A Pictorial History of Nuclear Instrumentation

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Dawn of Nuclear Instrumentation
End of 19th Century

Wilhelm Röntgen (1845-1923)

(1895) W. Roentgen observes florescence in barium platinocyanide due to invisible rays from a gas discharge tube. Names them X-rays

First medical X-ray

Henry Becquerel (1852-1908)

(1896) H. Bacquerel detects that uranium salts spontaneously emit a penetrating radiation that can blacken photographic films

Independent of chemical composition

Pierre Curie (1859-1906) Marie Curie (1867-1934)

(1987) Pierre & Marie Curie found that both uranium and thorium emit radiation that can ionise gases – detected by electroscopes.

Coin the name '*Radioactivity*' to describe this natural process

Early Instrumentation

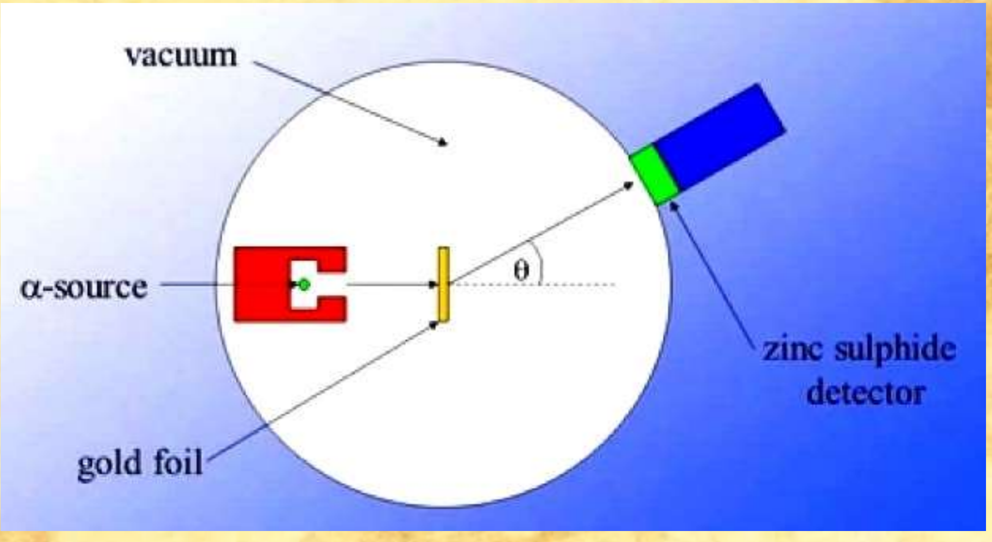
Equipment used for these path-breaking discoveries were developed much earlier :

- **Optical fluorescence (1560) Bernardino de Sahagún**
- **Thermo-luminescence (17th Century)**
- **Gold Leaf Electroscope (1787) Abraham Bennet**
- **Photographic Emulsion (1839) Louis Daguerre**

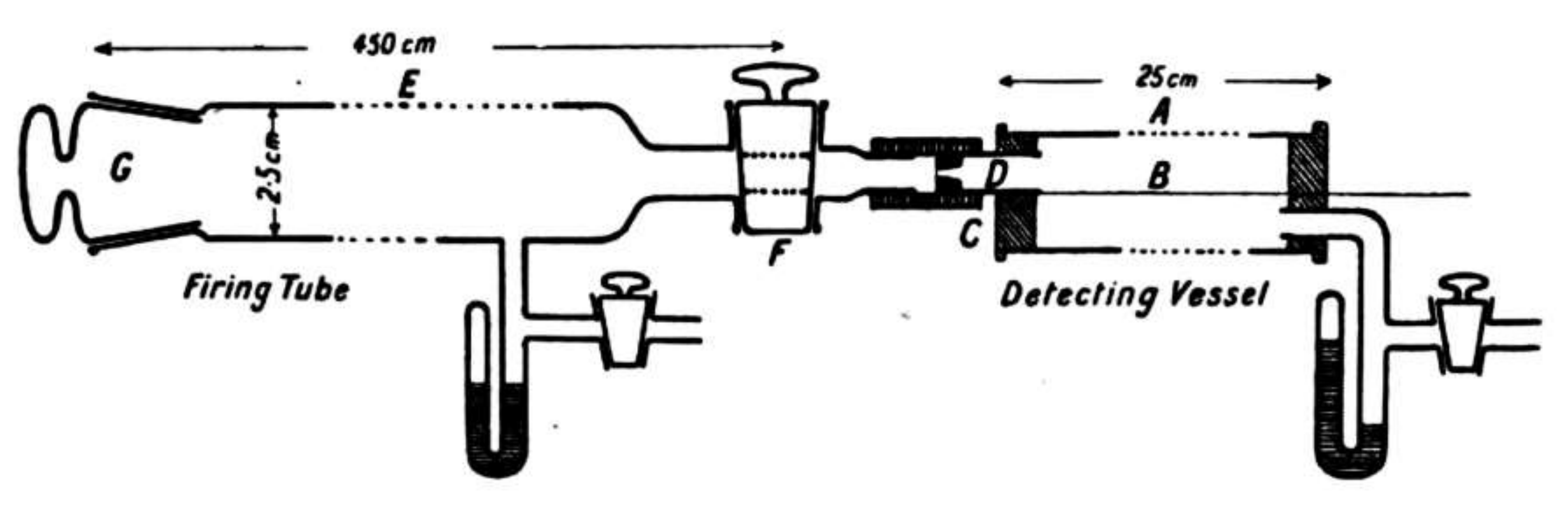
Early instruments were sensitive to radiation dose only, could not detect individual radiation

Spinthariscope (1903)

- Spinthariscope was invented by William Crookes. It is made of a ZnS screen viewed by an eyepiece
- Scintillation produced by an incident α-particle can be seen as faint light flashes
- Rutherford's famous α-scattering experiment proved the existence a 'point-like' nucleus inside the atom



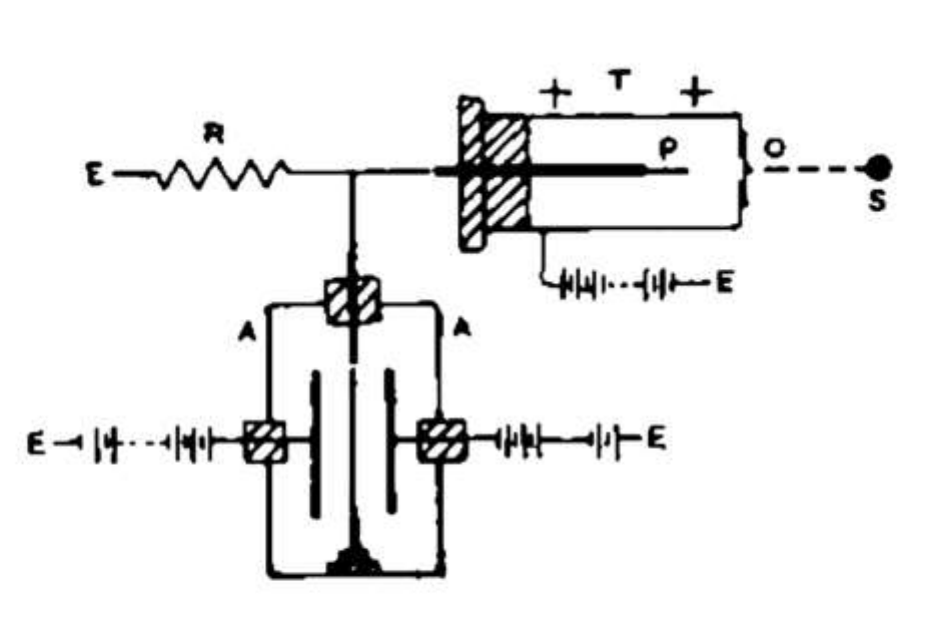
Geiger Counter (1908)



First instrument to detect individual α-particles electronically was developed by Geiger. Chamber filled with CO_2 at 2-5 cm of mercury

Central wire at ground potential connected to an electrometer. Successive 'kicks' in the electrometer indicated the passage of a charged particle; response time ~1 sec

Geiger Muller Counter (1928)



An improved design (1912) had a string electrometer for detection. Counting rates up to 1000/sec could be achieved by photographic recording.

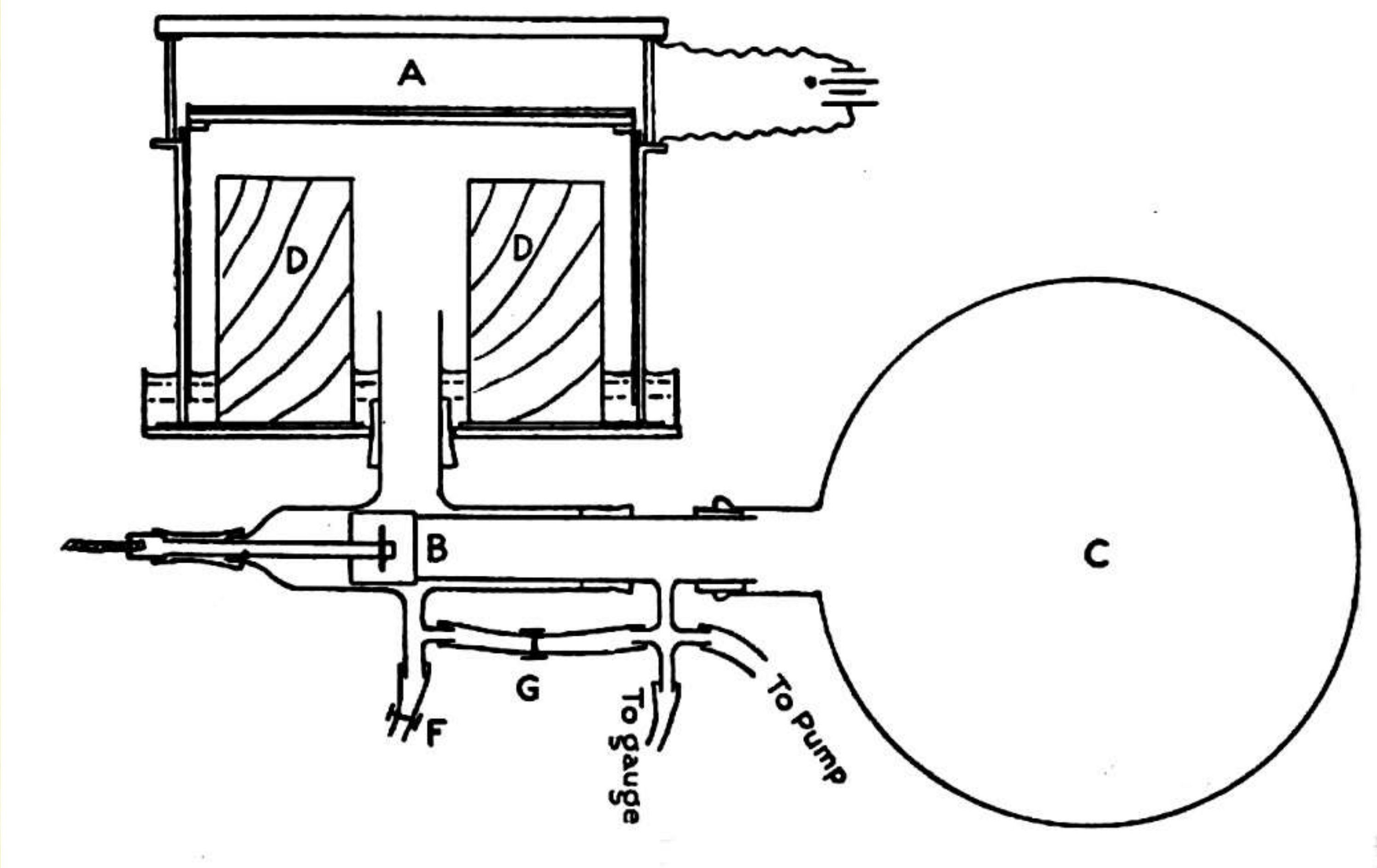
Major improvement was done by Muller in 1928 by adding a quench gas. Sensitive to α, β, γ radiation

Cloud Chamber (1912)

T.R. Wilson (1869-1959) invented the cloud chamber in 1912.

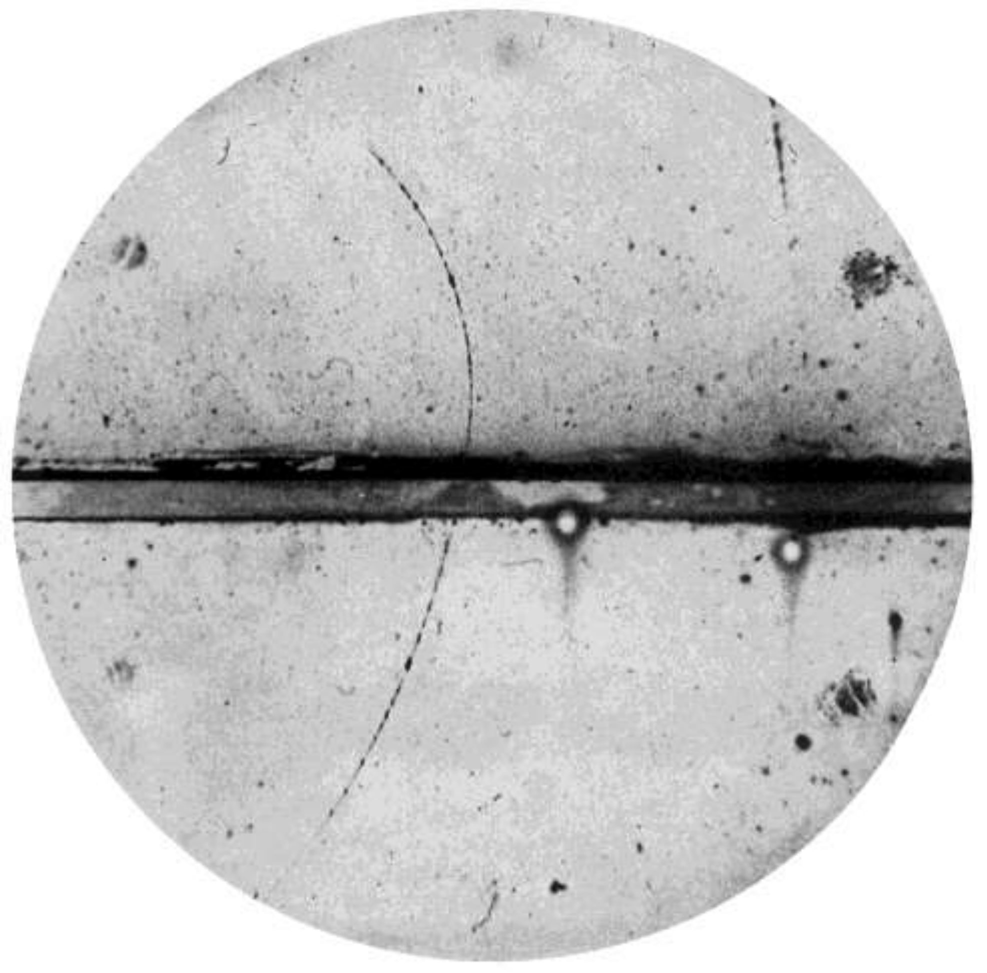
Air, saturated with water vapour was suddenly expanded causing condensation along ionising track.

