Detectors for Nuclear Physics

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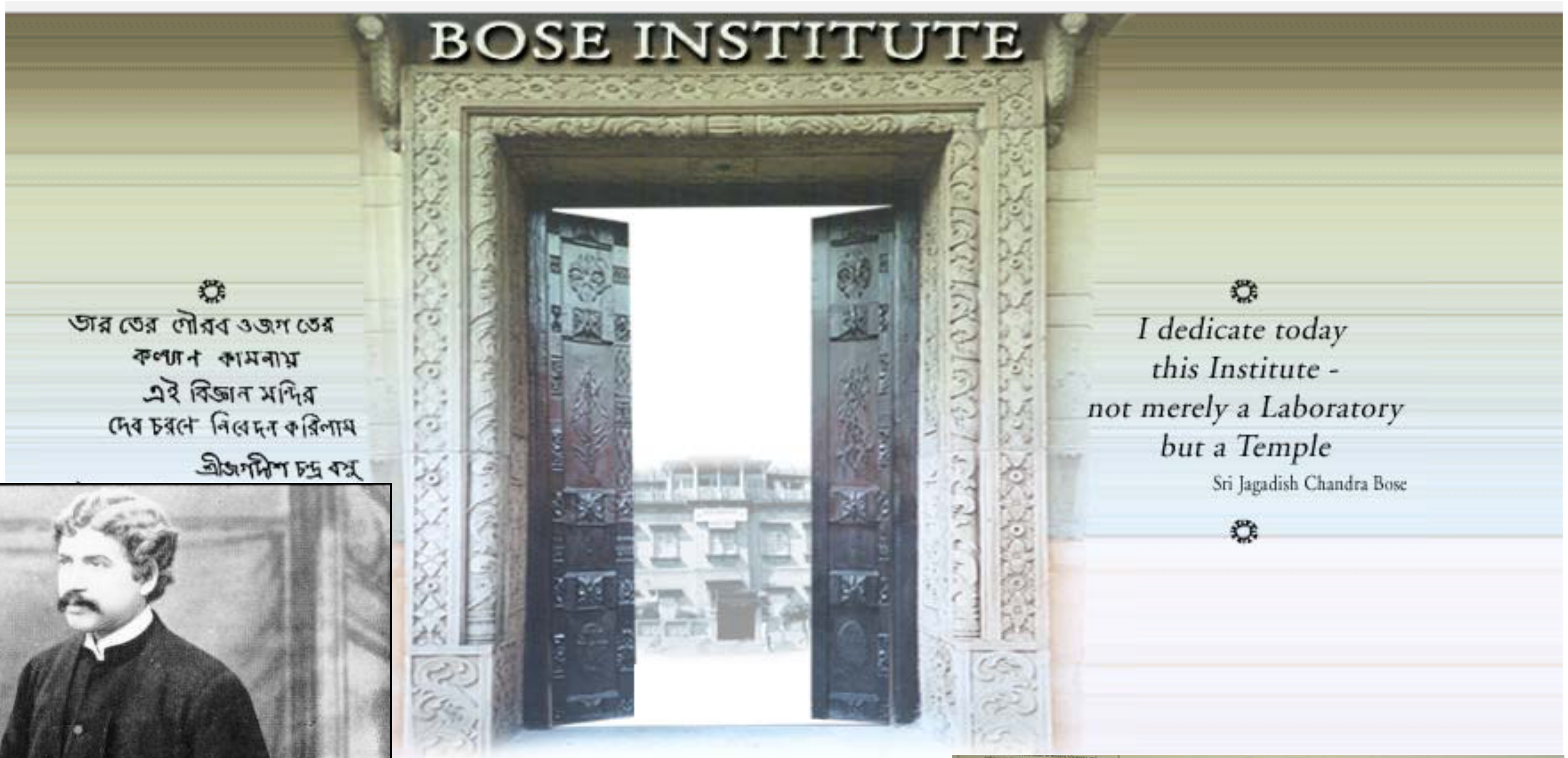
Variable Energy Cyclotron Centre
Kolkata, India

Celebrating centenary year



Jagadish Chandra Bose
(1858-1937)

Plan of the talk

- Introduction: Scope of detection in Nuclear Physics
  - things we can detect & measure
  - what we learnt from that

- VECC activities: to develop, characterize and use detectors in experiments within the field of fundamental Nuclear Physics

Share our knowledge and insight to mark this momentous occasion !

Fundamental Nuclear Physics

Nuclear Physics

How do the **nucleons** work together to form matter?

- Nuclear structure

Many of these nuclei, you need to make them react with target nuclei in order to understand what is going on.

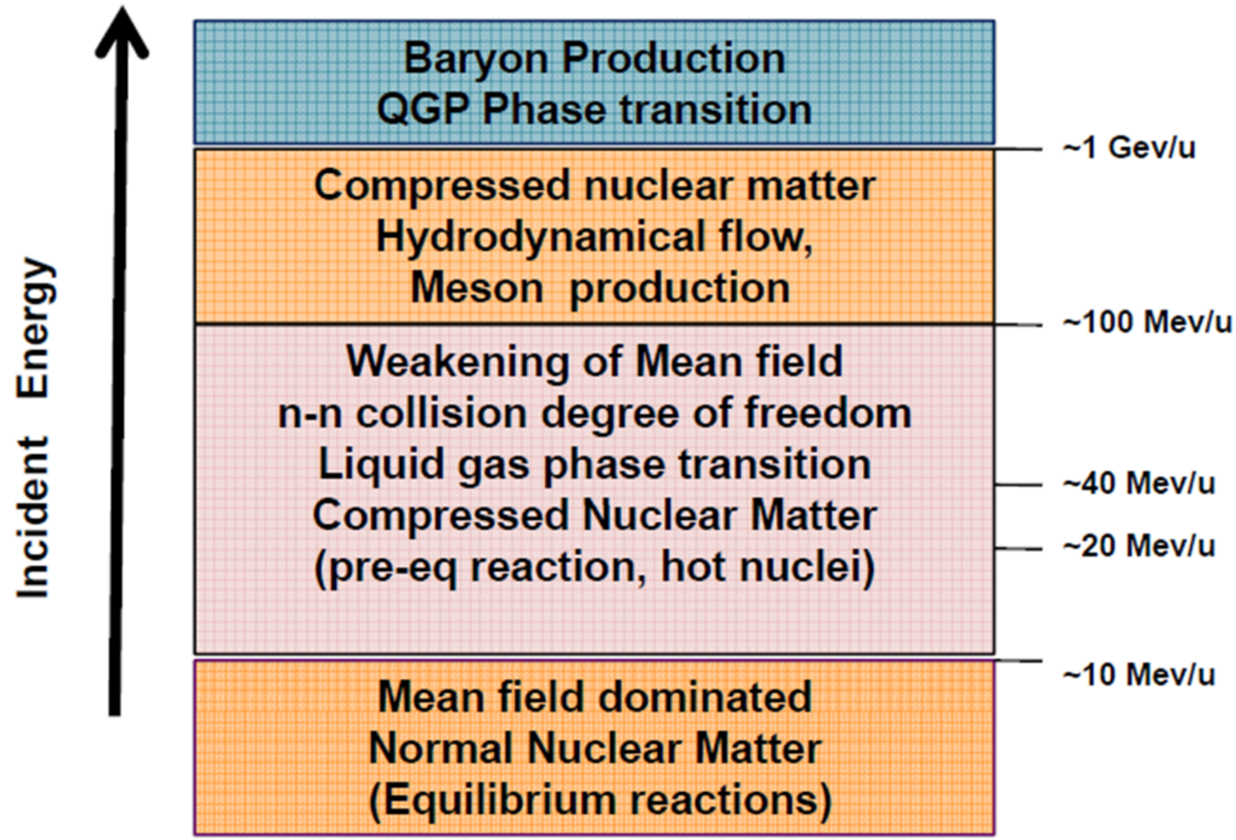
The rearrangement of the nucleons inside nuclei helps us to understand the macroscopic or bulk properties of the **nuclei.**

- Nuclear reaction

High Energy Physics

On the other hand, Particle physics is the study of fundamental particles, i.e. **quarks and leptons** and their interactions.

Nuclear and High Energy Physics



Detection system: With increase in beam energy, particle multiplicity, types increases

Accelerator facilities for Nuclear Physics in India

Higher energies: LINACs at Delhi & Mumbai and K500 Cyclotron in Kolkata

Things we need to measure

(I) Z, A of emitted particles :

– tells us what the reaction was, what was made

Detection: by various means –dE/dx, time-of-flight

(II) Energy (E) and angles (θ) of emitted particles:

– excitation energies of the residual nuclei

– shapes of angular distributions can tell us about the reaction mechanism and properties of the residual nuclei

Detection: by direct energy measurement and position

(III) Cross sections :

σ, $\sigma(\theta)$ or $d\sigma/d\Omega$, $\sigma(E)$ or $d\sigma/dE$, $d^2\sigma/dEd\Omega$, *etc.*

– Magnitude of the cross section can inform us about a variety of properties.

Detection: by counting the scattered particles

Energy, time, position and count

Detectors @ VECC

I. Gas detectors

- PPAC
- MWPC
- Hybrid gas detector
- Ionisation chamber

II. Semiconductor detectors

- CPDA : an array of 24 silicon detector telescopes

III. Scintillation detectors

- CsI, phoswich detectors, BaF2 array (LAMBDA)

IV. Neutron detector array

- BC501A liquid scintillator based, array of 50 detectors

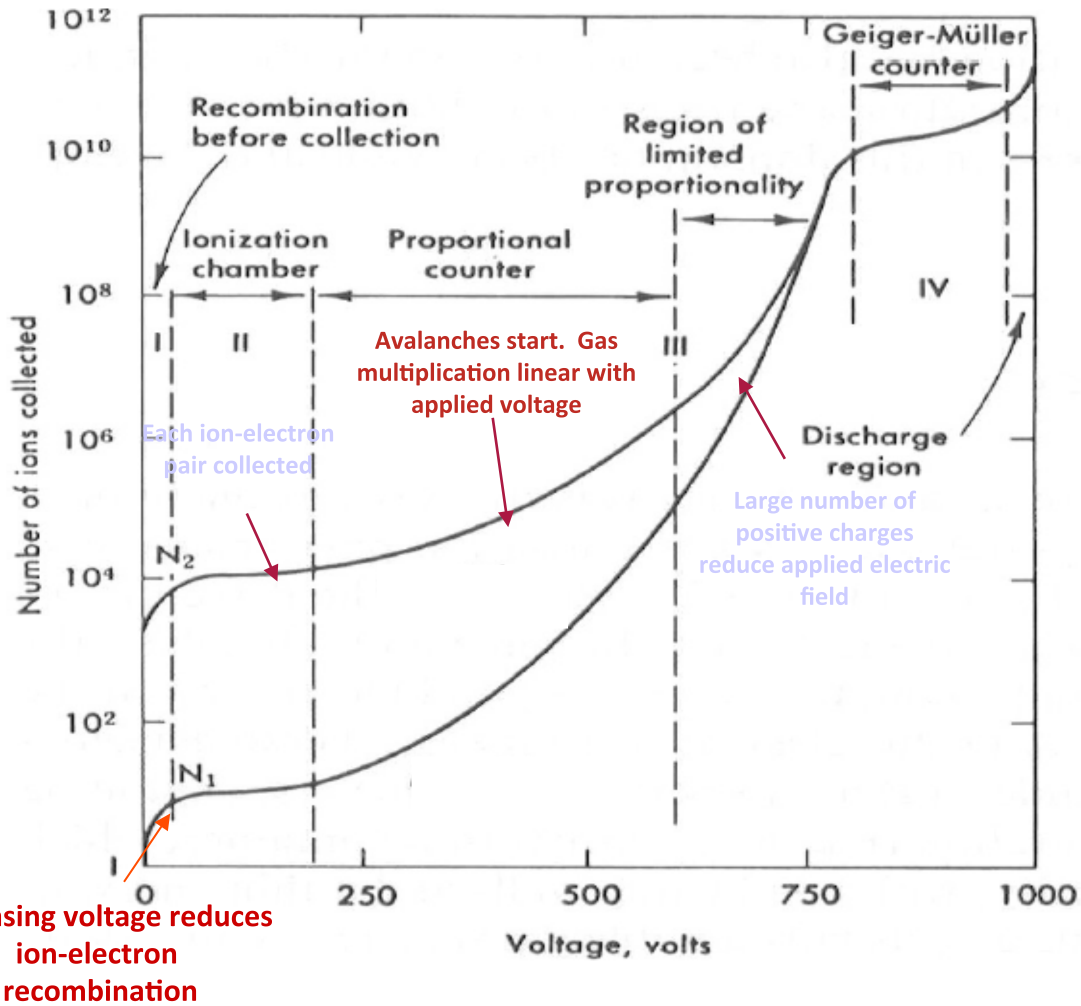
V. Gamma detector array: VENUS

Gas detectors @ VECC

Mode of operation regimes of the detectors

- PPAC
- MWPC
- Hybrid gas detector

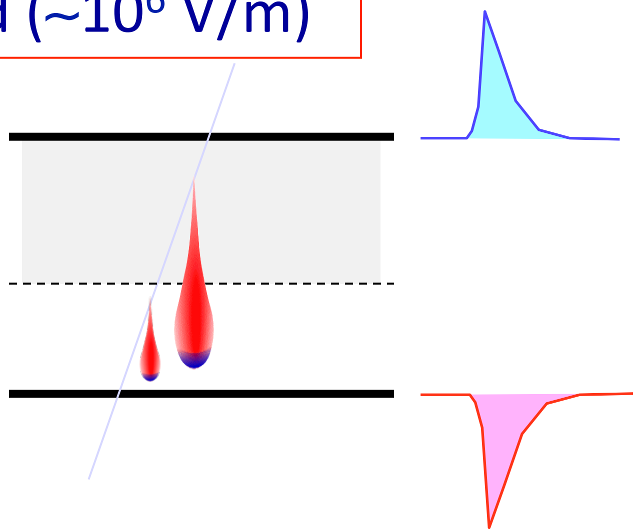
- Ionisation chamber



Parallel Plate Avalanche Counters (PPAC)

