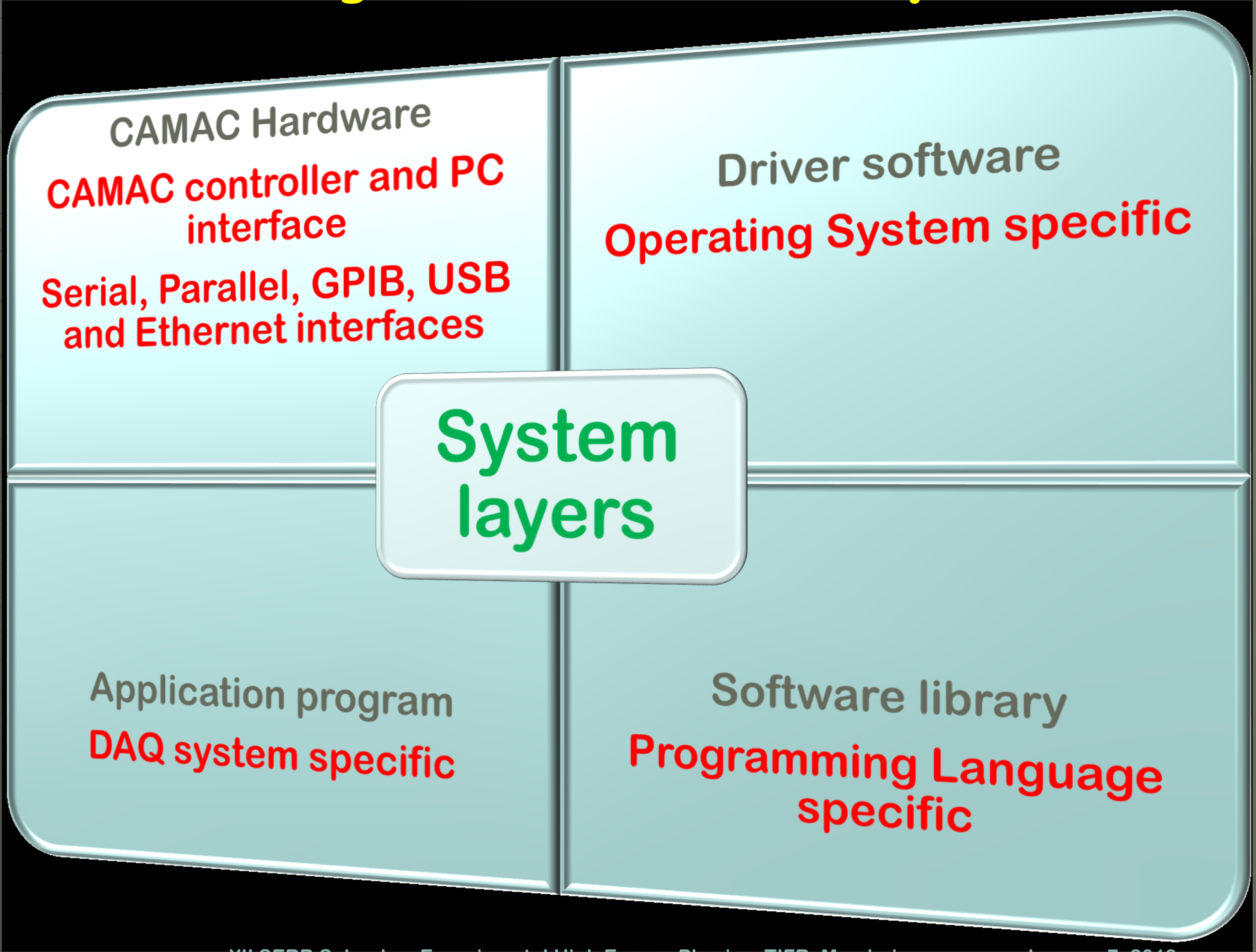
CAMAC dataway timing charts





Computer Automated Measurement and Control

CAMAC system development



System layers

CAMAC Hardware

CAMAC controller and PC interface

Serial, Parallel, GPIB, USB and Ethernet interfaces

Driver software

Operating System specific

Application program

DAQ system specific

Software library

Programming Language specific

Thank you for your attention ☺