Tracks could be recorded photographically allowing visual identification



Discovery of Positron (1932)

- One of the important application of cloud chambers was the discovery of positron by C. Anderson (1905-1991)
- By applying a magnetic field the magnetic rigidity can be measured
- In the figure, 63 MeV positron coming from below loses energy in 6 mm thick Pb to become 35 MeV positron
- Muon was discovered by Anderson (1937) by measuring dE/dx of cosmic rays in a cloud chamber

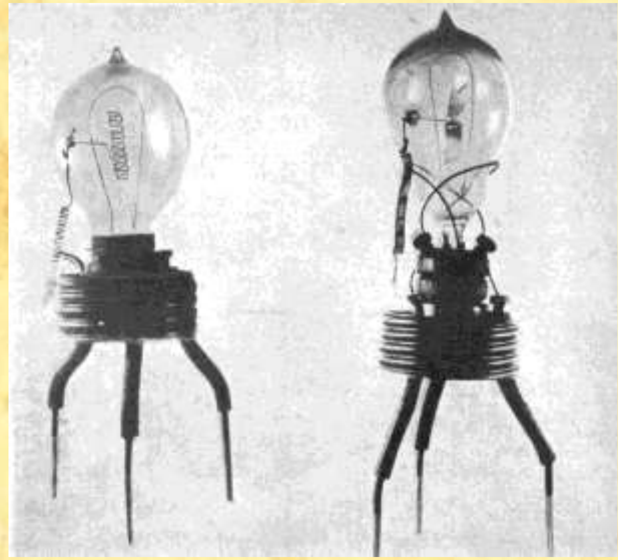


Bubble Chamber (1952)

- Natural extension of Cloud Chamber was Bubble Chamber which uses a superheated liquid to generate bubbles along ionized track.
- D.A. Glaser developed bubble chamber in 1952 using liquid hydrogen
- Some of the important discoveries
  - Strange particles → Ω^-
  - Meson and baryon resonances → SU(3)
  - Neutral weak current

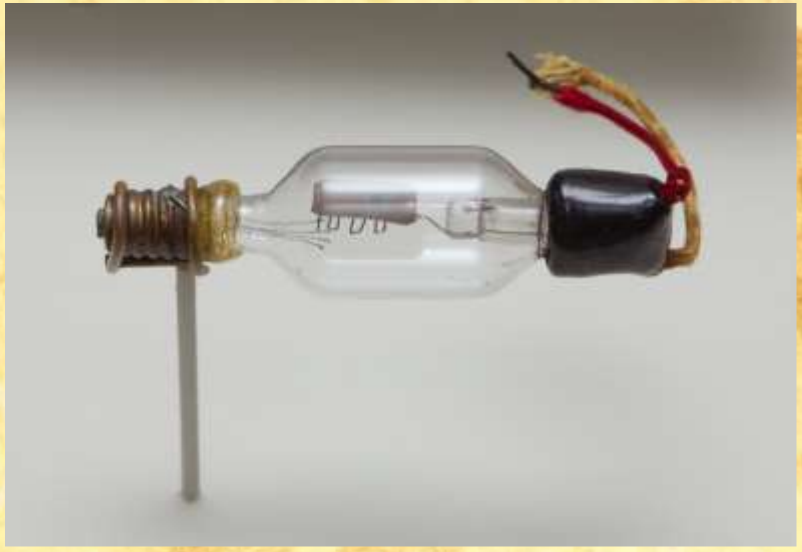
Era of Vacuum Tubes

- **1904 J.A. Fleming discovers thermionic diode**
- **1906 Lee Dee Forest invents triode**
- **1919 Tetrode (W.H. Shottky)**
- **1926 Pentode (B.D.H. Tellegen)**



Development of valves resulted into two major developments in nuclear physics:

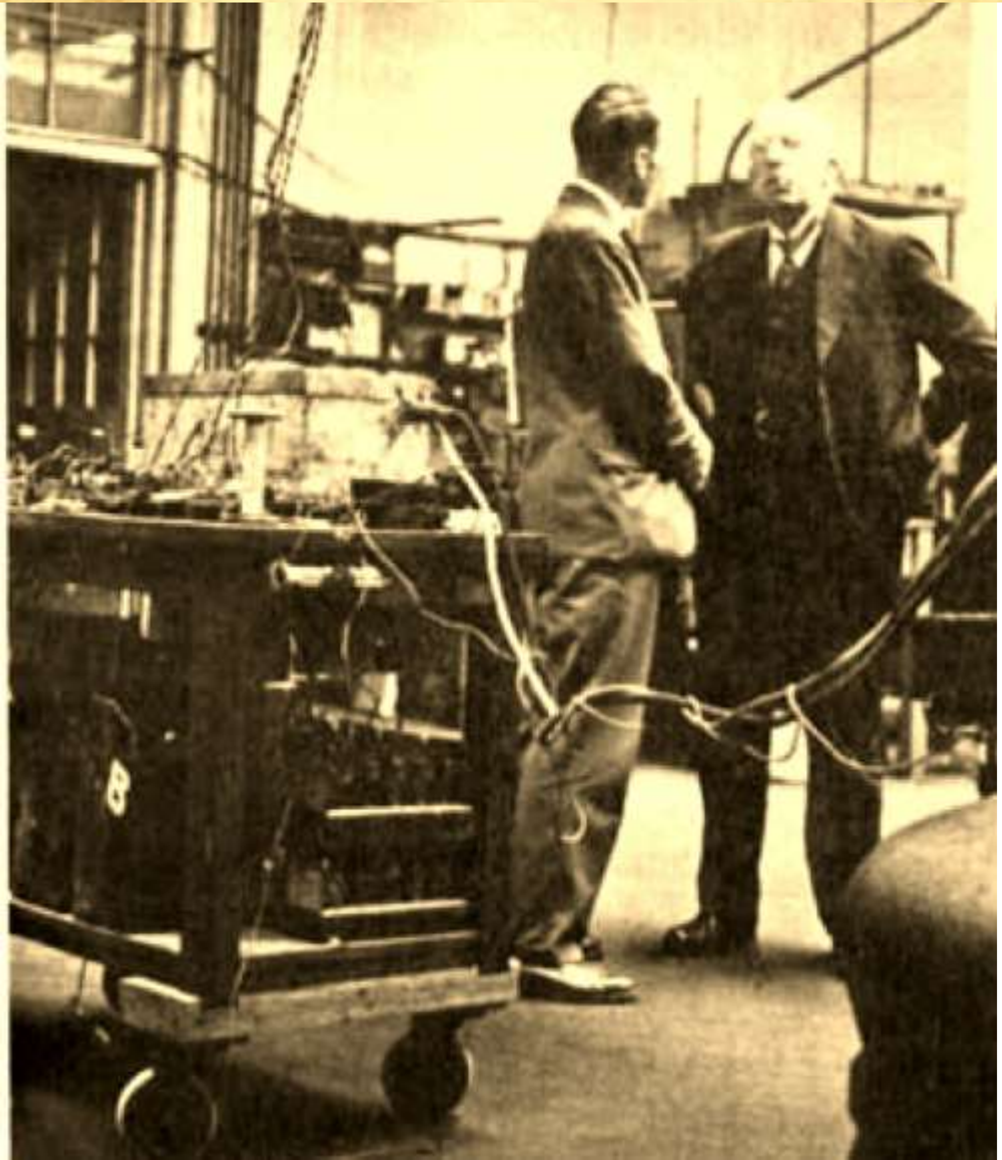
Valve amplifier Valve Counter



C.E. Wynn-Williams (1903-1979)

- Ph.D under E. Rutherford (1929)
- Encouraged by Rutherford to apply valve techniques to amplify nuclear signals
- Developed a 5-valve amplifier (1929) to amplify α-energy signals by 10^9
- Signals recorded by photographic method using a moving-coil galvanometer

Valve Amplifier by Wynn-Williams



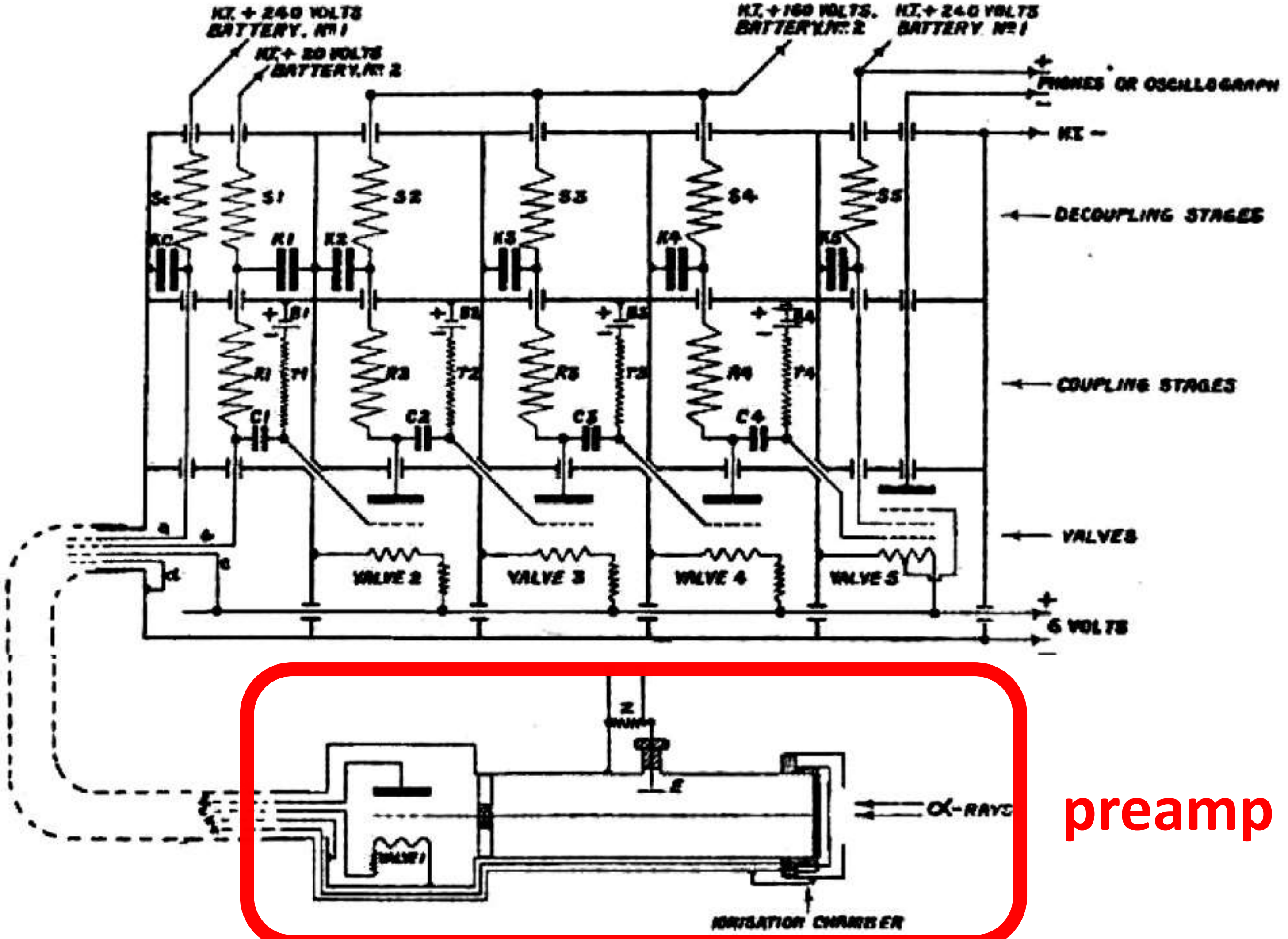
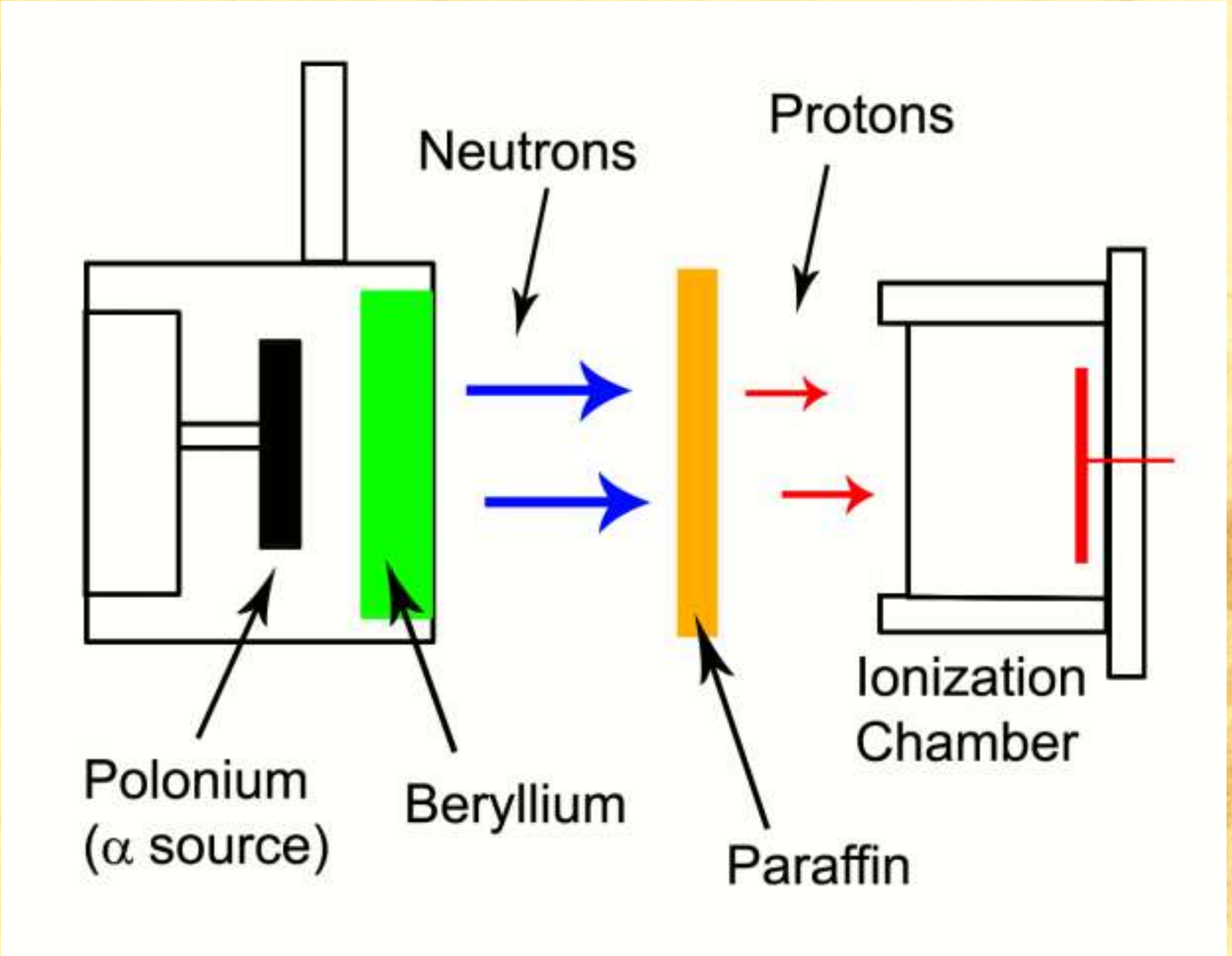


FIG. 2.—Diagram of amplifier and ionisation chamber.