Two parallel plate electrodes separated by a small gap
Proportional gas inside

Low gas pressure
High filed (~10^6 V/m)



Avalanche formation in uniform field

Townsend equation

$$dn = n\alpha dx$$

$$n(x) = n_0 e^{\alpha x}$$

Multiplication factor or Gain:

$$M(x) = \frac{n}{n_0} = e^{\alpha x}$$

- Provide fast timing information
- Energy loss of the particle can be obtained (poor resolution)

Geometry of proportional counter

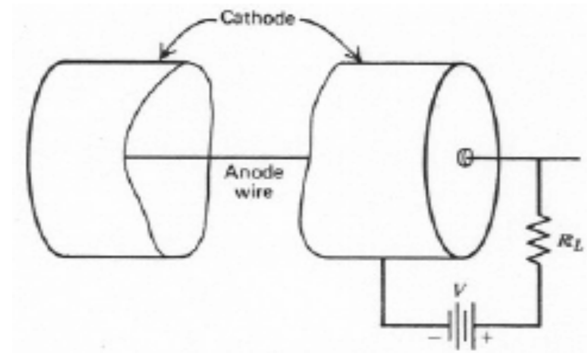
Gas multiplication requires large values of the electric field

Cylindrical geometry:

$$\varepsilon(r) = \frac{V}{r \log(\frac{b}{a})}$$

low *r*, high filed

V **= applied voltage**
a **= anode wire radius**
b **= cathode inner radius**



Example: Take, V = 2 KV , *a* = 50 micron, *b* = 1 cm. Calculate the electric field at the surface of the anode wire.

?(r) = 7.54 x 10^6 V/m

Parallel plate geometry:

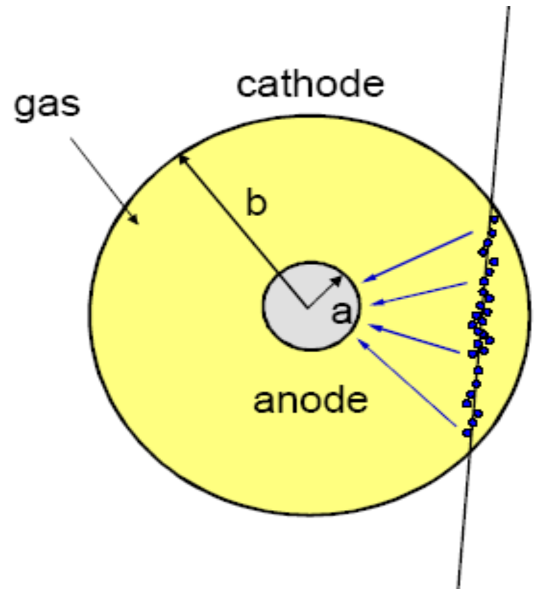
Anode spacing = 1 cm

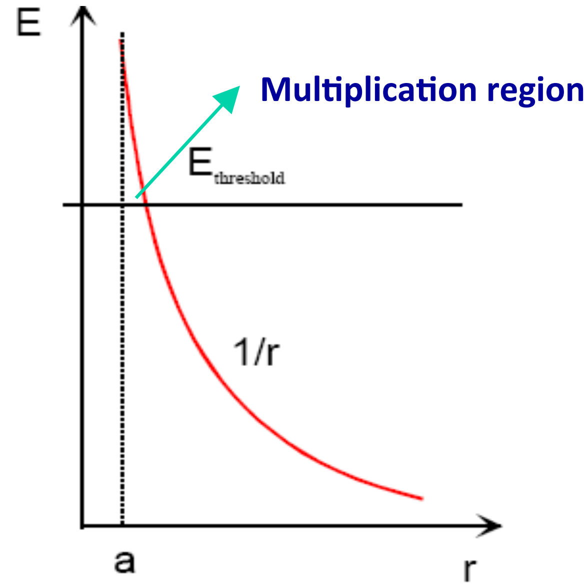
Voltage require to generate the same filed= 75,400 Volt

Choice of detector geometry

Region of gas multiplication must be confined to very small volume for uniform multiplication

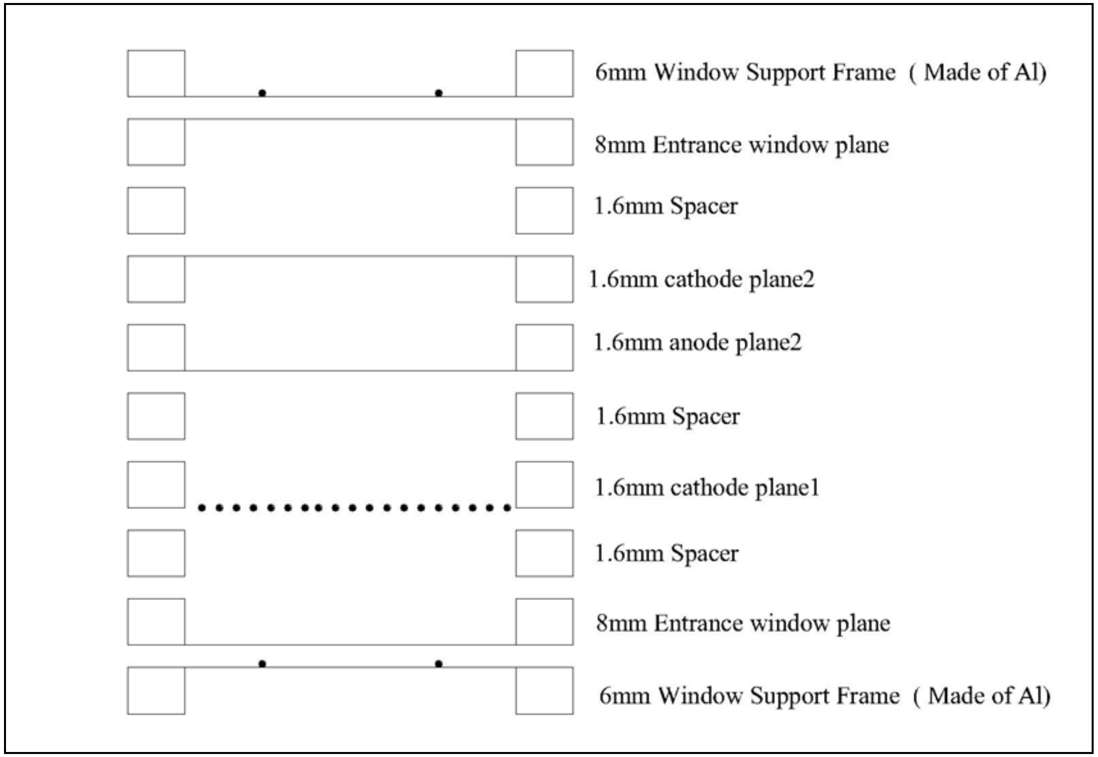
$$\varepsilon(r) = \frac{V}{r\log(\frac{b}{a})}$$

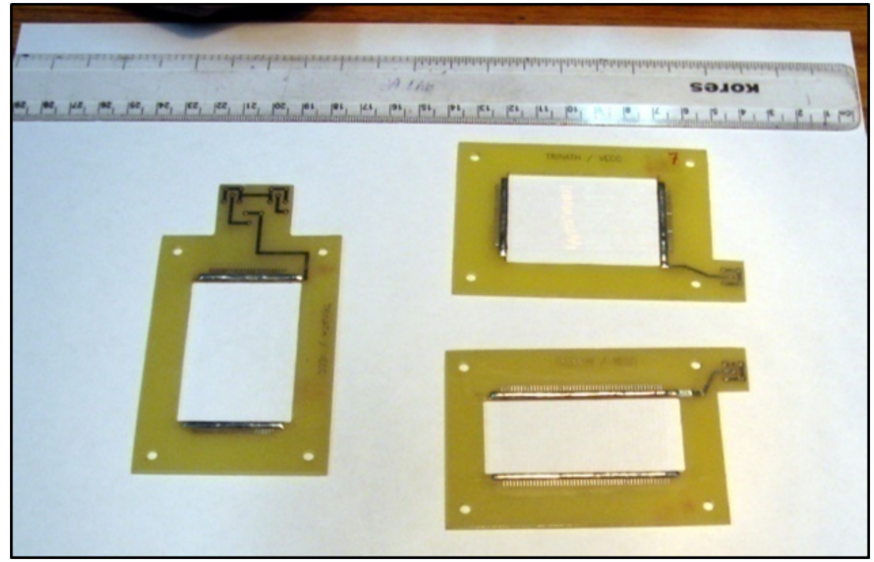




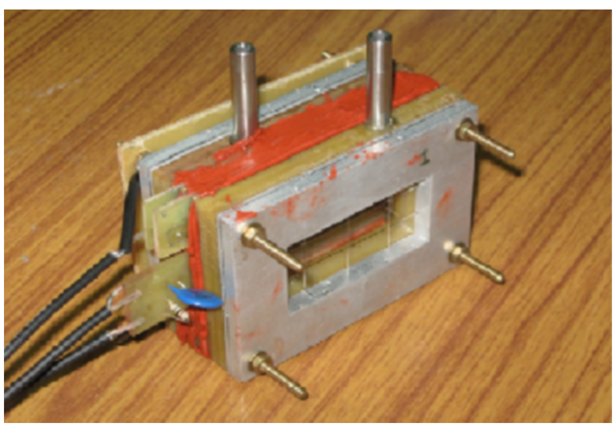
In cylindrical geometry, each electron undergoes the same multiplication regardless of it's original position of formation.

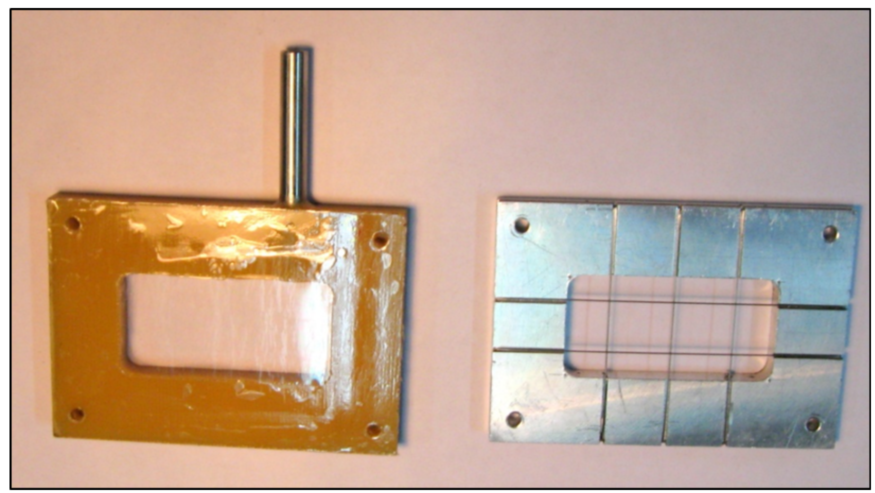
Parallel Plate Avalanche Counters (PPAC)





Active area: 50 mm x 30 mm



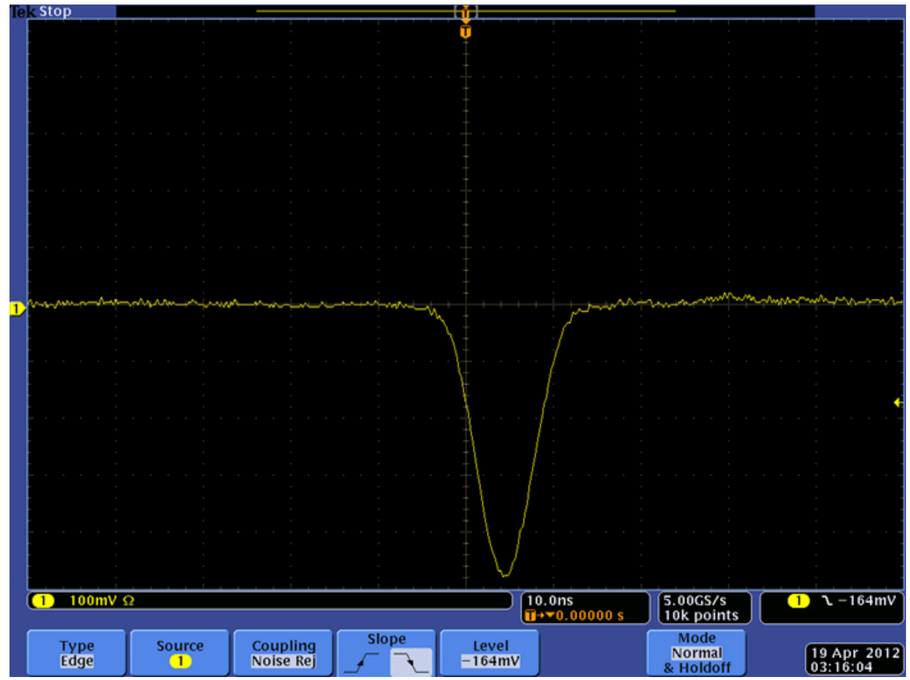


Parallel Plate Avalanche Counters (PPAC)

+ HV: 280 Volt

- HV: 180 Volt

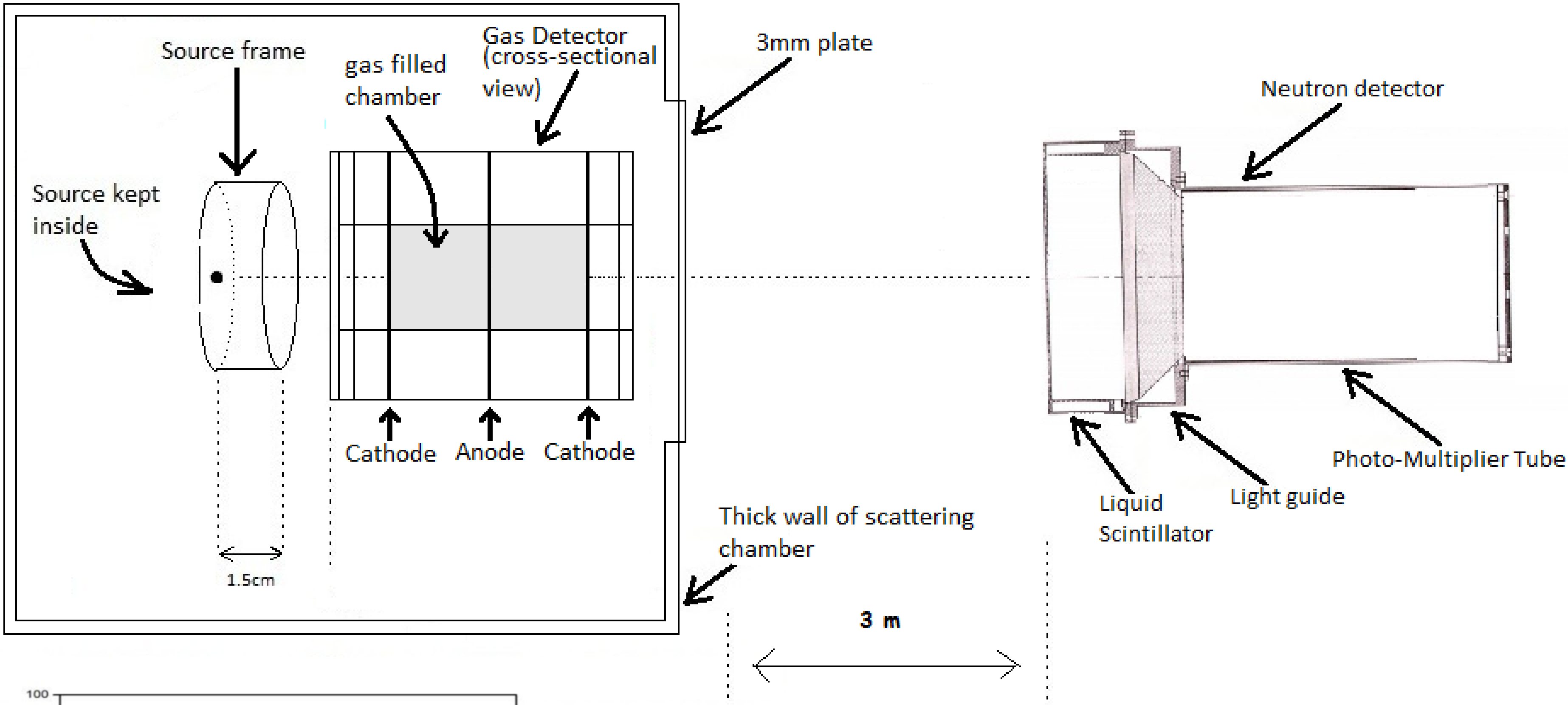
Isobutene @ 3 torr

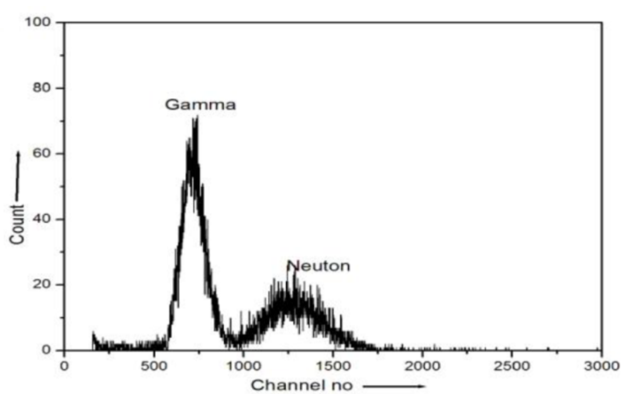


~ 0.5 Volt pulse with

< 4 ns rise time

Parallel Plate Avalanche Counters (PPAC)

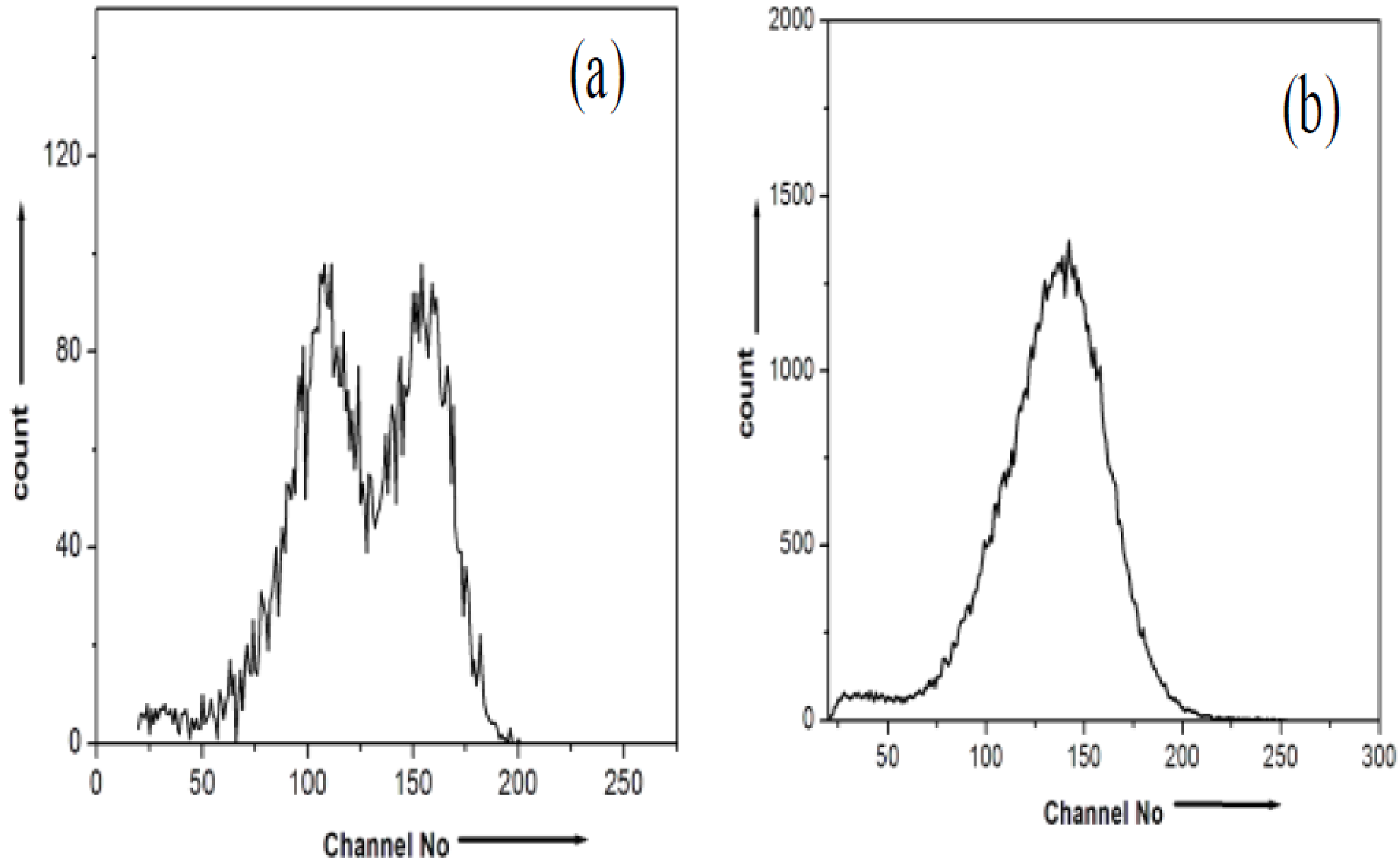




Time resolution: 470 ps

Parallel Plate Avalanche Counters (PPAC)

Efficiency measurement with silicon detector

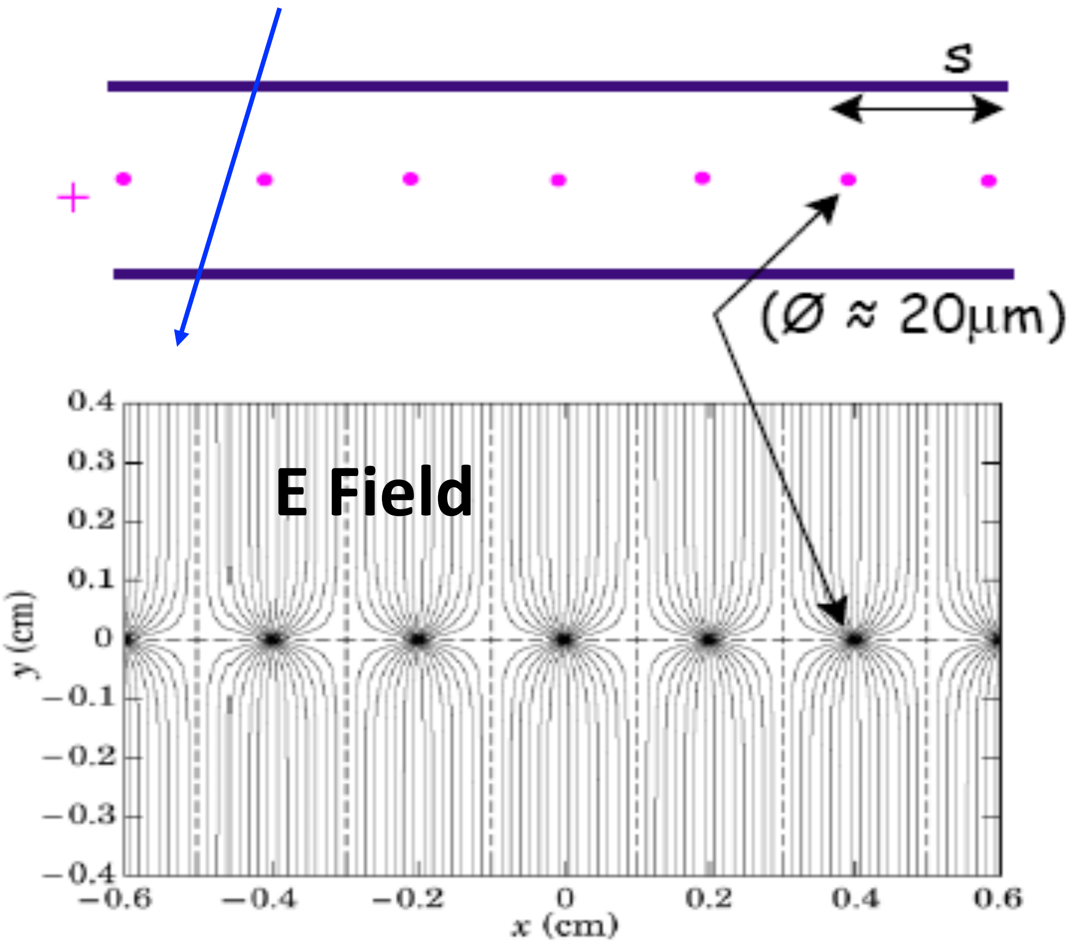


Efficiency > 99.5 %

Multi-wire Proportional Counter (MWPC)