Discovery of neutrons by Chadwick (1932)

- **A major application of valve amplifiers was measuring the proton recoil energies in the discovery of neutrons**
- **The ionisation counter signal was amplified and viewed in an oscillograph**
- **By comparing recoil energies in different scatterers, it was concluded that neutron and proton have similar mass**



Ushering of Digital era

- One of the most important contributions of Wynn-Williams was the development of ‘scale of 2’ circuit (1931)
- By providing feedback between two valves, they alternately go to ‘on’ and ‘off’ position with successive input
- Switching time of ~ 1 ms
- Building block of all digital computation

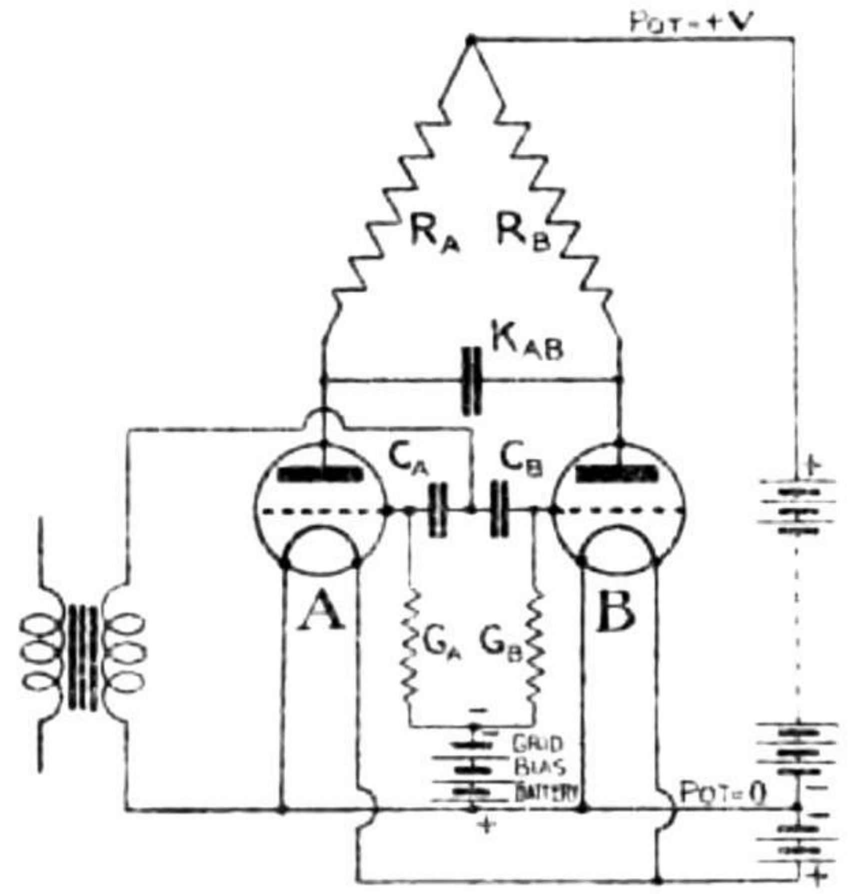


FIG. 1.—Circuit diagram of a single two-thyratron unit

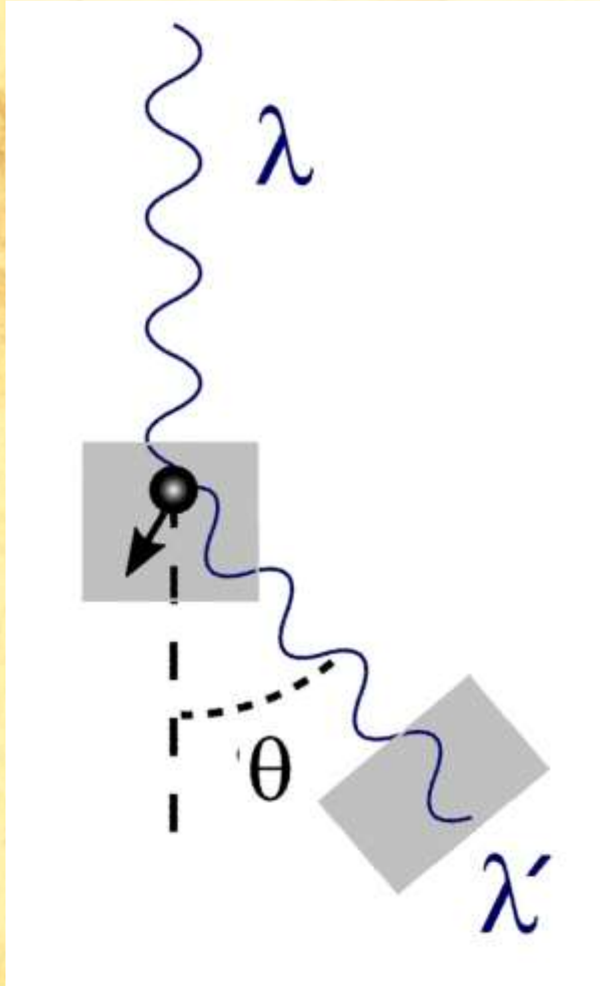
Electronic Recording of Radiation

Using a cascade of scale of 2 circuits, output count rate reduced for input of mechanical counter

Fully electronic method for radiation detection

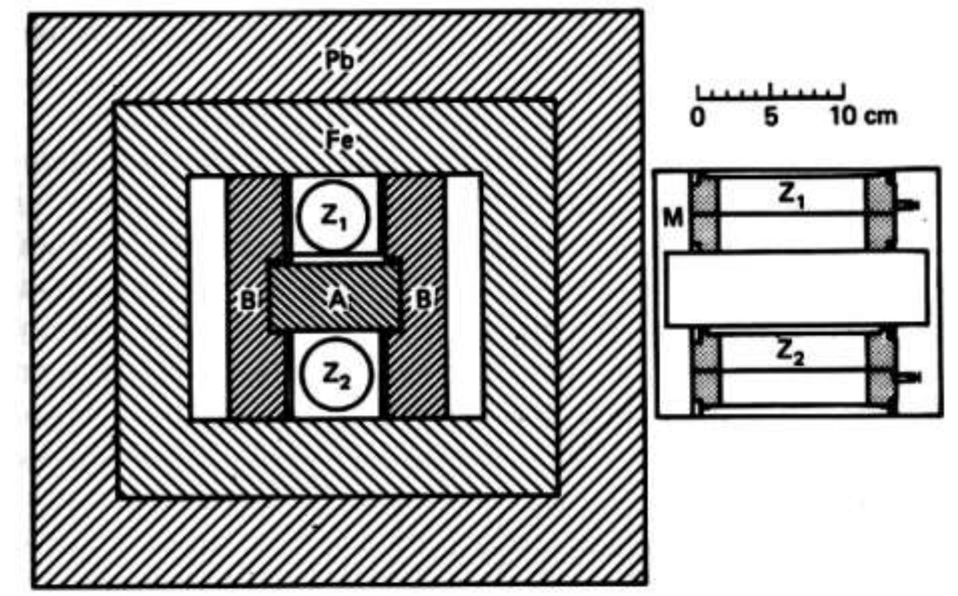
Coincidence Method (Bothe)

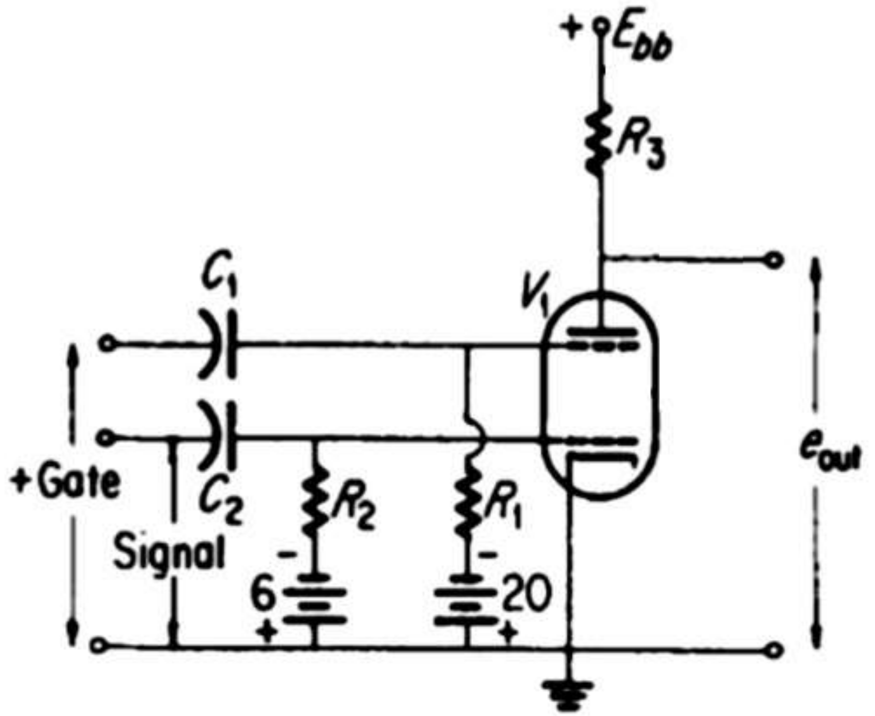
- **First application of coincidence method was done by Walter Bothe (1924) to find whether in Compton scattering, electron and photon were emitted simultaneously.**
- **The energetic electron and scattered photon were detected in two Geiger counters, shielded against fast electrons, placed closed to each other.**
- **Deflections of String electrometers were recorded photographically.**
- **Coincidence resolving time of 10^{-3} sec was achieved**



Cosmic Ray Studies

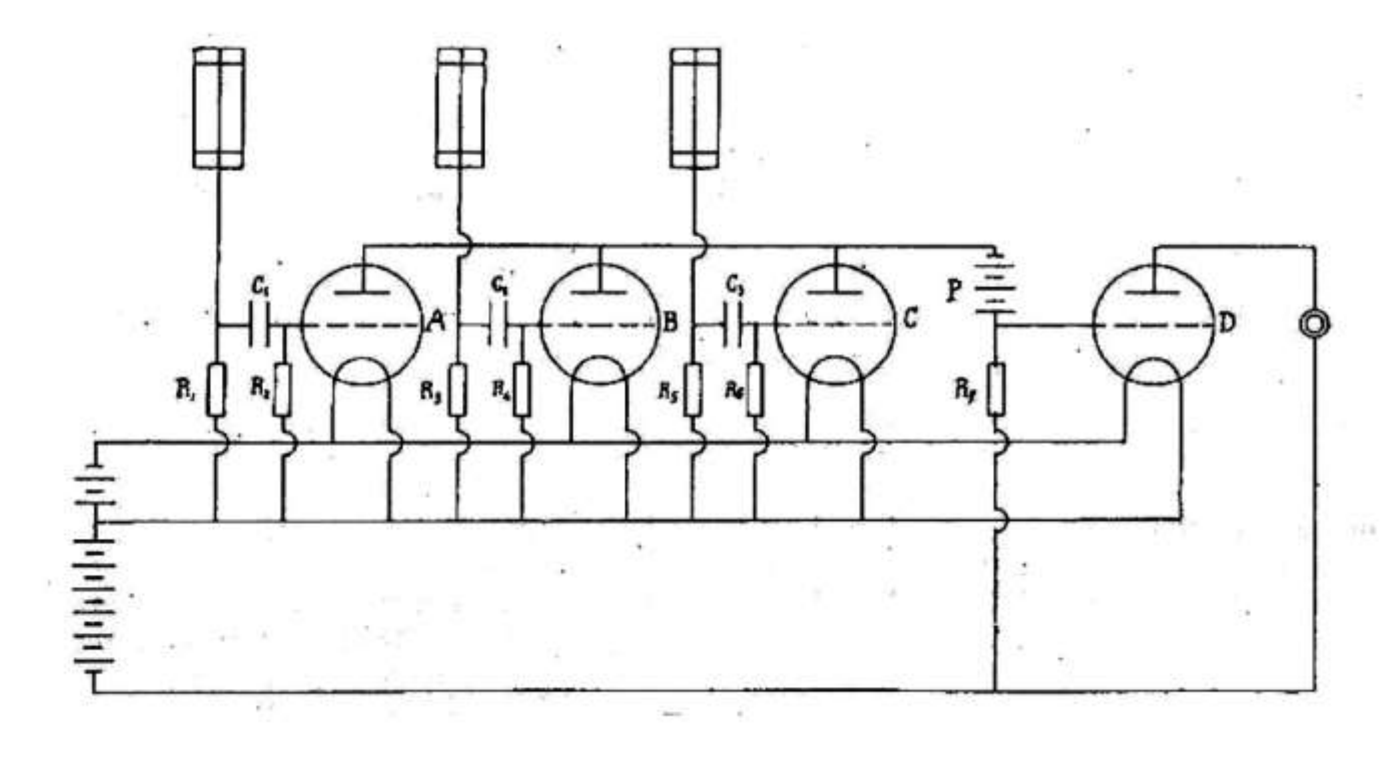
- In 1929, Bothe and Kohlhörster showed that cosmic rays could pass through large thicknesses of lead and iron but still be detected in GM counter
- Coincidence between two counters detected by photographic method
- Concluded that cosmic rays are energetic charged particles penetrating through 4 cm of gold
- An electronic circuit for recording coincidences using a tetrode was reported by Bothe (1929)
- Application in nuclear spectroscopy





Coincidence Method (Rossi)

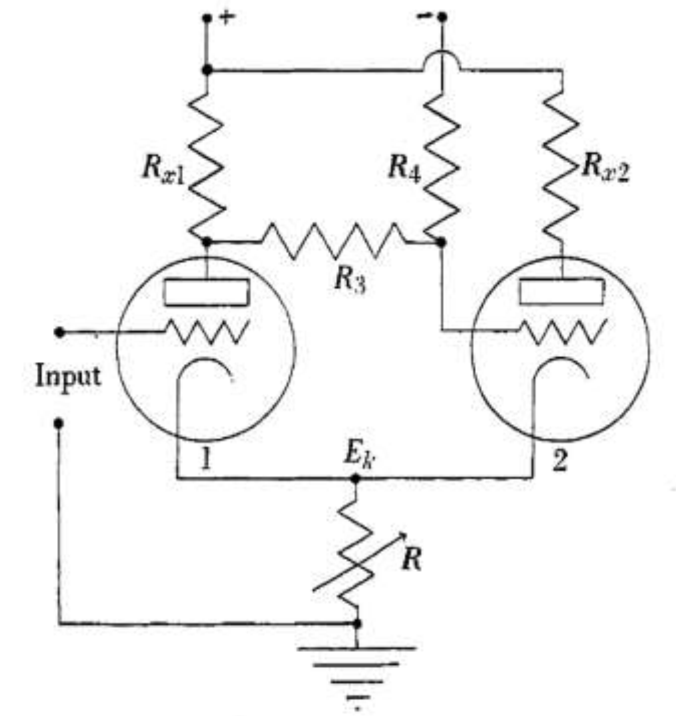
- An improved method for detecting coincidence between many counters was developed by Rossi (1930)
- Valves A-C are conducting with last valve D cut off
- Simultaneous –ve pulses to grids of A-C would cause D to conduct
- Order of magnitude improvement of resolving time (< 10^{-5} sec)



Rossi Circuit (1930)
First implementation of ‘AND’ gate

Pulse Height Measurement

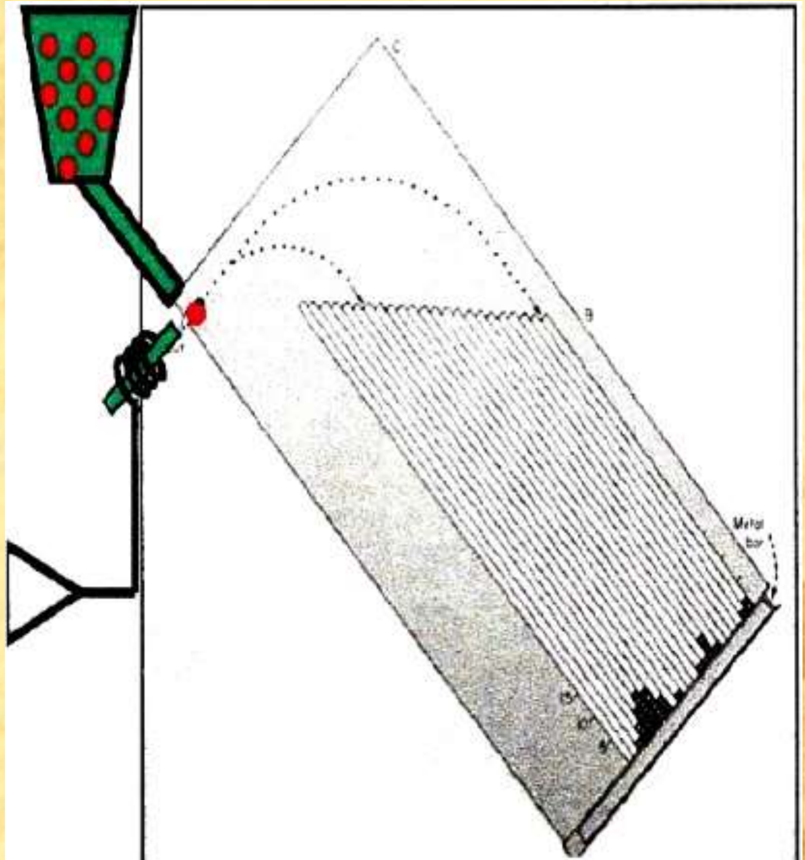
- Scintillators, ionisation counter and proportional counters have linear output
- Need for pulse height measurement
- O. Schmitt developed Schmitt trigger (1937) as threshold discriminator
- Combination of two discriminators can be used as a single channel analyser
- Sweeping LLD & ULD together allows spectrum measurement (1947)