One of the breakthroughs in detector physics

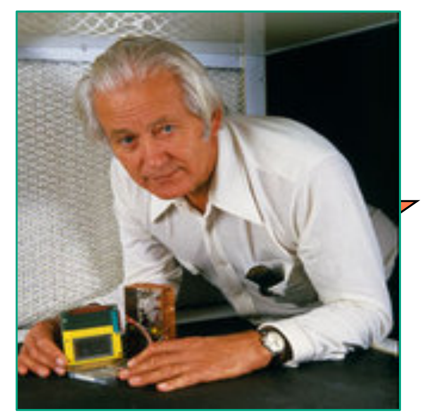
Anode sense wires & cathode planes



Spatial resolution $\sim s/\sqrt{12}$

Wire distance s ≈ 2mm

δs ≈ 0.6 mm

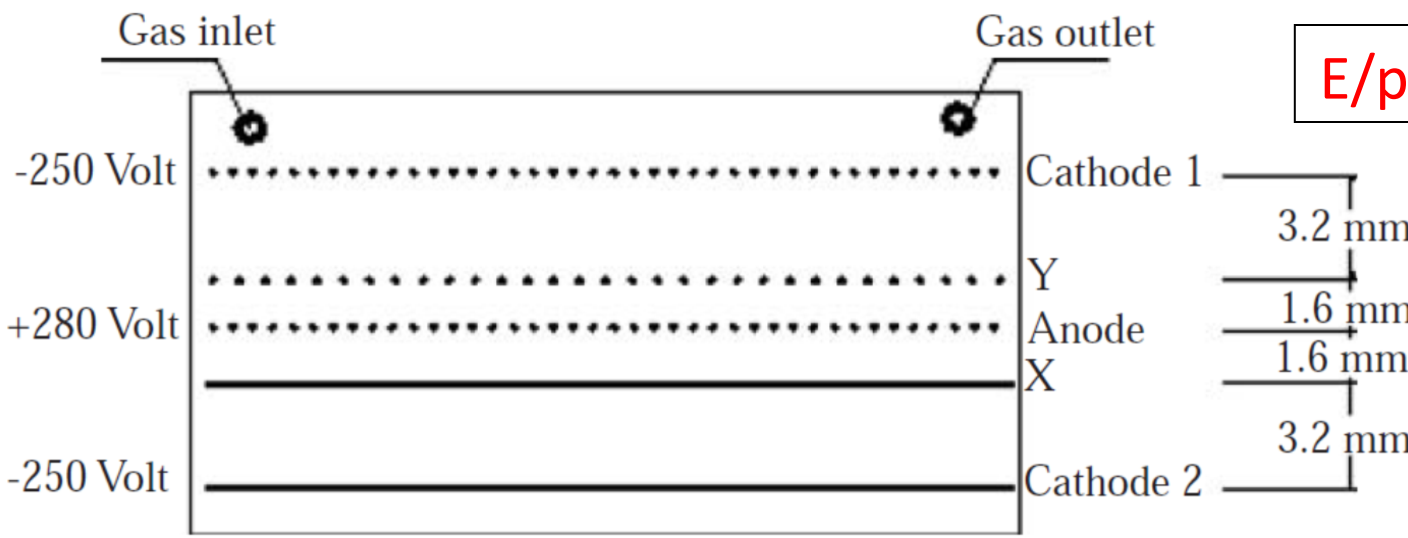


Georges Charpak

Nobel Prize in Physics in 1992

An array of many closely spaced anode wires in the same chamber can each act as independent proportional counters

Development of MWPC at VECC



E/p: 300 V/cm/torr

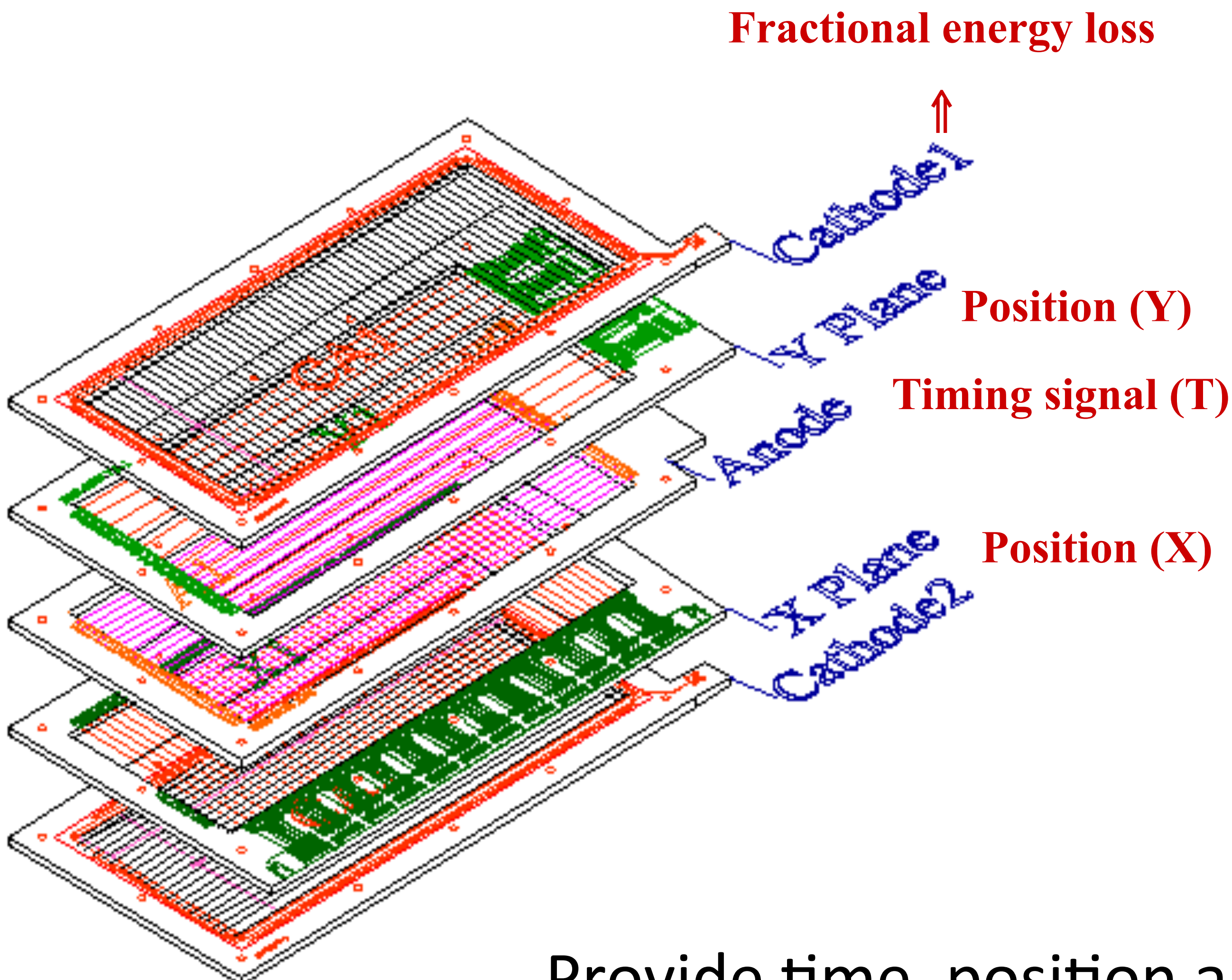
- Produce secondary multiplication of the primary electrons produced in the region between cathode and sense wires.
- The very large electric field near the anode wires causes a large localized avalanche of electrons and ions in the vicinity of the anode.
- Fast rising -ve pulse at the anode and +ve signals at the sense wires.

Multi-wire Proportional Counter (MWPC)

Effective area:

20 cm × 6 cm

24 cm × 10 cm

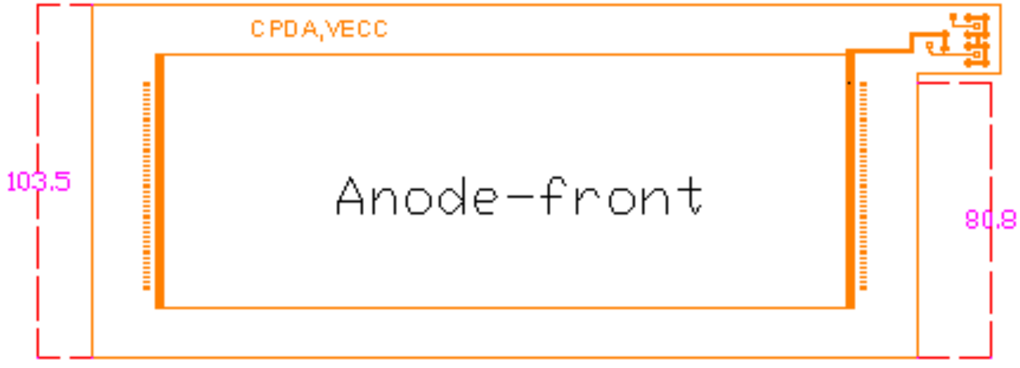


Breskin type detector

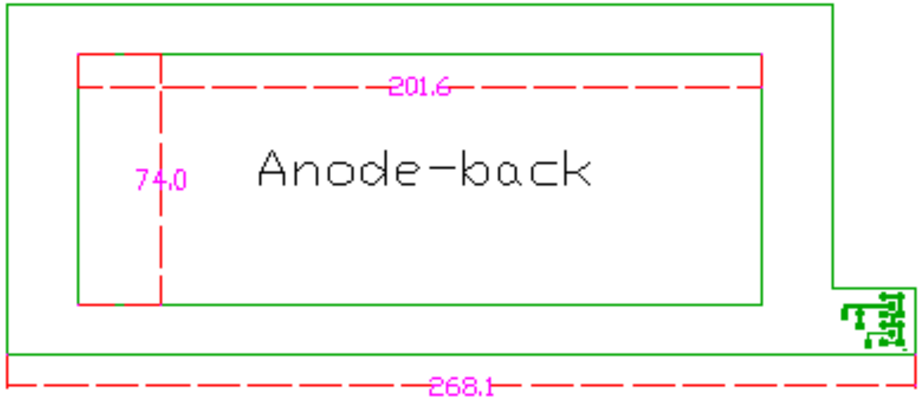
Provide time, position and energy loss info

PCB design

Anode:



Double sided board (anode plane): All dimension in mm
solder side viewed from solder side
Thickness: 1.6 mm

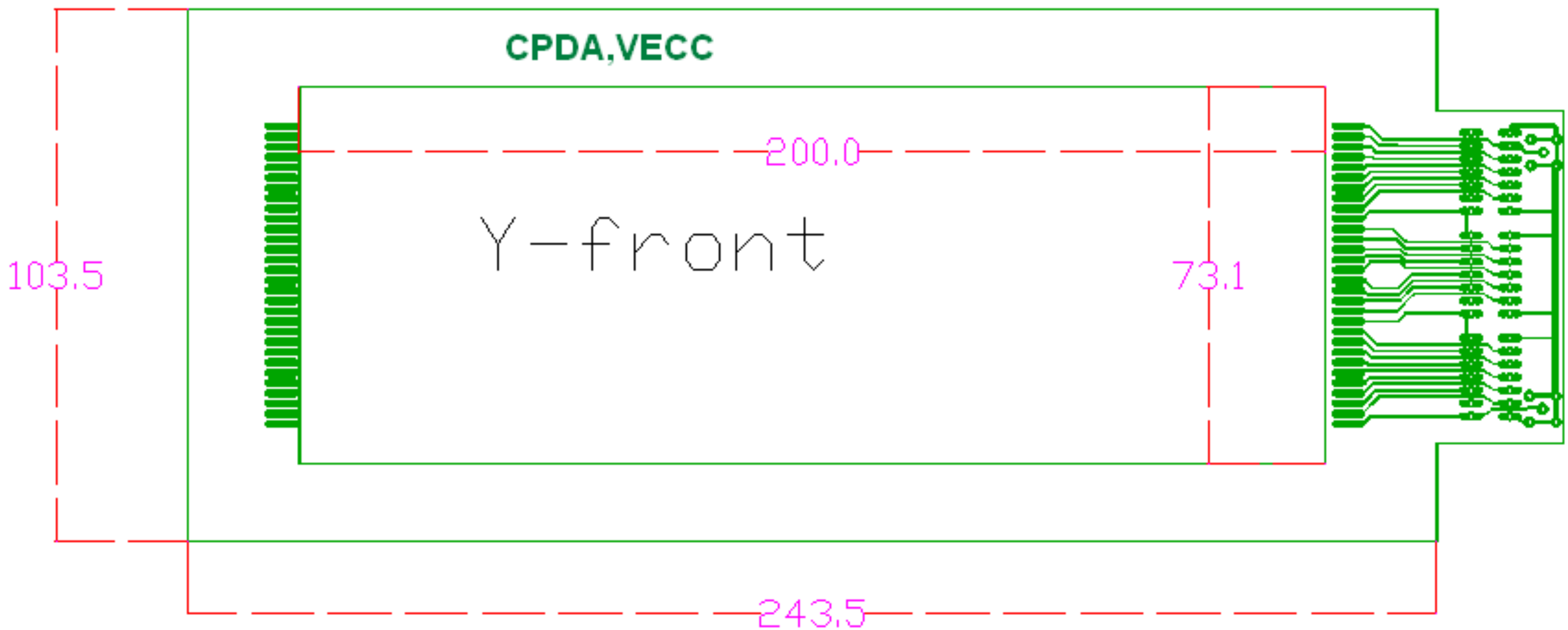


- **1.6 mm thick pcb**
- **10 µm gold plated tungsten are soldered at 1 mm separation**

PCB design

Y-plane: The position signals were read by tapped delay lines

Rhombus Industries, Inc. TZB-36/ 5 ns/tap

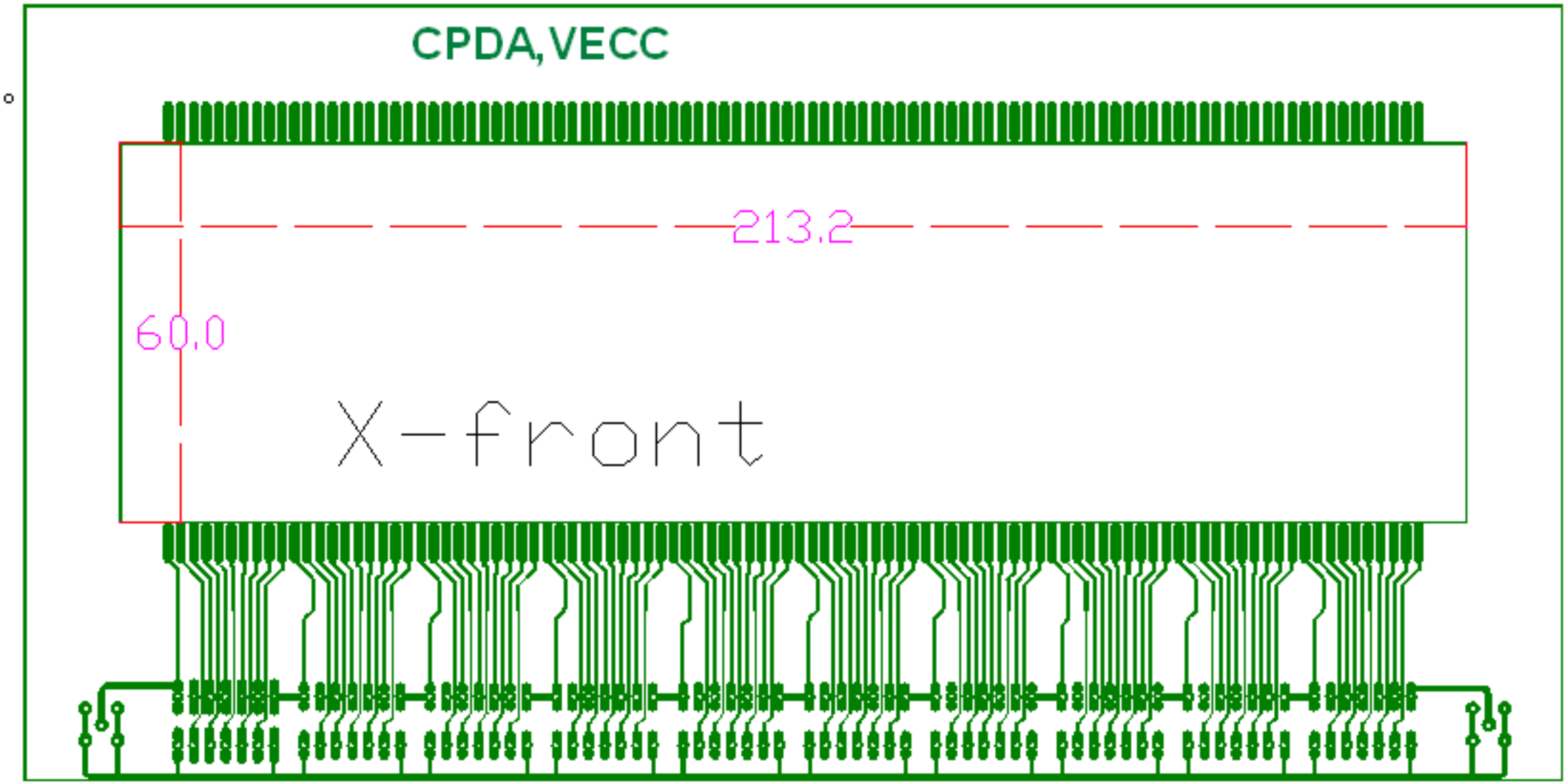


Double sided board (Y- plane): All dimension in mm
solder side viewed from solder side
Thickness:3.2 mm

PCB design

X -plane:

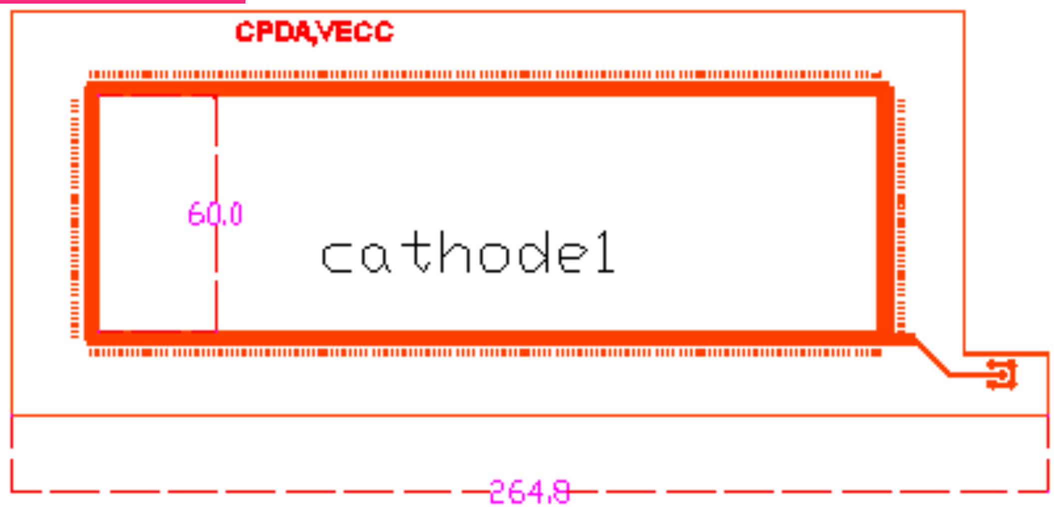
Delay lines: TZB-12/ 2 ns/tap



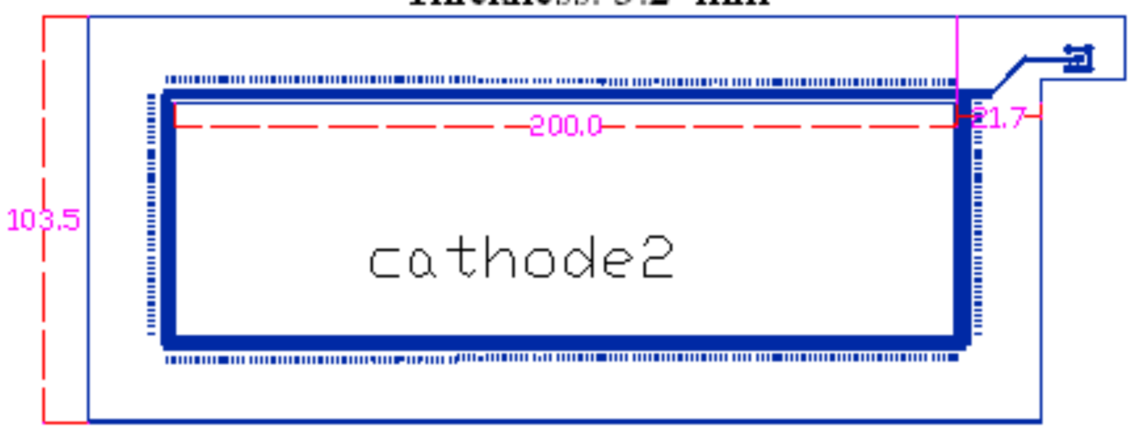
20 micron dia gold plated tungsten wire are soldered to individual pads at 2 mm separation

PCB design

Cathode

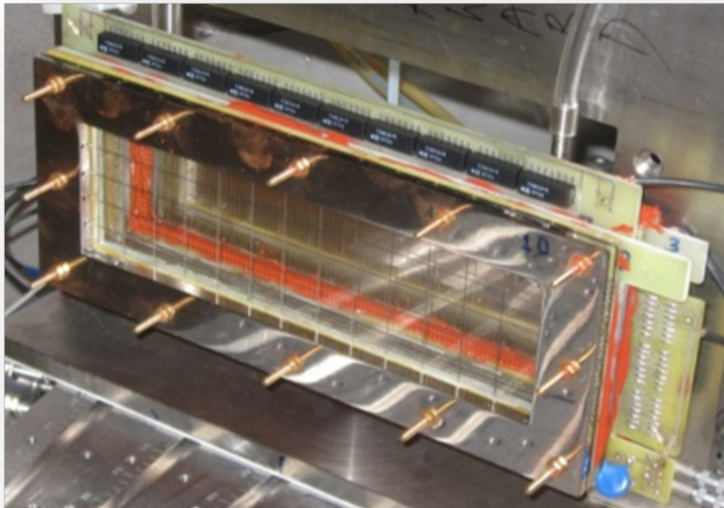


One sided board (cathode plane): All dimension in mm
solder side viewed from solder side
Thickness: 3.2 mm

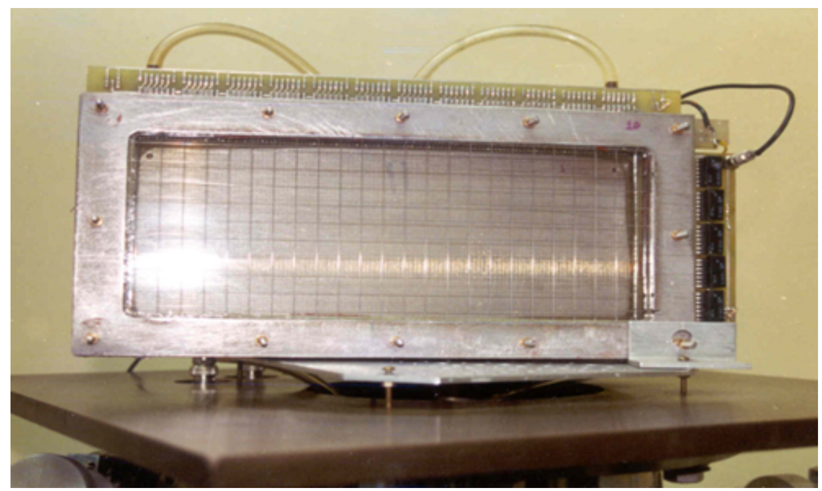


- Cathode wires are soldered to conducting pads.
- Two cathodes are shorted from outside to take out the energy loss signals.