Thermionic trigger circuit

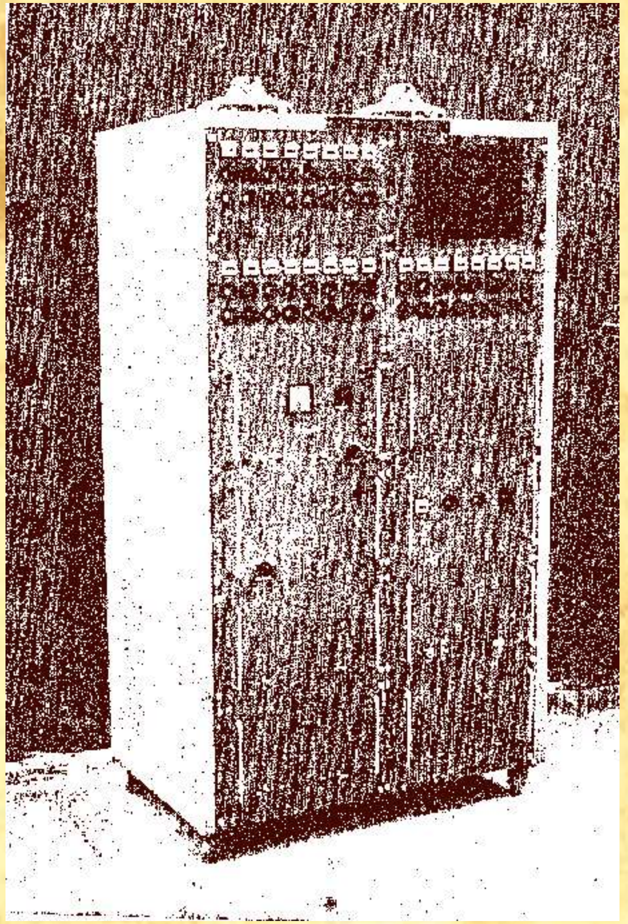
Multi Channel Analyser

- An early version of pulse height analyser was a mechanical Kicksorter (1940) that sorted the pulses into bins by electromechanical method
- Electronic versions were valve-based multiple single channel analysers with own storage
- Poor differential linearity
- D. H. Wilkinson developed the ramp ADC in 1949 ; Good linearity but slow conversion
- 1959: First transistorised MCA by Goulding
- Emileo Gatti introduced sliding scale method (1963), Charge Sensitive Preamp (1955) and Silicon Drift Detector (1983)

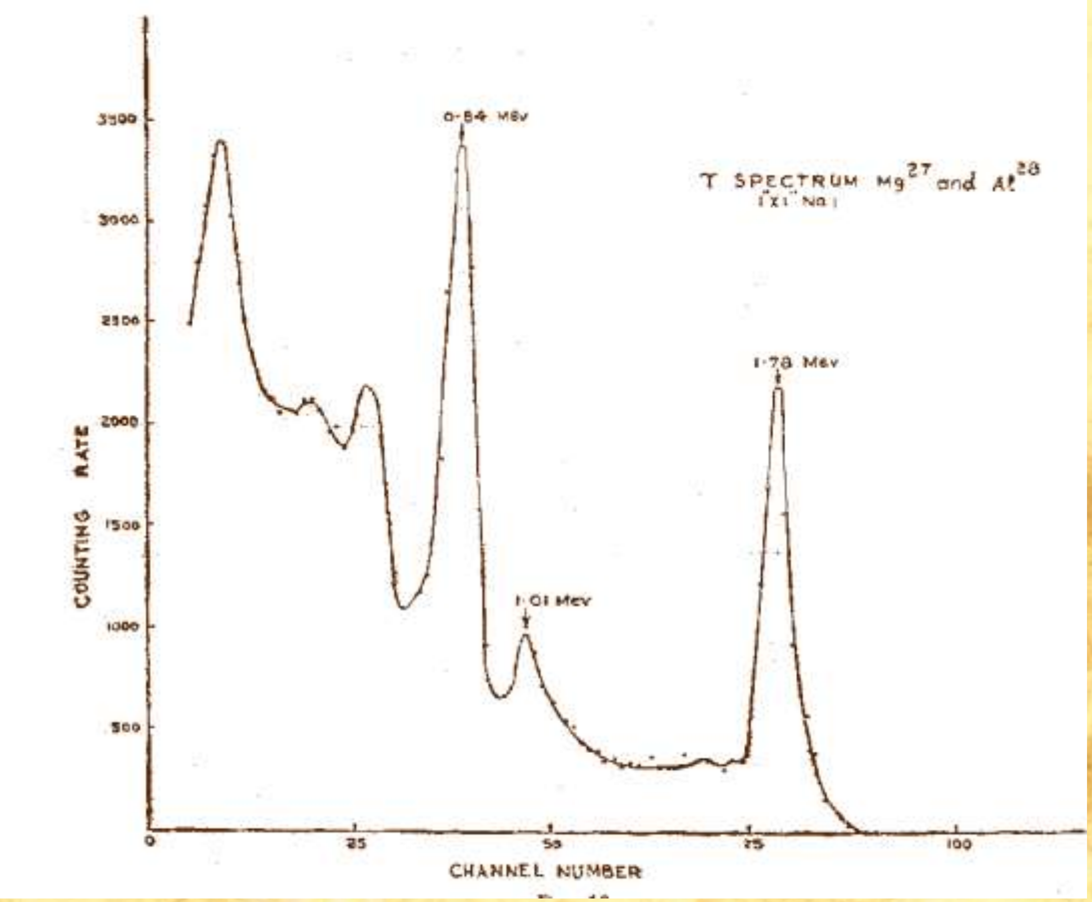


Mechanical Pulse Height Analyser

A Multichannel Pulse Amplitude Analyser
P.K. Iyengar et al. , Proc. IAS 46A(1957)61



100 channel valve-based MCA



Development of Gas Detectors

Availability of low noise amplification by valve amplifiers led to significant advances in gas detectors:

- **Gridded ionisation chamber (1940)**

  Otto Frish, while working on fission process, developed the gridded ionisation chamber. Position-independent pulse height; good resolution

- **Proportional Counter (1941)**

  A systematic study of proportional counter operation carried out by S.A. Kroff. Optimised gas composition and pressure

- **Parallel Plate Avalanche Counters (1949)**

  Mode of operation distinct from proportional or Geiger counters. High count-rate capability and sub-ns timing

Gas Detector Development

- **Spark Chamber (1962)**

  Observation of visible light from Avalanche detector by Keuffel (1949)

  A stack of spark detectors can be used to photograph the particle track

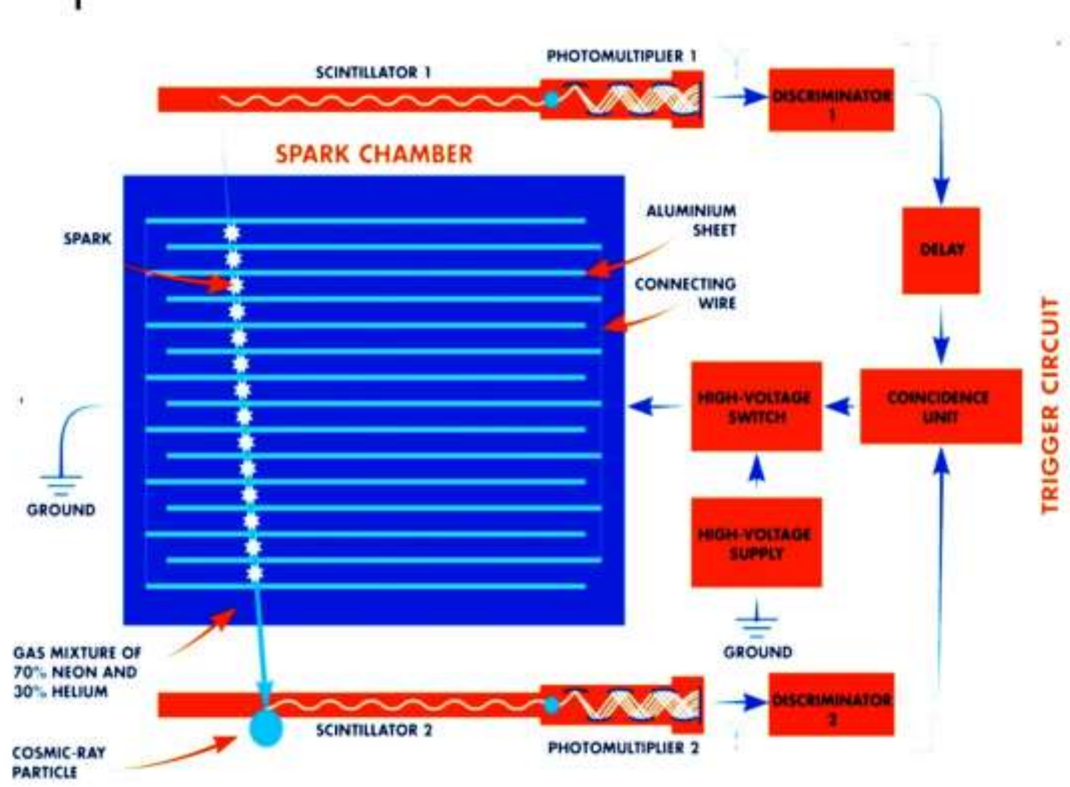
  Ledermann (1962) confirmed the two neutrino hypothesis using Spark Chamber

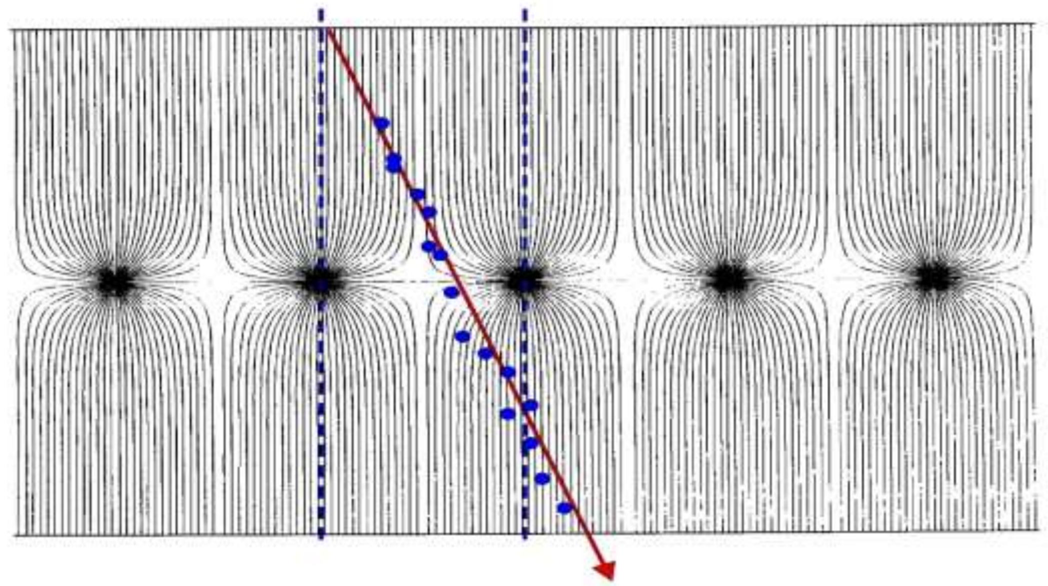
- **MWPC (1968)**

  Optical imaging replaced by electronic imaging with development of MWPC

  Position resolution ~ *0.3 d*

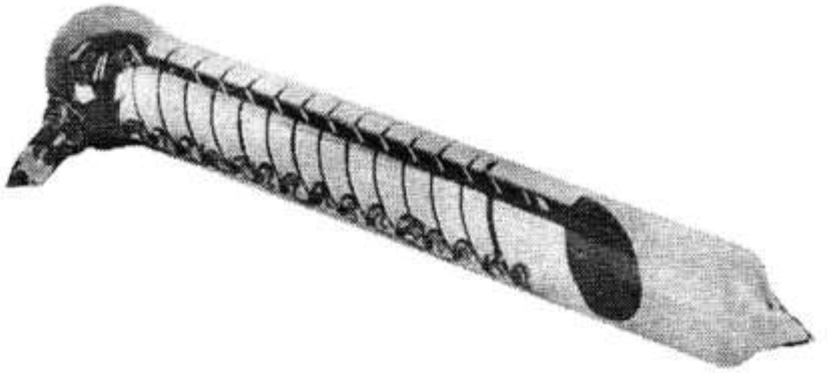
  Charpak awarded Nobel Prize in 1992

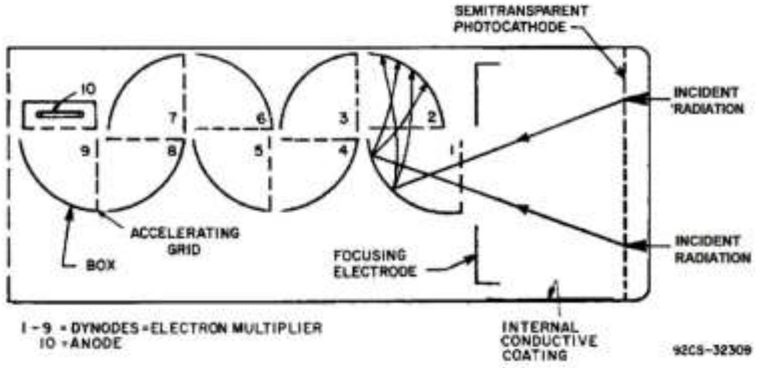




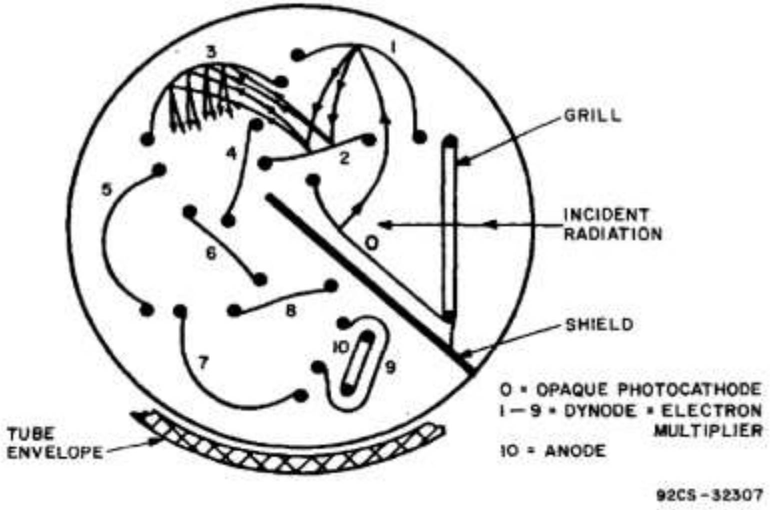
Photomultipliers

- **1887 Photoelectric effect (H. Hertz)**
- **1902 Secondary electron emission (Austin & Starke)**
- **1930 Multistage PMT proposed by L.A. Kubetsky**
- **1933-34 A number of multi-stage tubes with magnetic focussing developed by Kubetsky (gain 10^3-10^4)**
- **1935 Single-stage photomultiplier developed at RCA (Iams & Salzberg)**
- **1936 Multistage photomultiplier with electrostatic focussing developed at RCA (Zworykin)**
- **1939 First commercial PMT (RC-931) developed**





The box-and-grid multiplier structure.