Multi-wire Proportional Counter (MWPC)



Active area: 20 cm x 6 cm



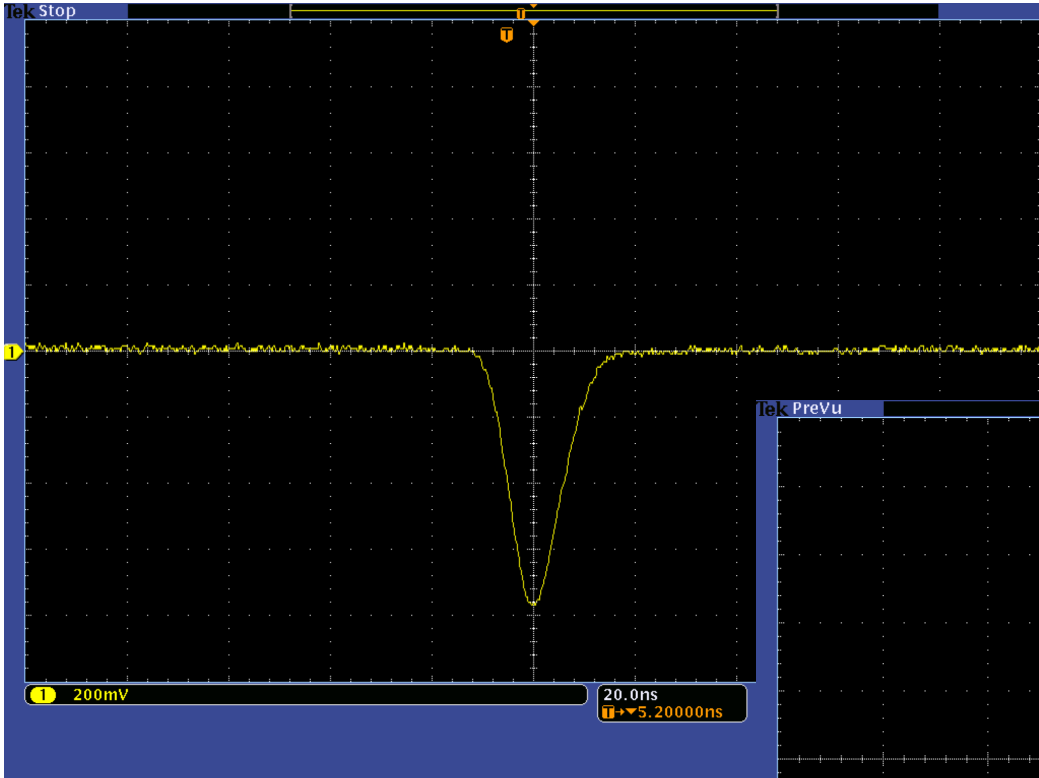
Active area: 24 cm x 12 cm

Window foil supported by 1 mm diameter wire

Multi-wire Proportional Counter (MWPC)

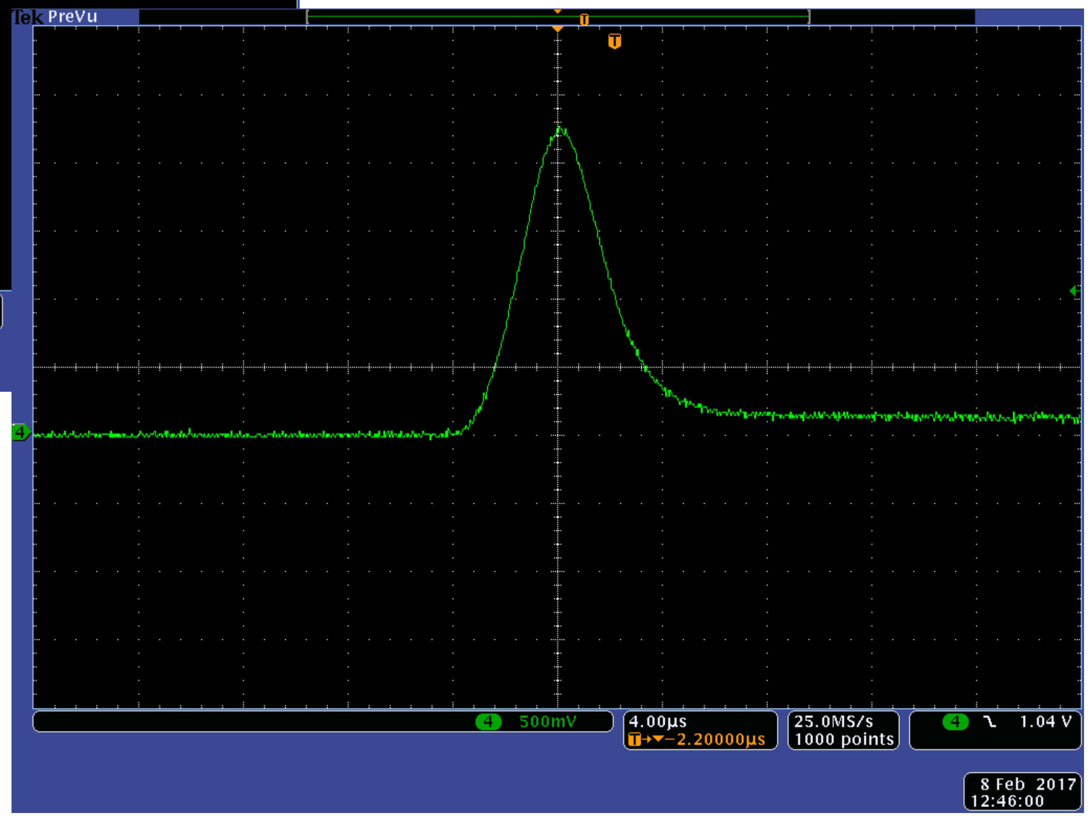
Detector	Gas Pressure (Torr)	Source	Particle	Signal Strength		Detector Bias		Linear amplifier characteristics		
				Anode (mV)	Cathode (V)	Anode (V)	Cathode (V)	Shaping time (micro Seconds)	Coarse gain	Fine gain
MWPC 1	3.8	Cf	Alpha	80	0.8	245	109	0.5	50	14.9
			Fission fragments		2					
			Alpha	200	1	274	182		20	5
			Fission fragments	2000	5.2					
			Alpha	400	1.2	357	102			
			Fission fragments	2200	4.8					
MWPC 1	4.7	Am	Alpha	216	.140	324	256	0.5	50	5
				288	.150					
				276	.160					
				40	.072	275	184			
				50	.090					
				44	.060					
				60	.520	245	109			
				32	.560					
				80	.480					

Multi-wire Proportional Counter (MWPC)



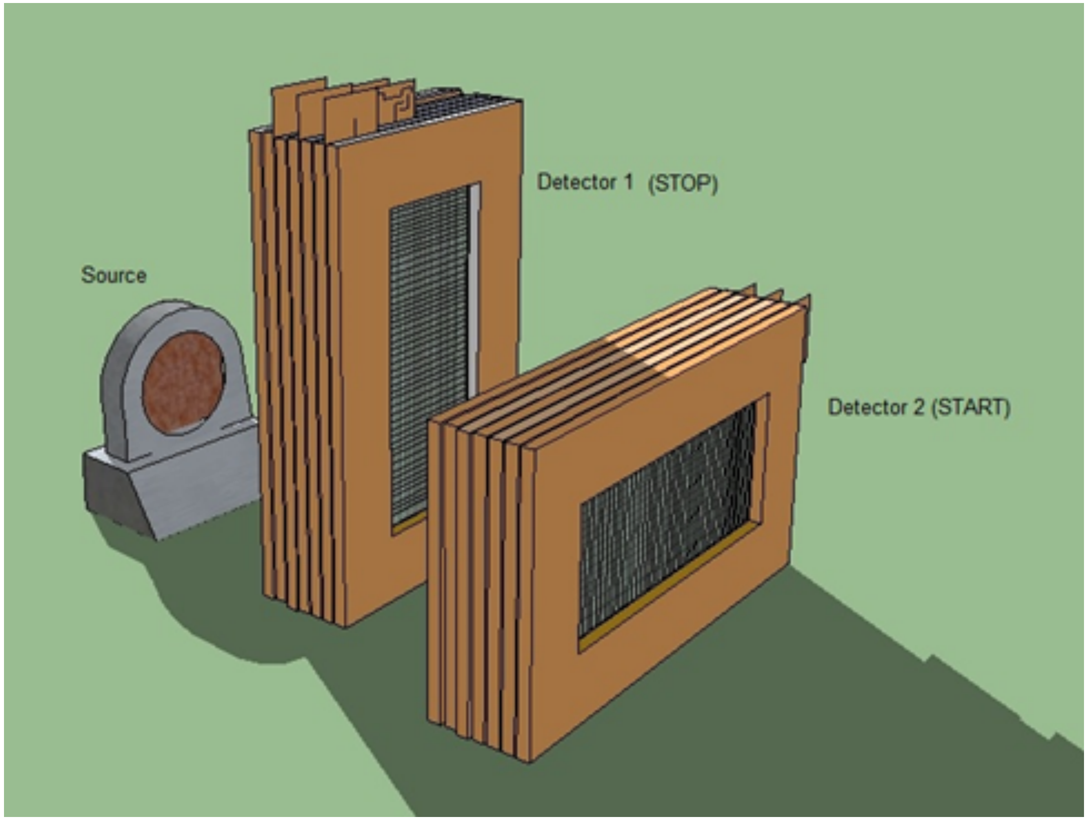
Anode signal: > 0.5 volt

Rise time < 5 ns

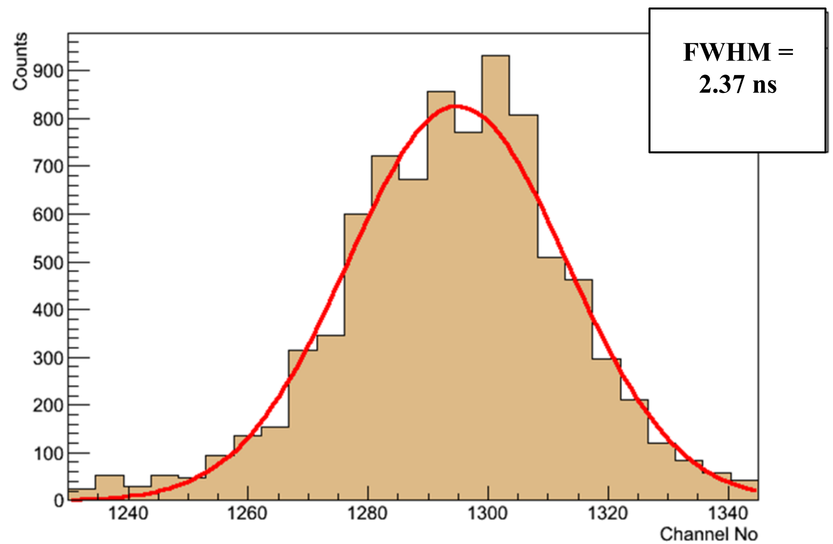


Cathode signal: > 2 volt

Multi-wire Proportional Counter (MWPC)