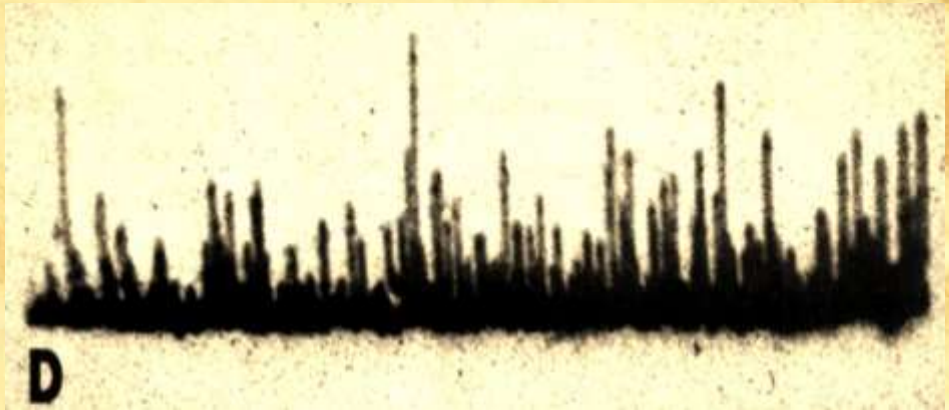


The circular-cage multiplier structure.

Vintage Photomultipliers (~1950)

SCINTILLATION DETECTORS

- **The modern electronic scintillation counter was invented in 1944 by Samuel Curran at Berkeley using ZnS as scintillator.**
- **During wartime, Hartmut Kallmann had the idea to use PMT for the detection of light pulses from phosphors. Actual work carried out after war. Naphthelene was found to be transparent to its own radiation allowing large volume detectors for γ detection (1947).**
- **Belland (1948) reported that Anthracine has larger light output**
- **Kallmann (1950) demonstrated liquid scintillation counters**



Contribution of R. Hofstadter

- Robert Hofstadter, after hearing about Callmann's work, started testing Tl activated alkali halide crystals. NaI(Tl) was found to have the largest output (1948).
- NaI(Tl) spectra showed narrow peaks with pulse height ∝ energy
- An important tool for gamma spectroscopy still used widely
- In recognition of his work in high energy electron scattering from nuclei, awarded Nobel Prize in 1961

IMPORTANT DISCOVERIES WITH SCINTILLATION DETECTORS

• Neutral pion (π^0) decay (1950)	decay photons
• Positronium decay (1951)	decay photons
• Mu-mesic atoms (1953)	‘X-ray’ transitions
• Electron scattering (1953)	electron detection
• Anti-proton discovery (1955)	Time of flight
• Parity violation in β-decay (1957)	C.S. Wu
• Mossbauer Effect (1958)	Rudolf Mössbauer

Transistor Era

- **1901 - J.C. Bose patents 'Cat's Whisker' for RF rectification**
- **1940 - Russell Ohl invents solar cell (*pn* junction)**
- **1947 – J. Bardeen invents the point contact transistor**
- **1951 – W. Shockley invents junction transistor**
- **1959 – J. Kilbey invents *Integrated Circuits***

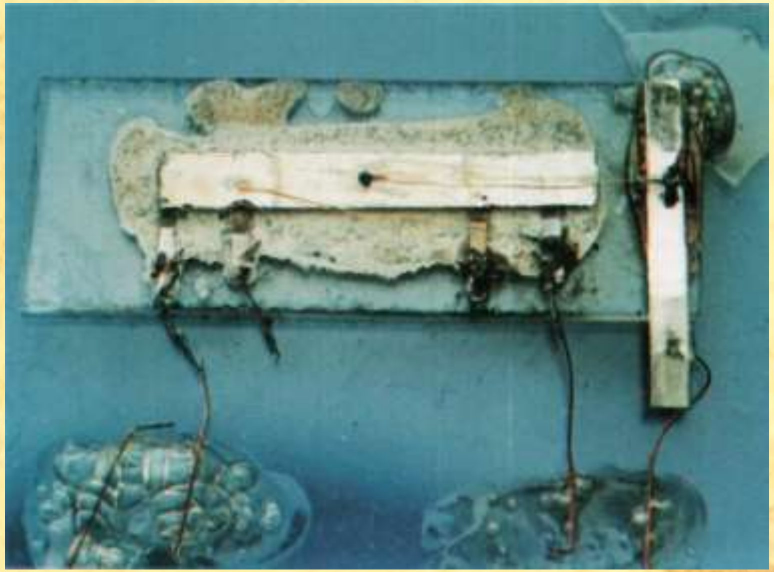




Early Semiconductor Devices

First transistor (1947)

Hybrid circuits (1960)

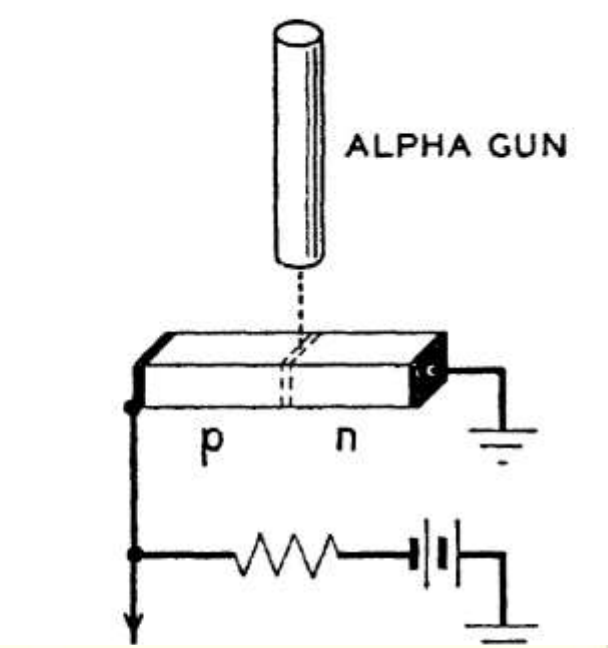


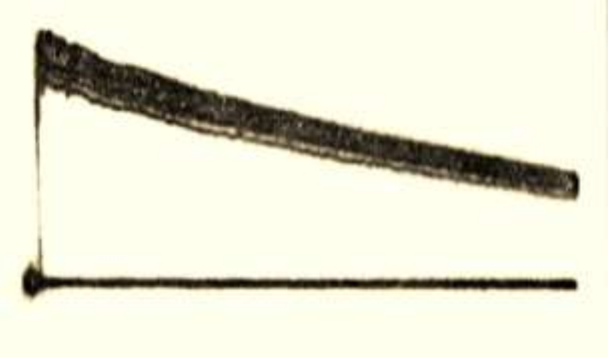
First integrated circuit (1959)

Fairchild IC (1962)

SEMICONDUCTOR DETECTORS

- K.G. Mckay (1949) demonstrated that a Ge point-contact diode can be used to detect α-particles. Better results were obtained from a Ge surface-barrier detector (1951)
- Average energy required for e-h production in Ge was measured to be 3.0 ± 0.4 eV
- After the demonstration of semiconductor diodes as radiation detectors, emphasis was on developing surface barrier silicon detectors (1959)
- Si(Li) drifted detector (1962)
- Ion-implanted Si detector (1967)

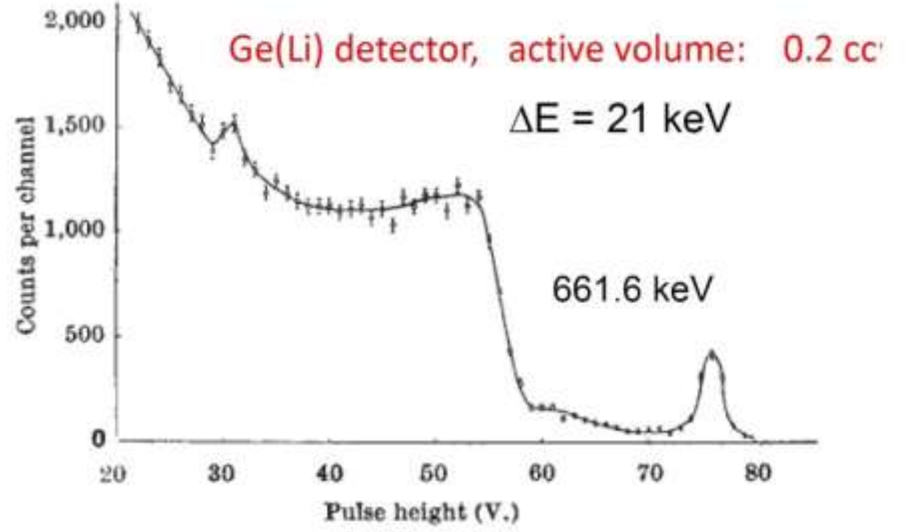


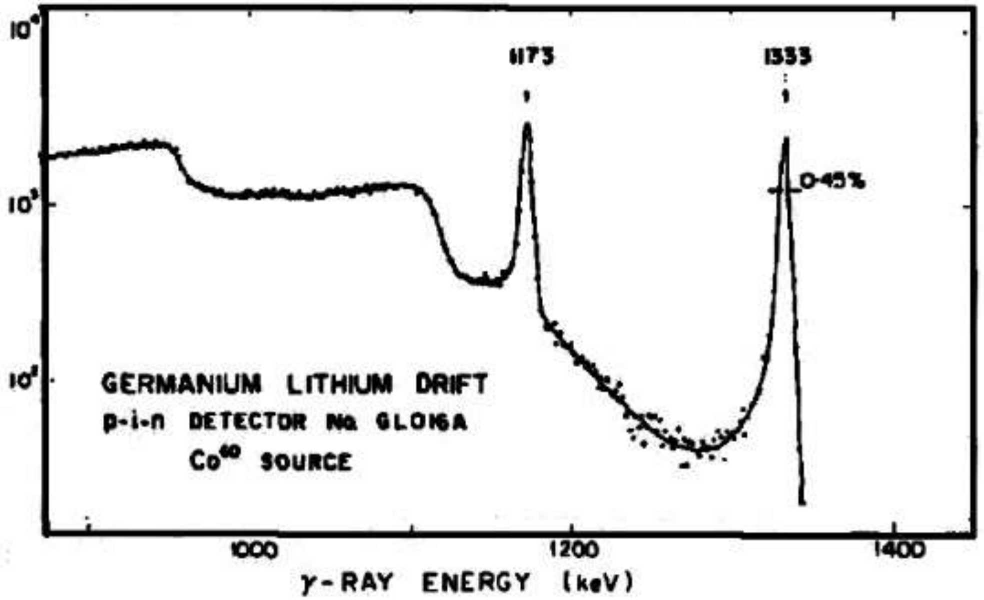


γ-Spectroscopy with Ge Detectors

- First Ge(Li) spectrum was reported by D.V. Freck (1962) with energy resolution of 21 keV
- In 1963, George Ewan developed high resolution γ-spectroscopy using a Ge(Li) detector of 1 cc active volume (energy resolution of 6 keV)
- Use of a cooled FET reduced input noise to 0.7 eV (1965)
- High Purity Ge detectors (HPGe) became available in 1970's

First Ge(Li) detector: D.V. Freck and J. Wakefield
Nature 193, 669 (1962)





Early Days of Nuclear Instrumentation : Summary

For a young experimentalist in 1970, the following tools were available to me:

• Energy Measurement:	Si(Li), NaI(Tl)
• Energy Loss:	Si SB, ionisation chamber
• Position measurement:	Si, MWPC, Resistive wire PC
• Timing:	SB, PPAC, Plastic scintillator
• γ-measurement:	NaI(Tl), Ge(Li)
• Electronics:	Transistor-based, discrete comp.
• Data Acquisition:	IBM-360/44 32 Kilobytes memory !
• Storage:	Magnetic tape (800 BPI)


Last Fifty Years
1970 - 2018
What’s New ?

Advances in Electronics

- **Development of electronics played a major role in instrumentation**
- **VLSI allowed more than 10^6 transistors on a chip (1990)**
- **Decrease in cost, space and power**
- **Increase in no. of channels required dedicated ASIC chips for processing**
- **Major advances in FPGA (1992) found wide applications in nuclear electronics**
- **More than 2 Million logic cells in a chip**
- **Digital Signal Processing mostly implemented in FPGA**

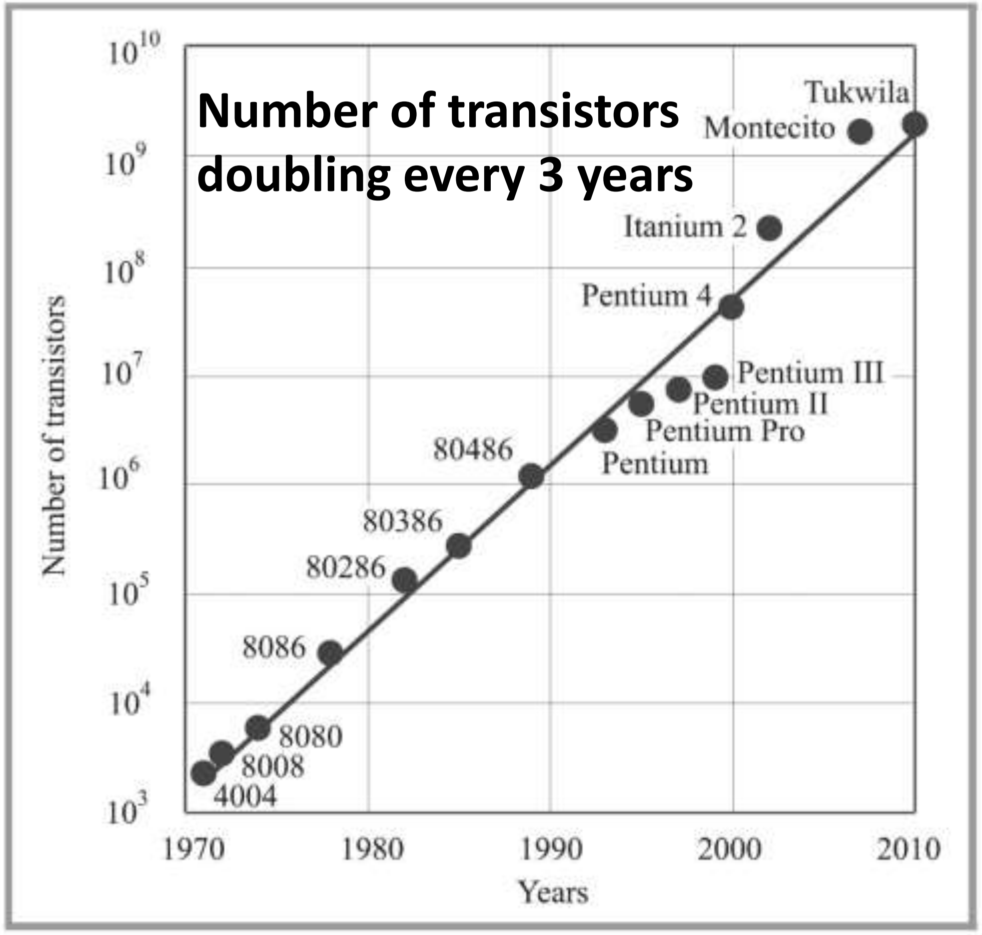
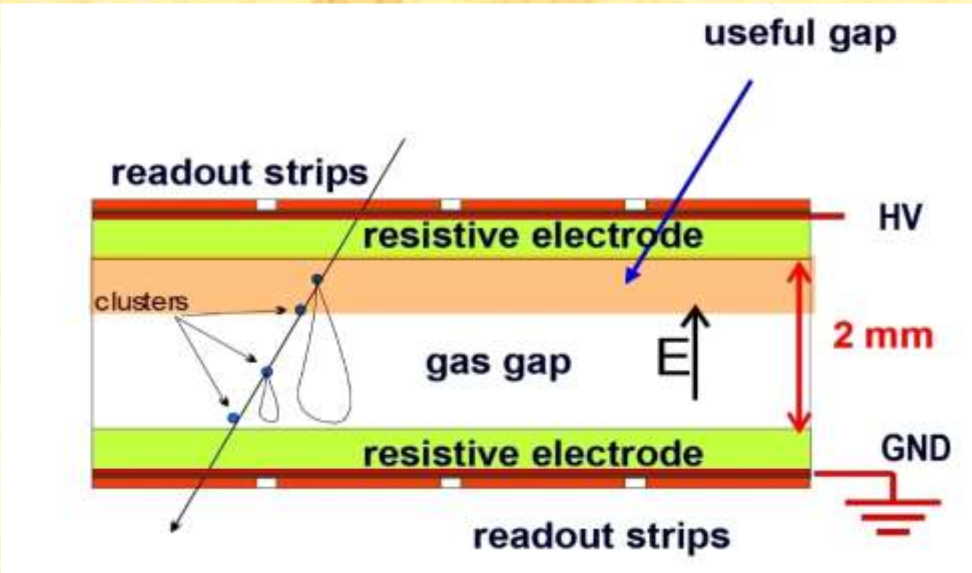


Fig. 7. Number of transistors in successive Intel processors as a function of time (data after [44]).

Avalanche Detectors

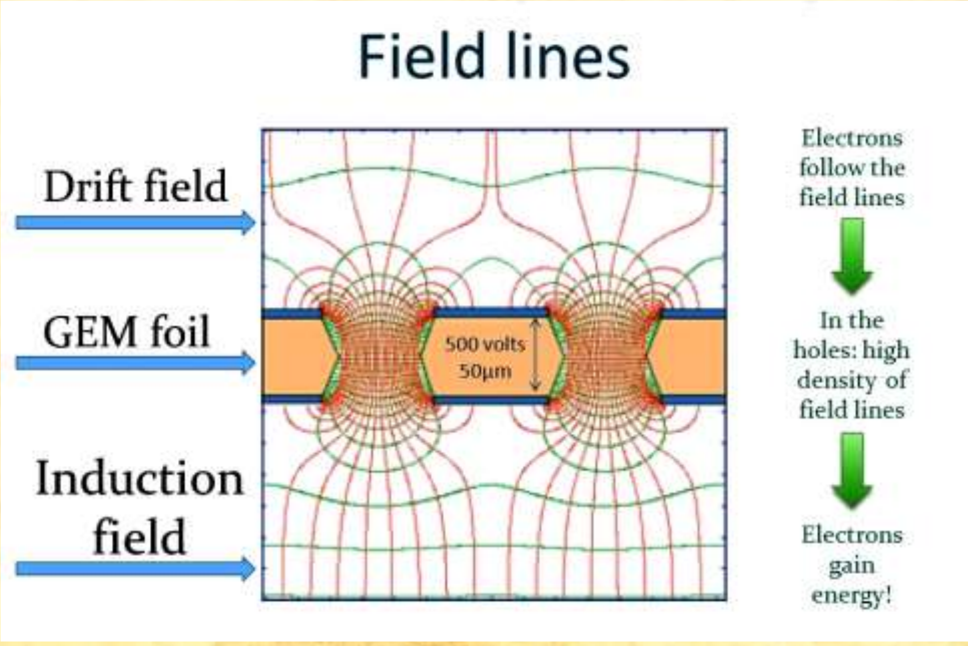
Resistive Plate Chamber (1981)

- Highly resistive Bakelite electrodes
- Resistive layer helps quenching discharge
- Signal pickup from conducting strips
- Fast ns timing
- Planned for INO facility



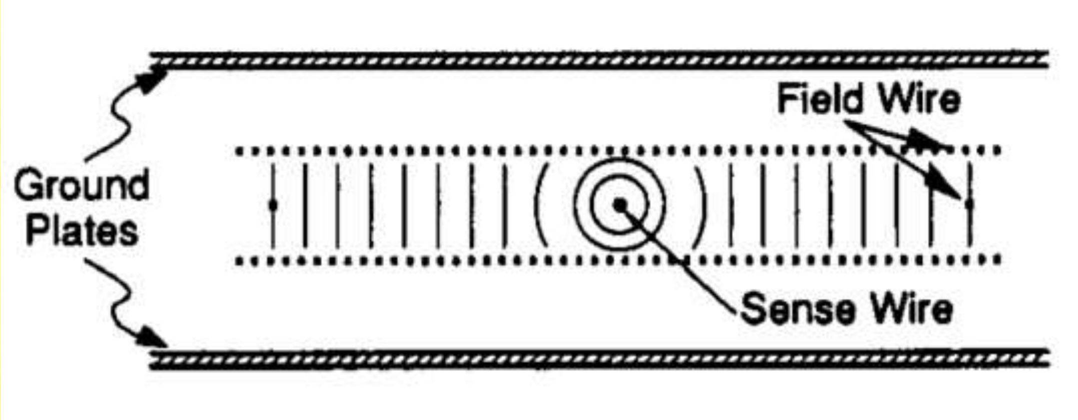
Gas Electron Multiplier (1980)

- Thin layer of insulated foil coated both sides with metal foil
- Contains chemically produced holes of dimension 50-120 μm and spacing 140 – 200 μm
- Position resolution ~ 100 μm



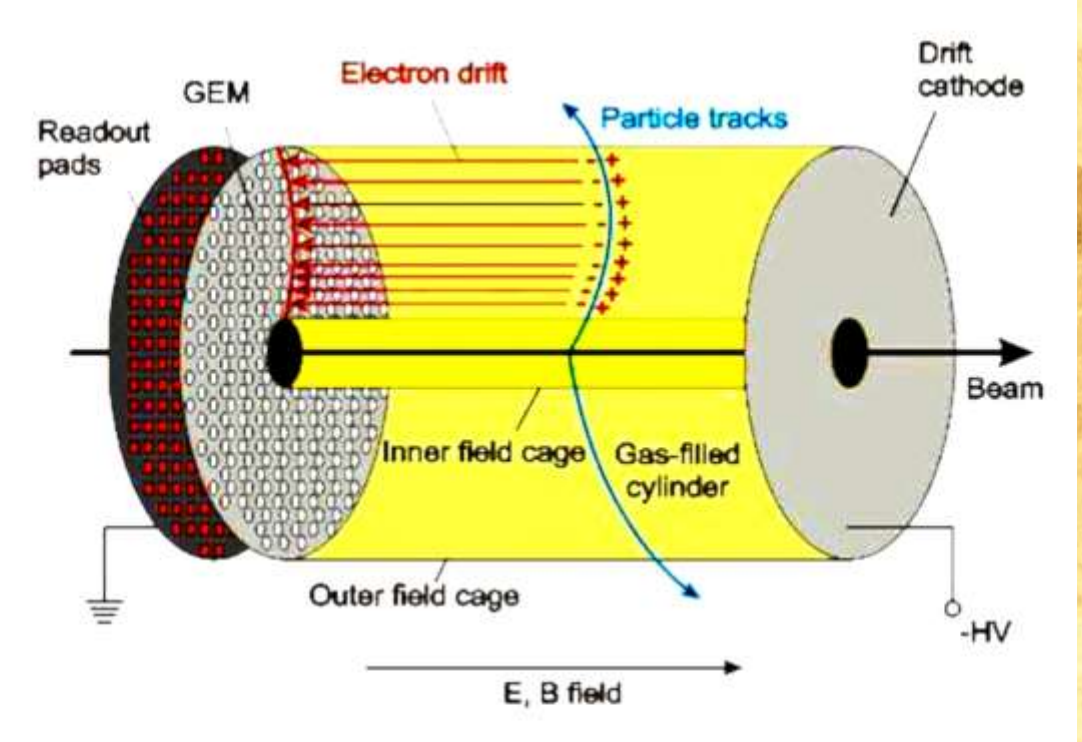
Drift Chamber (1971)

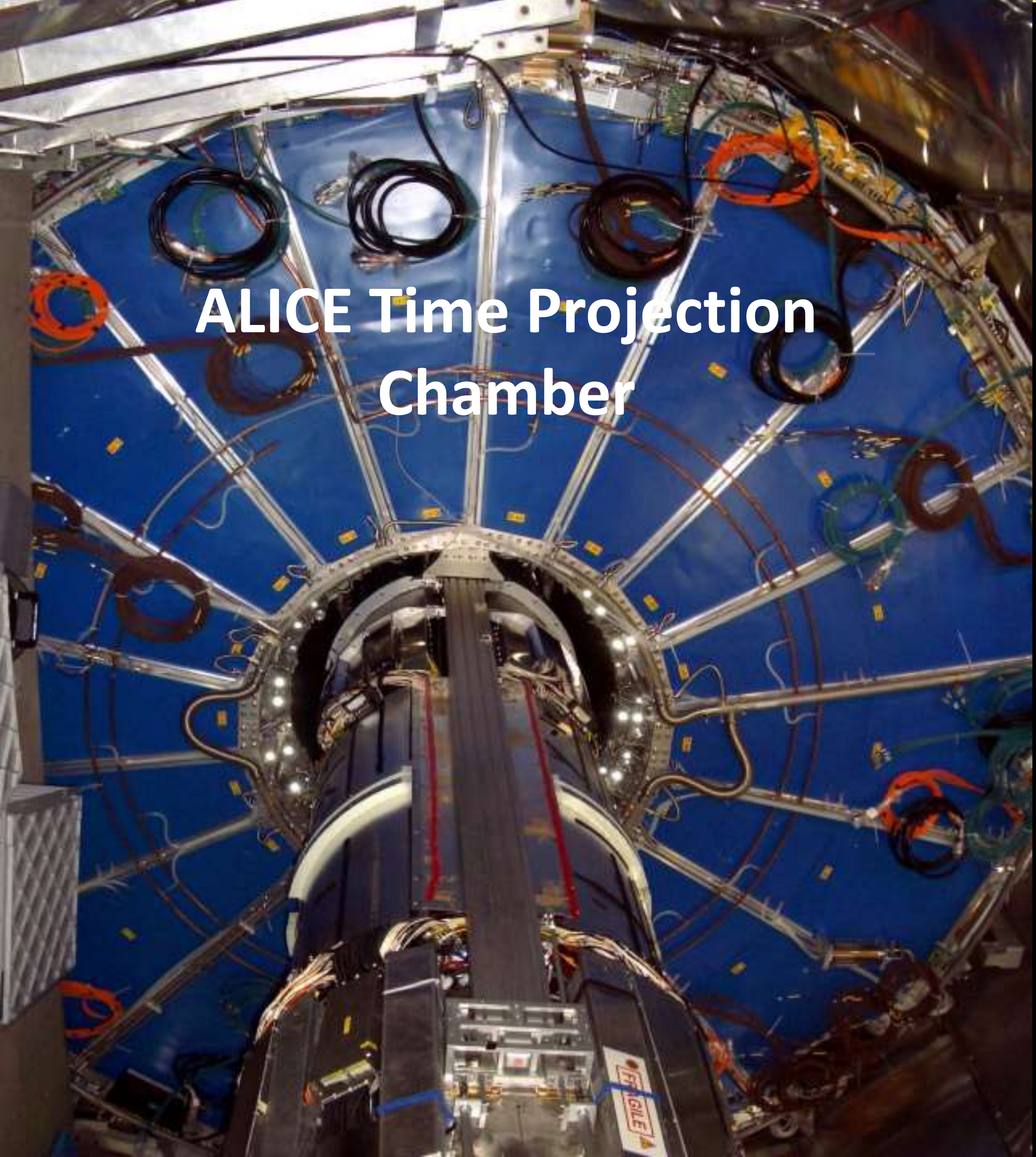
- Design similar to MWPC but increased sense wire spacing
- Uniform electric field maintained by guard wires
- Electrons drift towards anode before being collected (v ~ 5 cm/μs)
- Position measured from drift time



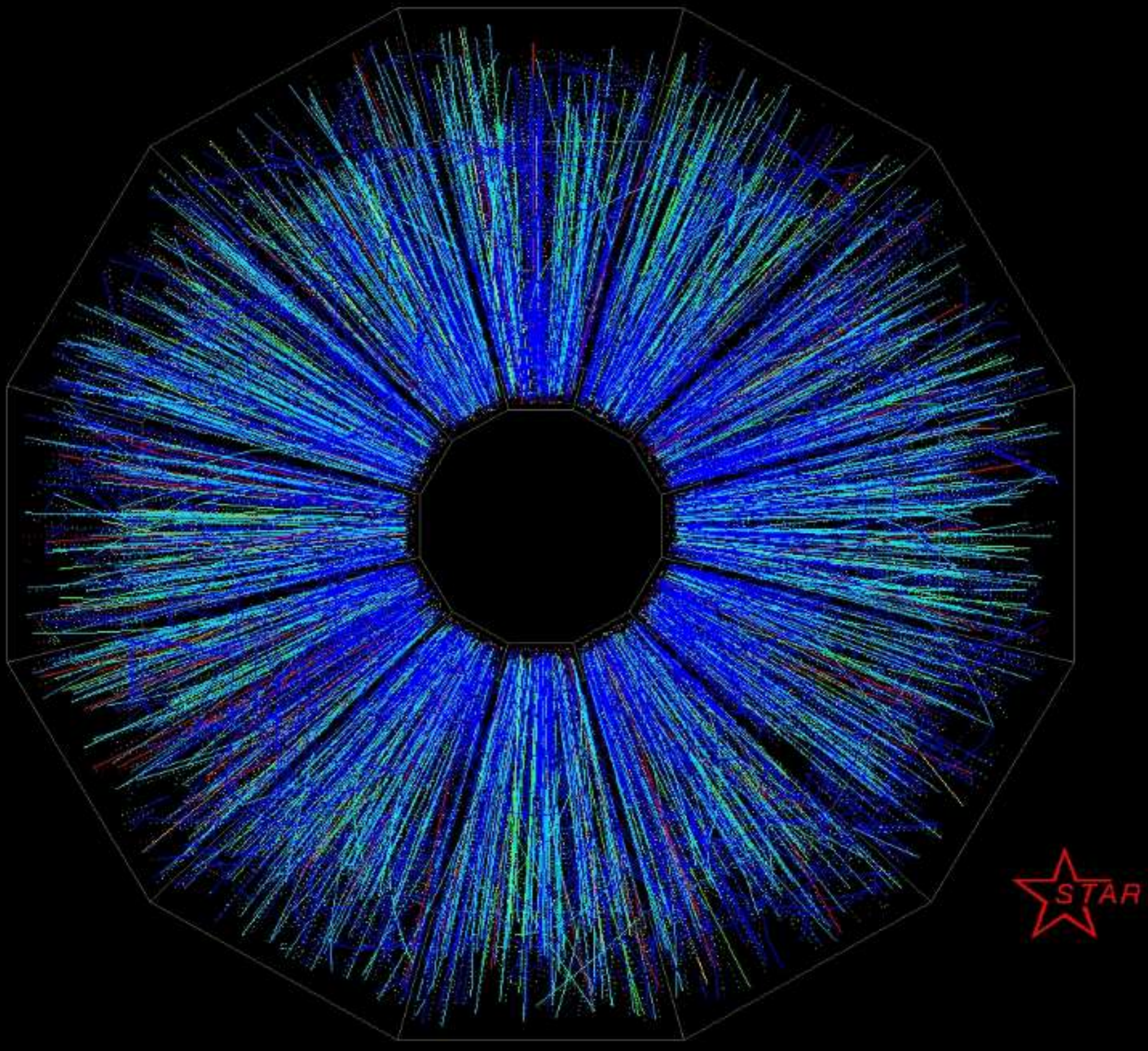
Time Projection Chamber (1974)

- Z-position from drift time
- Anode segmented to get x, y
- Measurement of particle trajectory possible