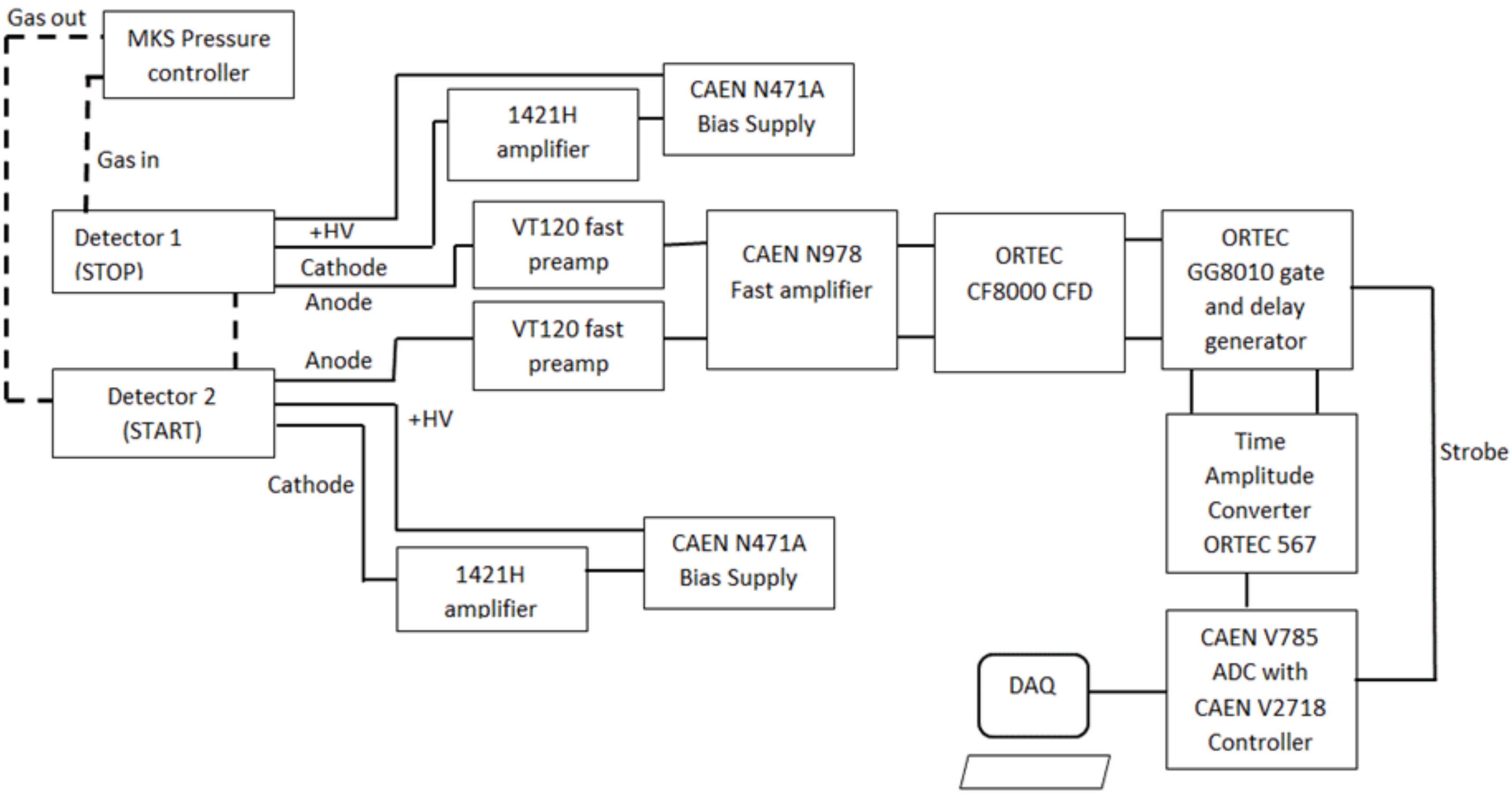


Gas pressure: 6 torr
Source: ^{241}Am

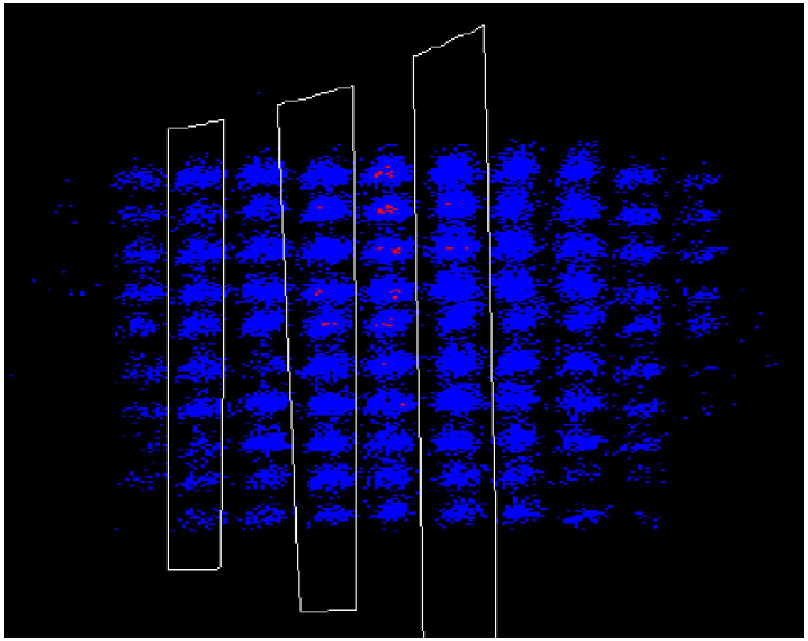


$$\sigma_{det} = 0.7 \text{ ns}$$

Multi-wire Proportional Counter (MWPC)



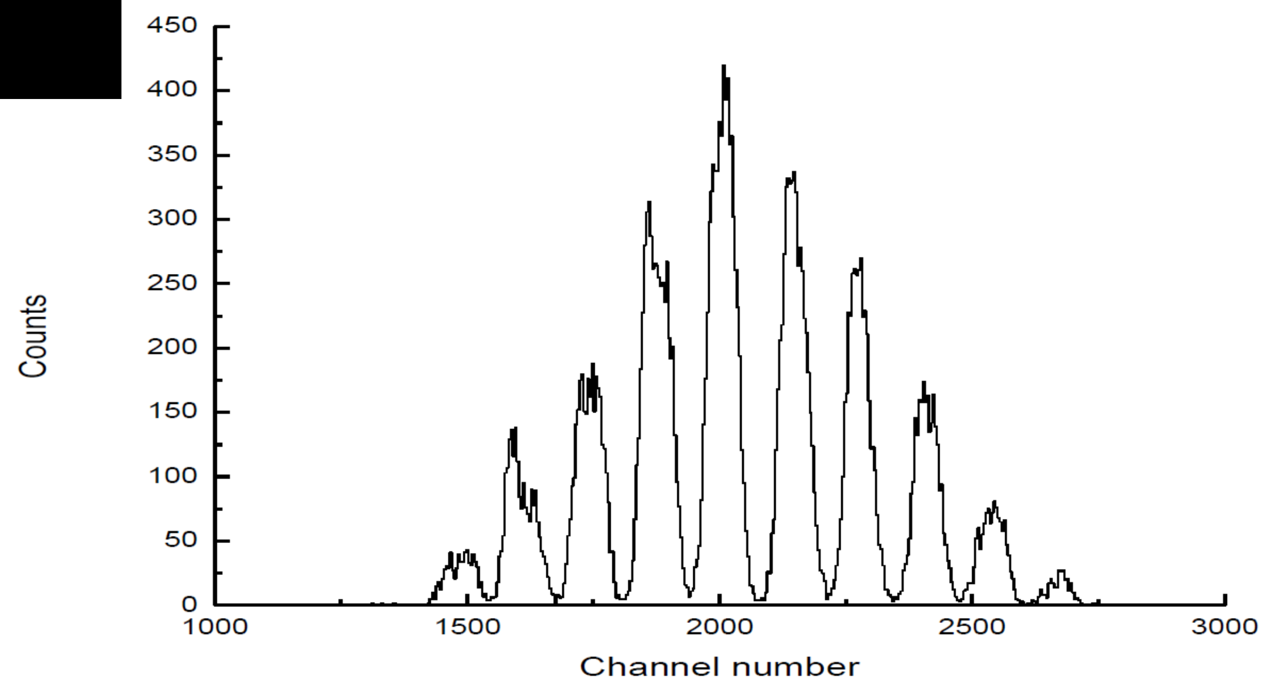
Multi-wire Proportional Counter (MWPC)



Illumination with mask

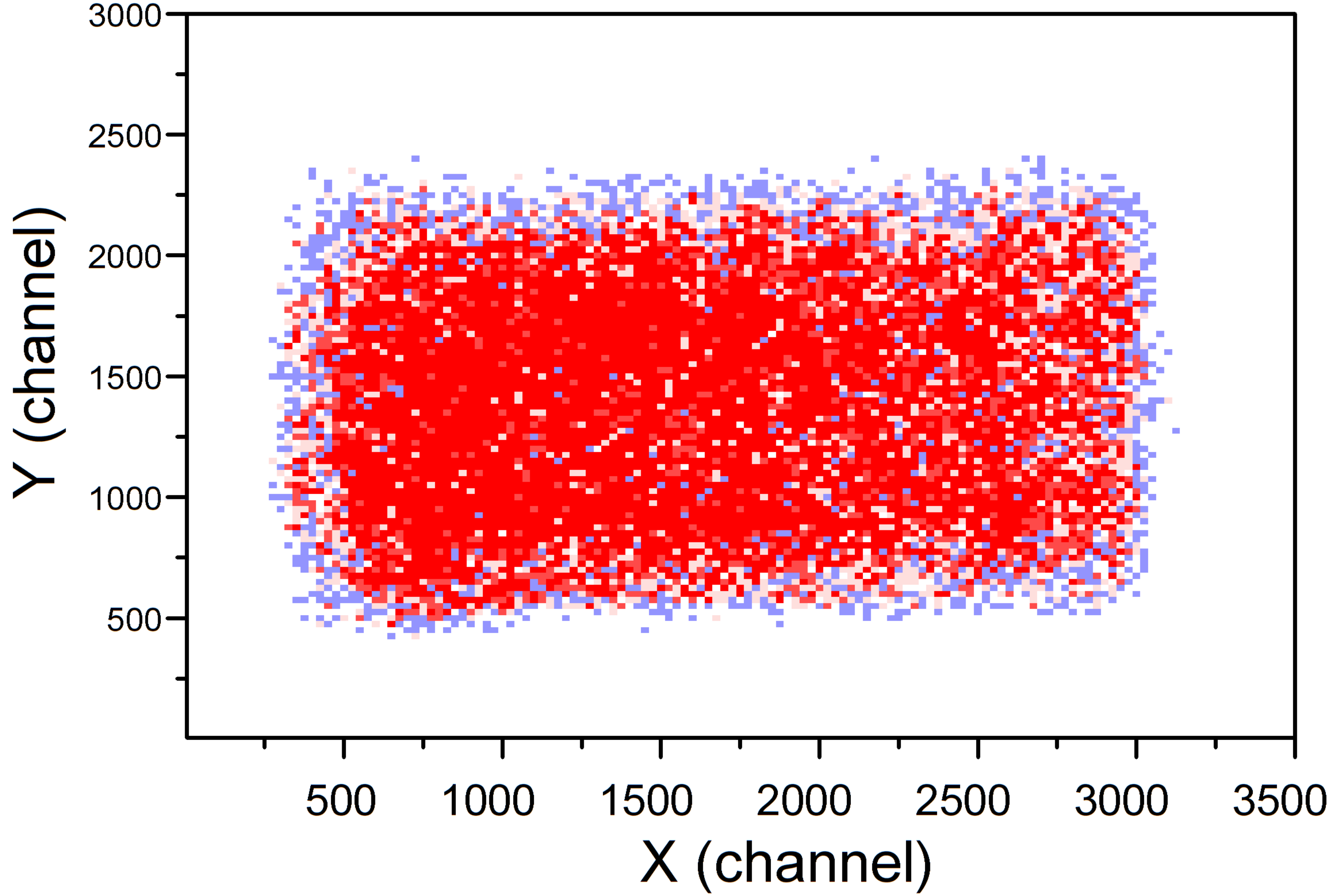
^{252}Cf source

Position resolution:
X (FWHM)= 1.2 mm
Y (FWHM)= 1.5 mm



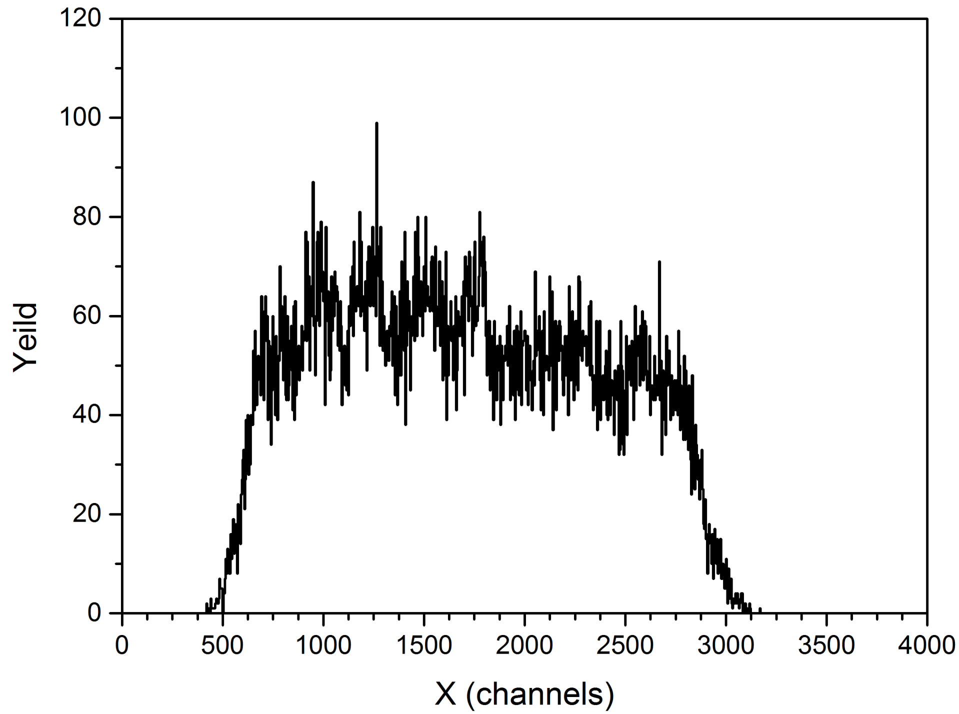
Multi-wire Proportional Counter (MWPC)