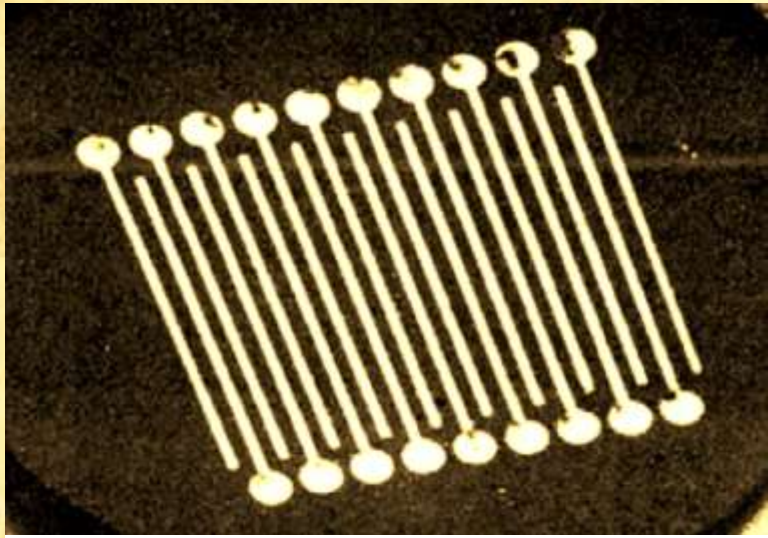


Electronic Visualisation of Tracks

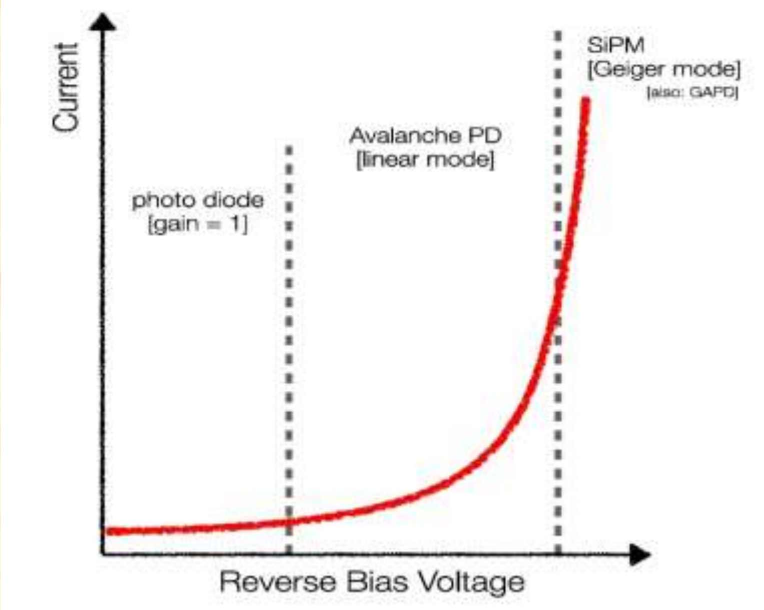


Development in Si Detector Technology

- Silicon Strip Detector (1980)
  - Readout from individual strips
  - 25 – 100 μm pitch possible
  - Advances in VLSI design allows 128 channel readout by a single chip (1984)
  - Pixel detectors (1997) have readout chips for individual pixels (55 x 55 μm)

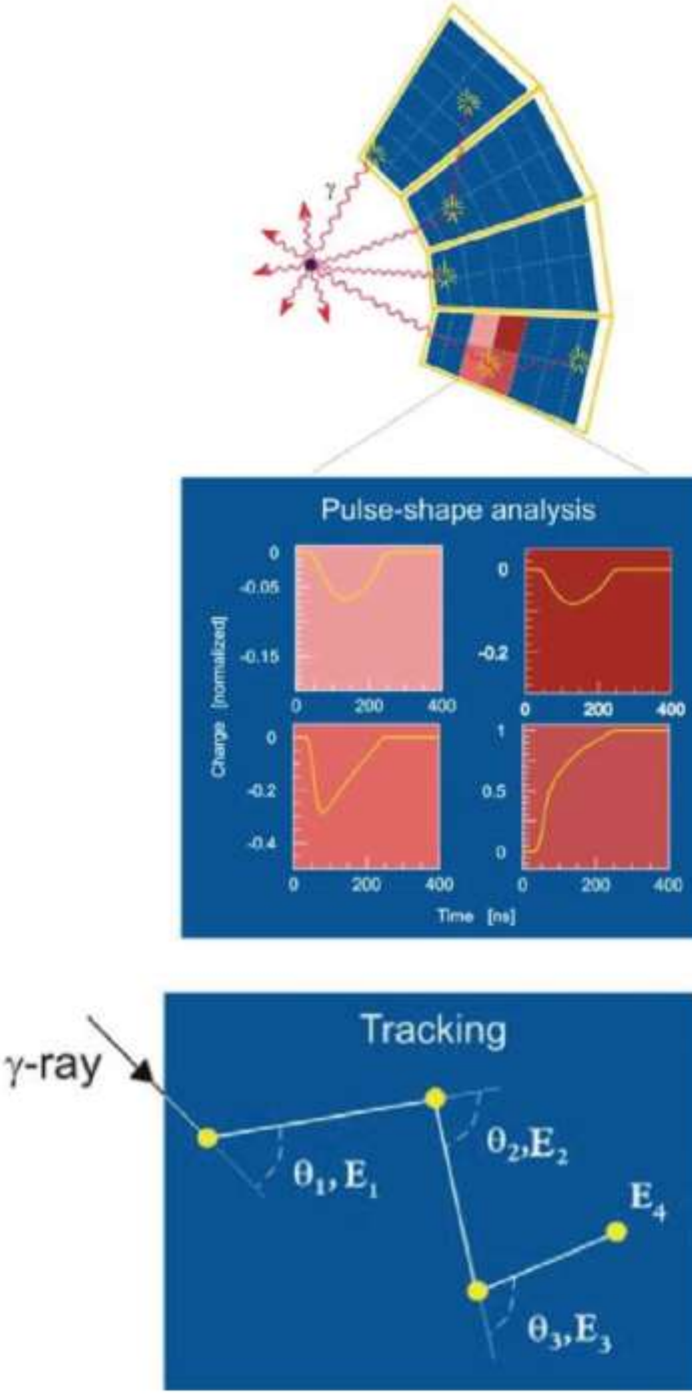


- Silicon Photomultiplier (1996)
  - Array of avalanche diodes connected in parallel operated in Geiger mode
  - Output proportional to no. of pixels triggered
  - Compact geometry insensitive to magnetic field



Time Evolution of Ge detectors

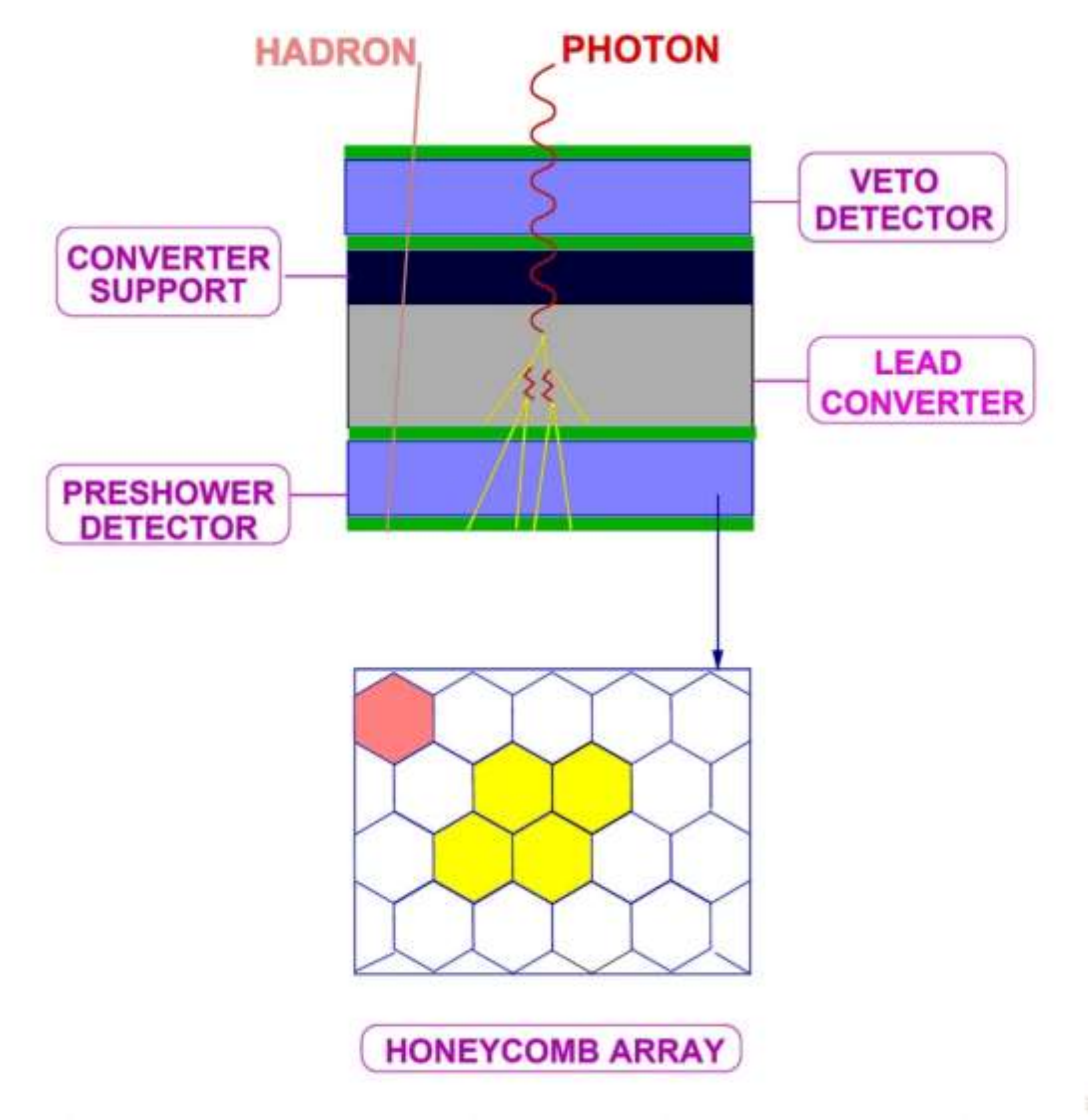
- High Purity Ge crystals developed (1971)
- Anti-Compton Shield (NaI 1971, BGO 1985)
- Segmented Ge(Li) detectors (1975)
- Ge(Li) - NaI array TESSA(1980)
- HPGe – BGO array NORDBALL(1985)
- Composite detectors CLUSTER (1992) & CLOVER(1999)
- GAMMASPHERE (1995), EUROBALL(1997)
- Electrically segmented detectors – Tracking (1999)
- GRETINA(2011), AGATA (2010) & GRETA (2014)



DETECTOR DEVELOPMENTS IN INDIA

Photon Multiplicity Detector at ALICE

- **100% Indian effort: Design, Fabrication, Installation and Data Acquisition**
- **4608 hexagonal proportional counters per module (48 modules)**
- **MANAS ASIC chip used for signal processing and multiplexing**
- **2. 10^5 readout channels**

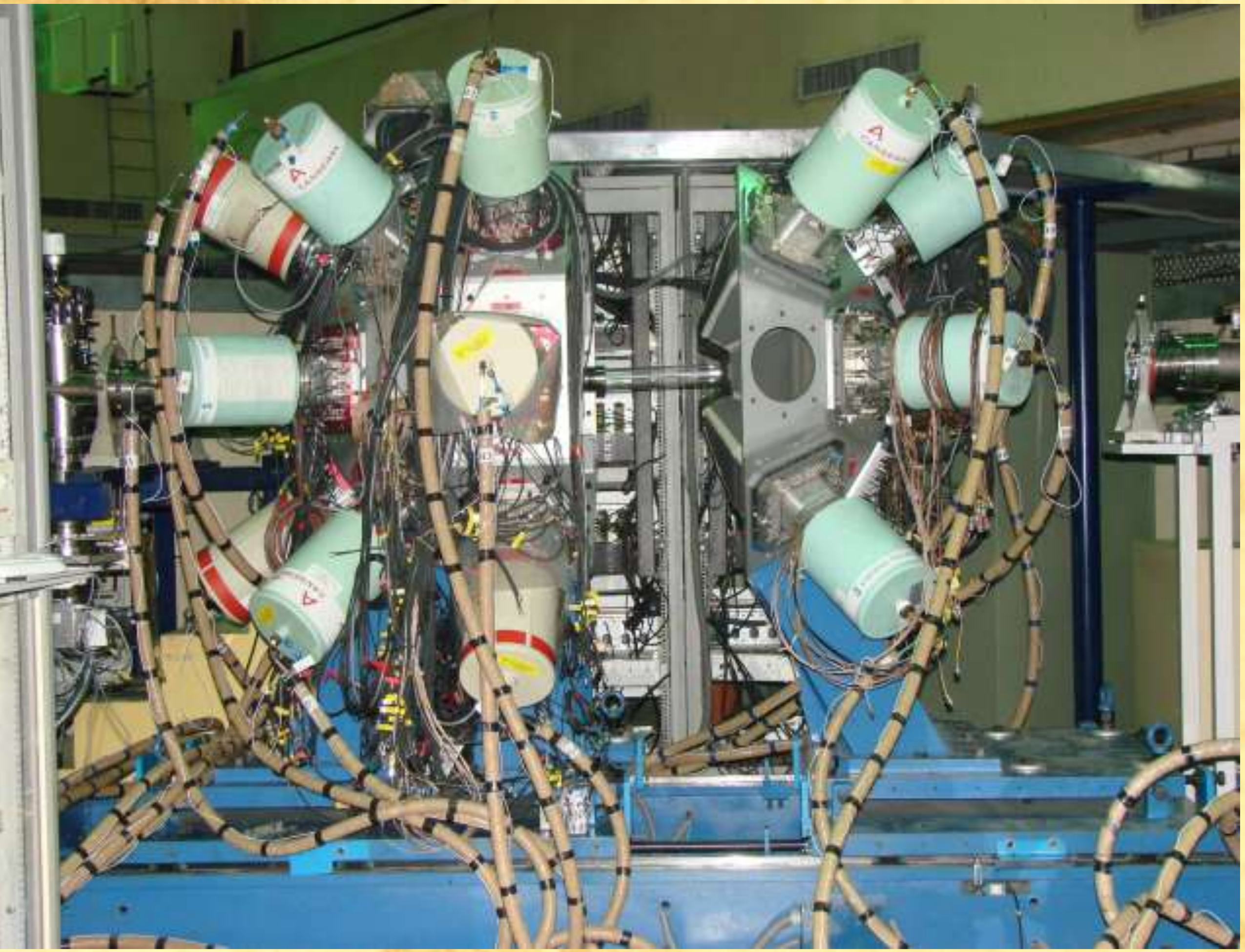


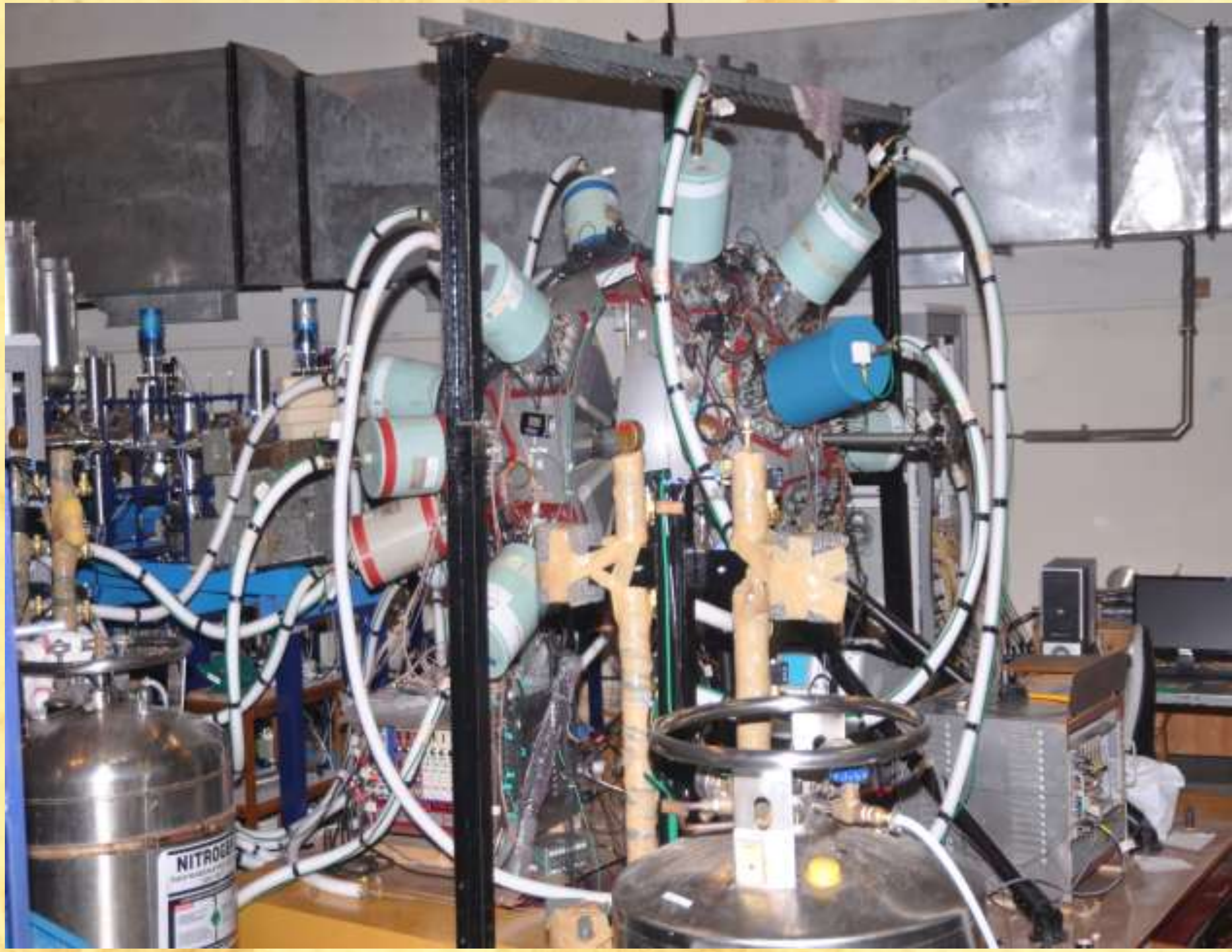
GEM development in India

- **Muon detector upgrade at LHC**
- **HI detection at VECC**

Indian National Gamma Array (INGA)

24 Clover detectors 120 channel readout Analogue/Digital Signal Processing

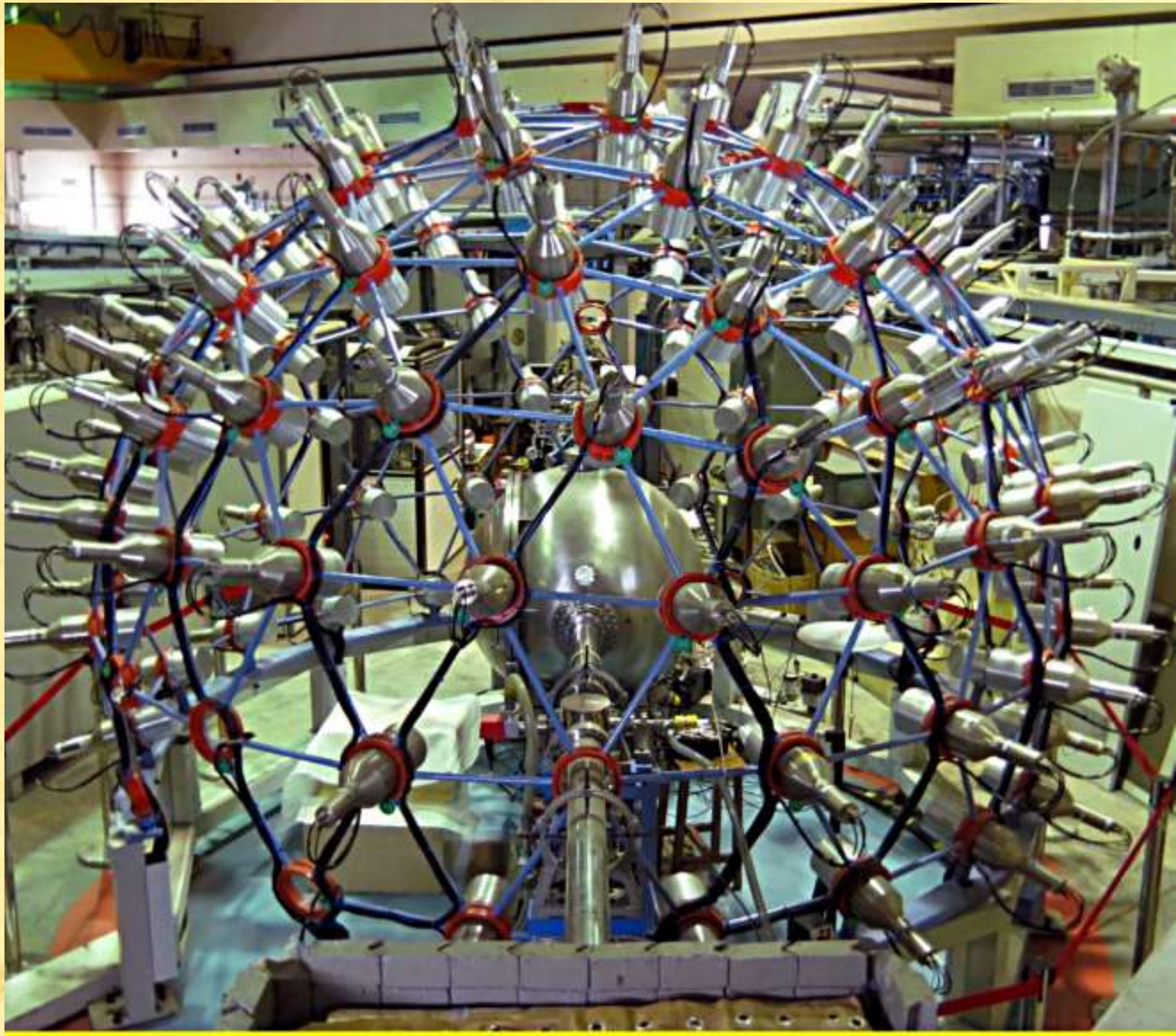




National Array of Neutron Detectors (NAND)

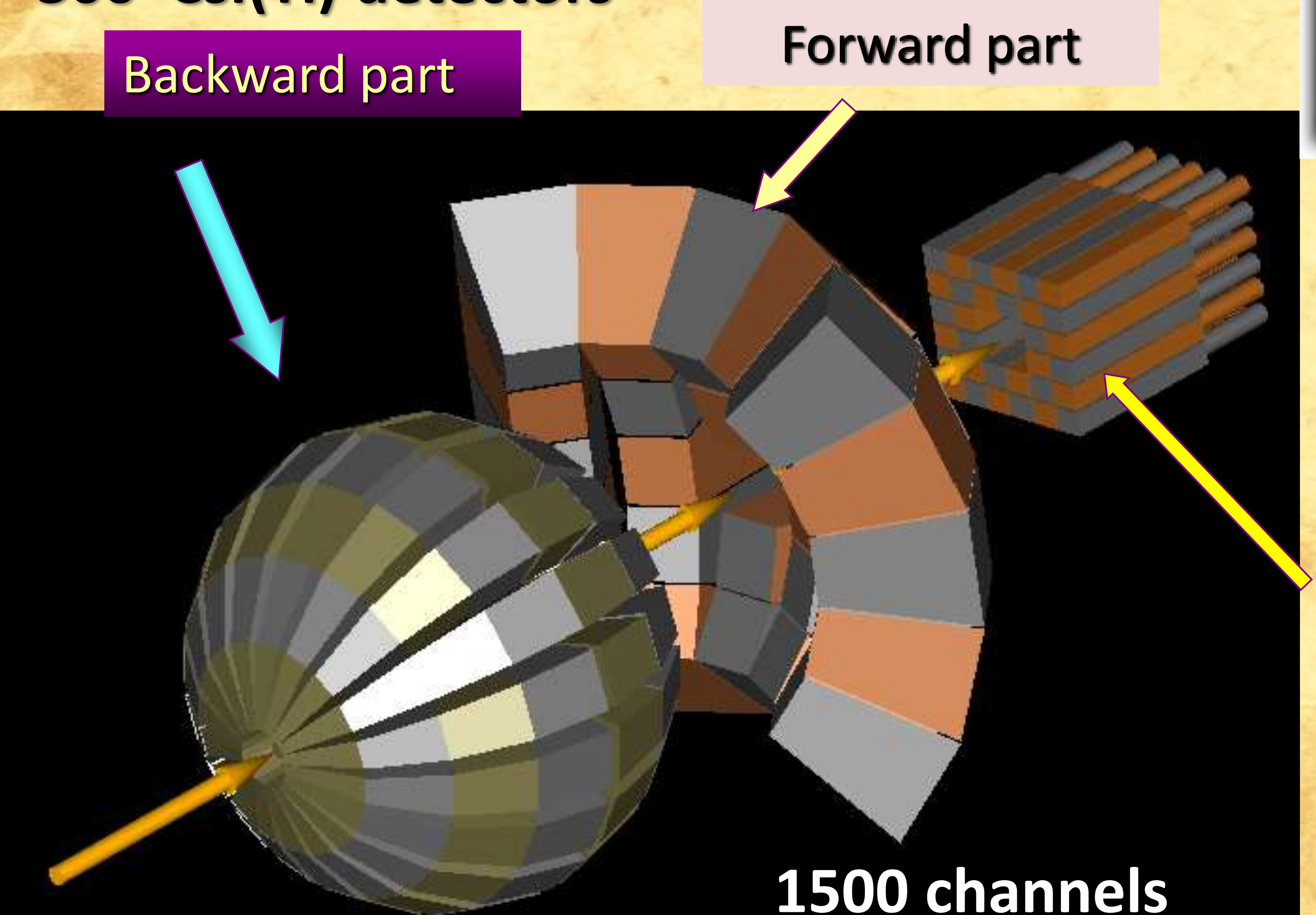
- **100 Neutron Detectors**
- **300 data channels E, PSD, t**
- **Analogue electronics developed in-house**
- **VME-based data readout**

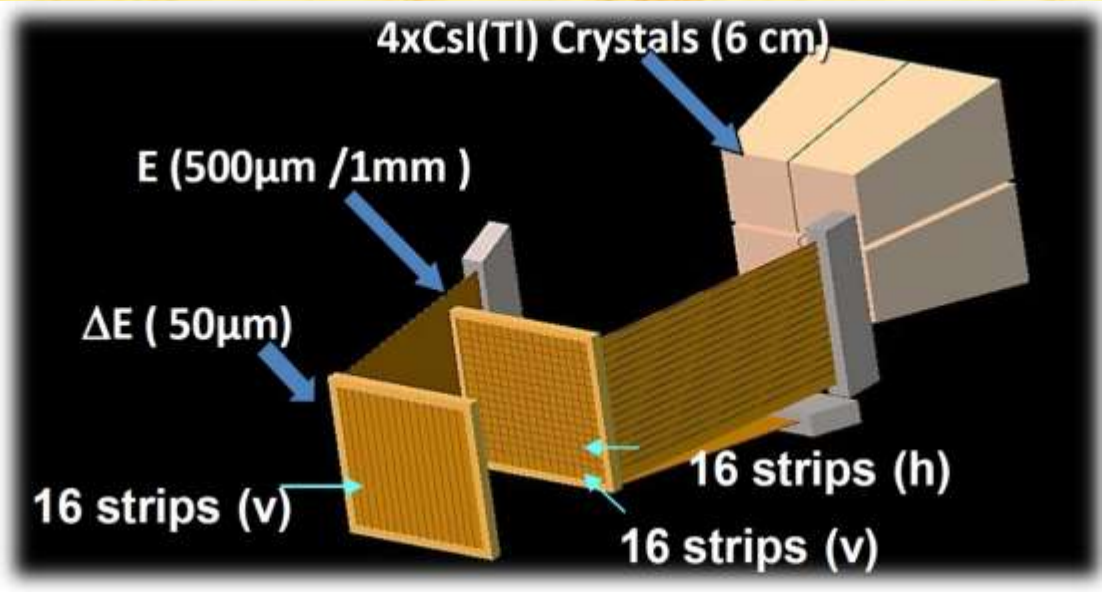
Neutron Arrays also developed at BARC, VECC and SINP



Charged Particle Detector Array at VECC

300 CsI(Tl) detectors





24 Si-Si-CsI detector

Forward Array

Angular coverage:
7^0 - 45^0

Extreme forward part

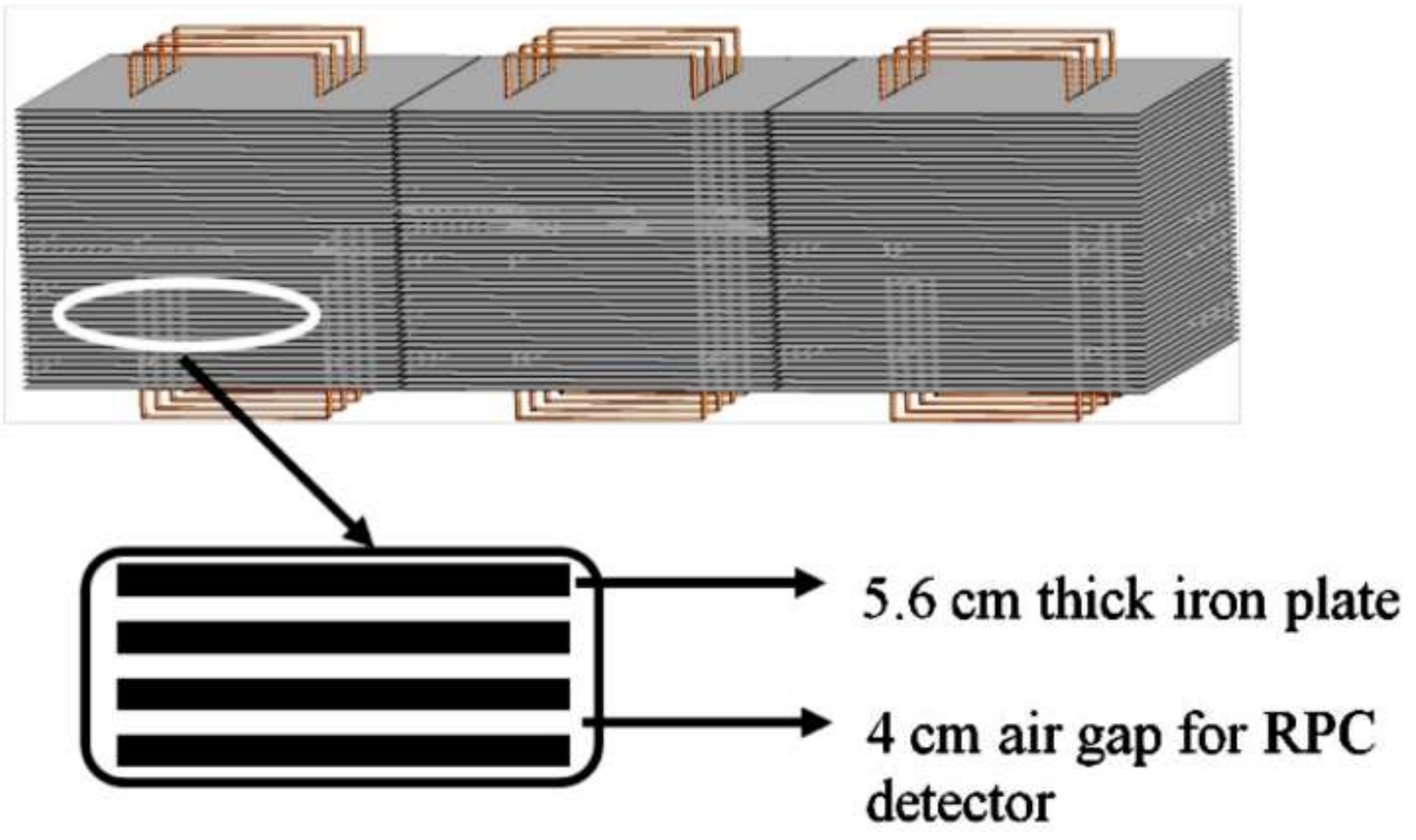
Angular coverage: 3^0 -7^0

32 Phoswitch Detector

Extreme Forward Array

India-based Neutrino Observatory (INO)

- Iron Calorimeter (ICAL)
- Largest Electromagnet in the world
- 1.5 T magnetic field
- 14000 Magnetised Iron plates 48m x 16 m x 14.5 m
- 30000 RPC
- 40,000,000 readout channels



Schematic view of the 50 kt ICAL detctor

FUTURE PERSPECTIVE

- **Increase in the number of channels per experiment**
- **Even ‘low energy nuclear physics’ experiments require more than 100 channels (100 detector NAND array)**
- **Shift from analogue to digital signal processing**
- **Require dedicated manpower in instrumentation for future generation experiments**
- **Future looks bright**