In-beam characteristics:



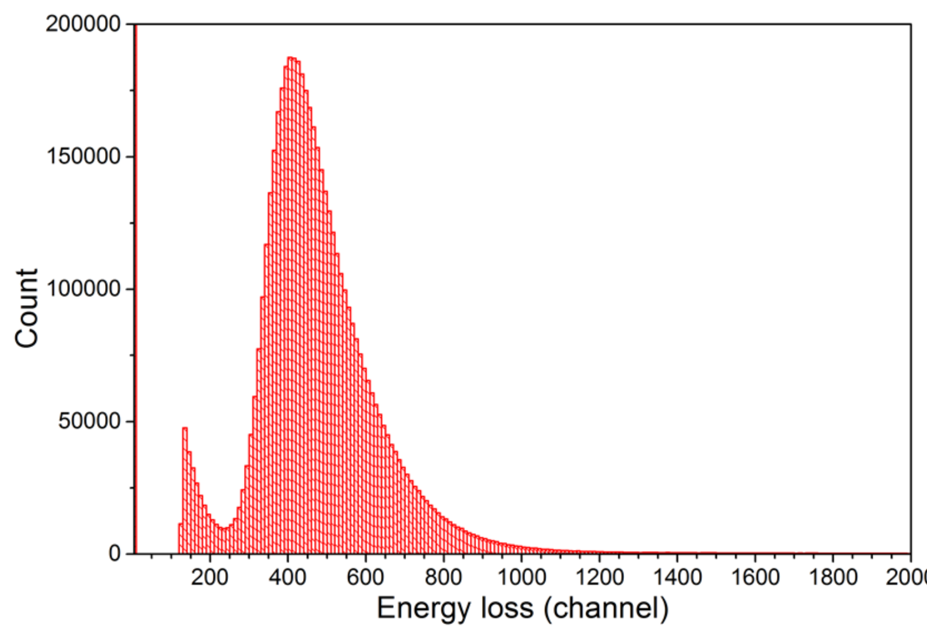
Multi-wire Proportional Counter (MWPC)

In-beam characteristics:



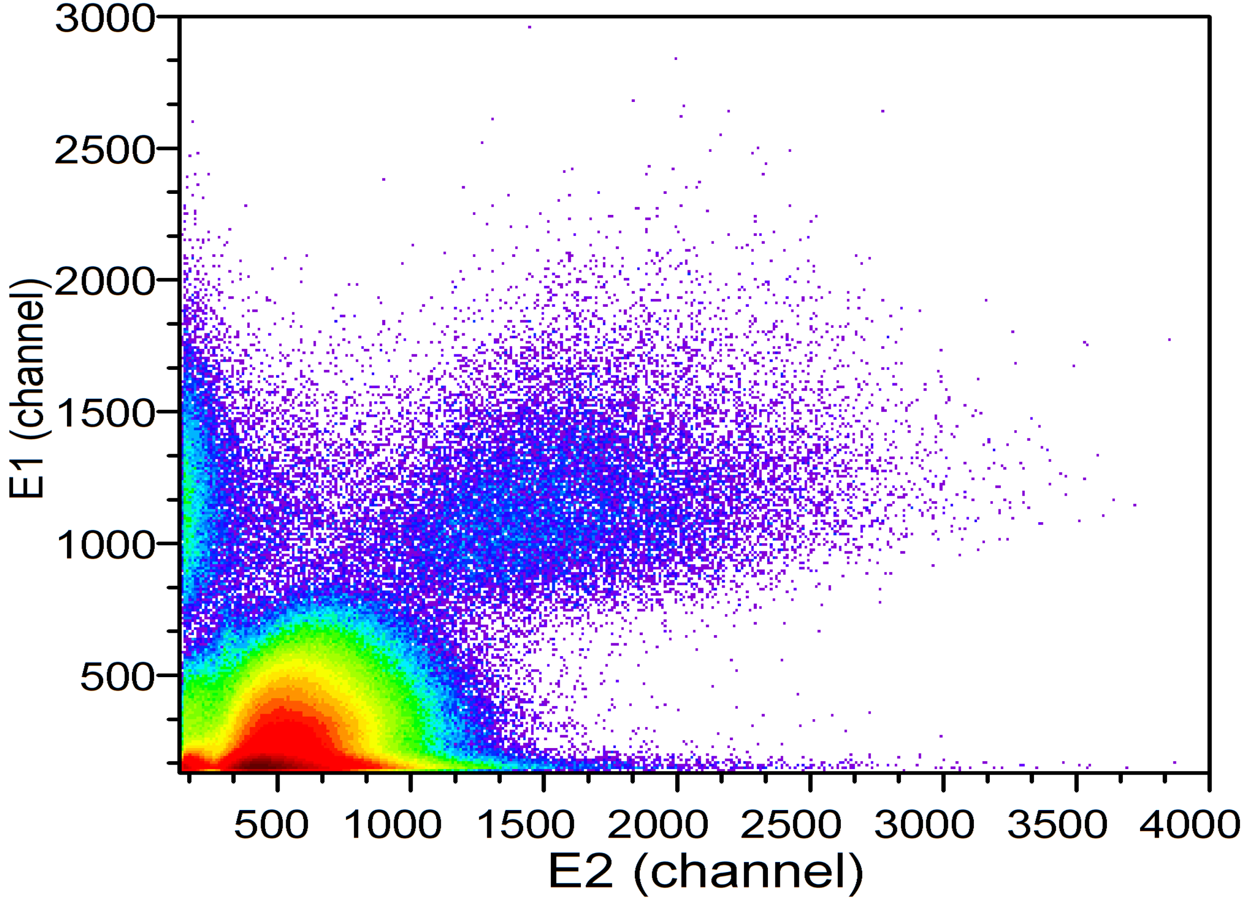
X- position spectra

Separation of elastics from heavy fragments in energy loss spectra



Multi-wire Proportional Counter (MWPC)

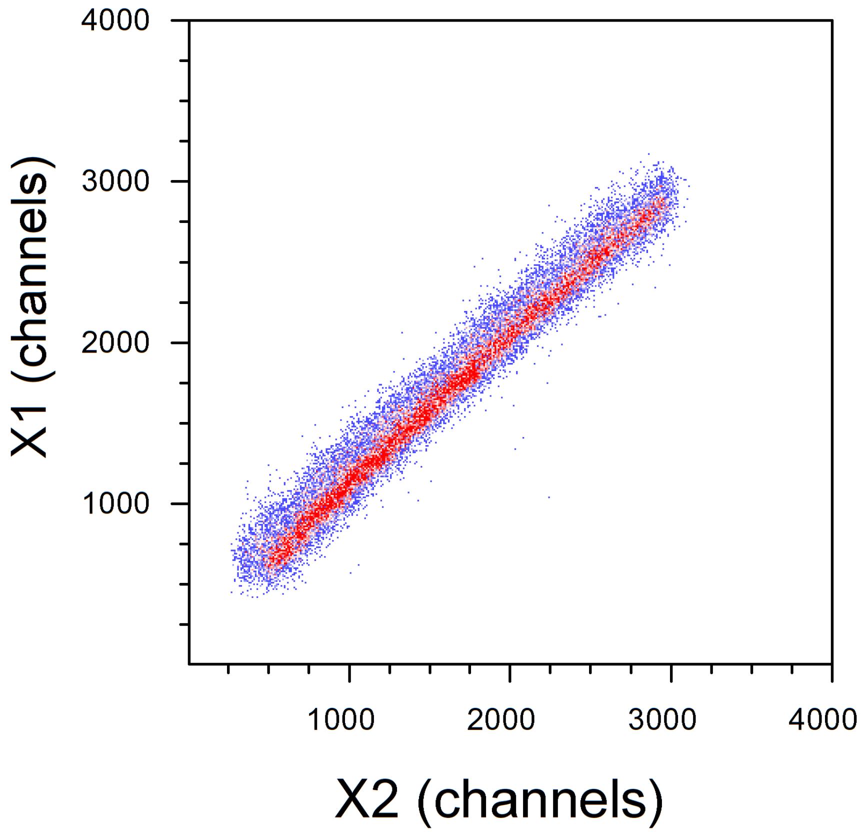
In-beam characteristics:



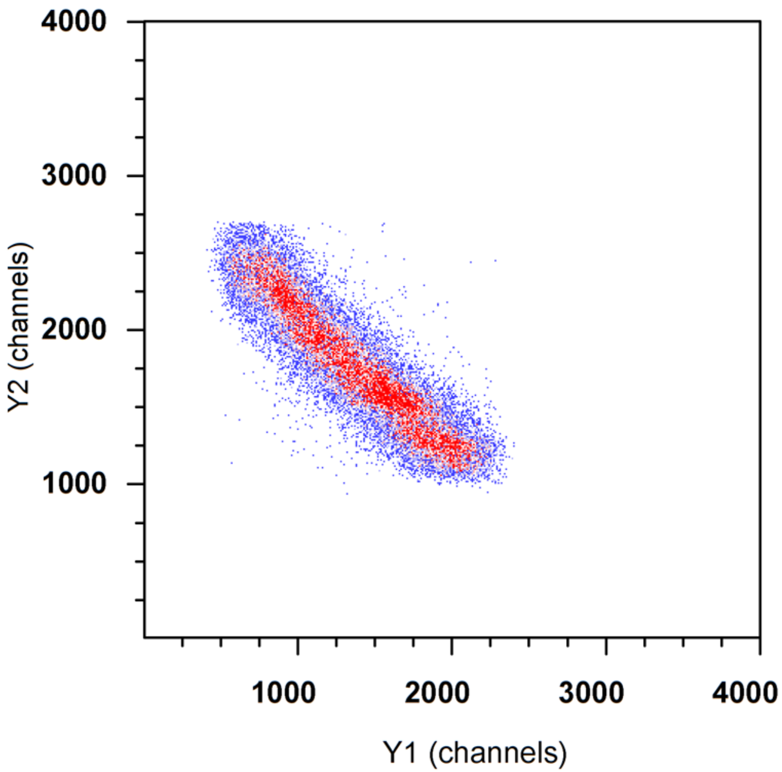
Separation of elastics from heavy fragments in energy loss spectra

Multi-wire Proportional Counter (MWPC)

In-beam characteristics:

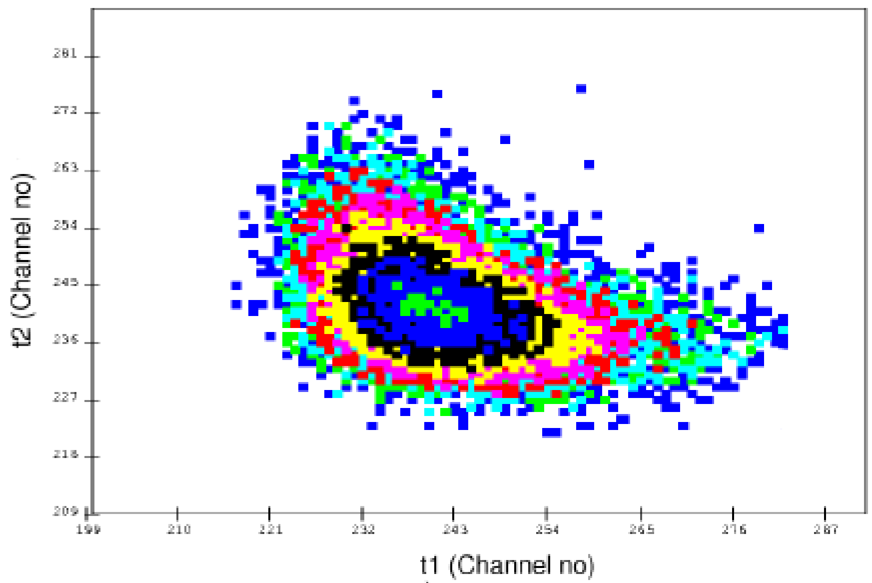


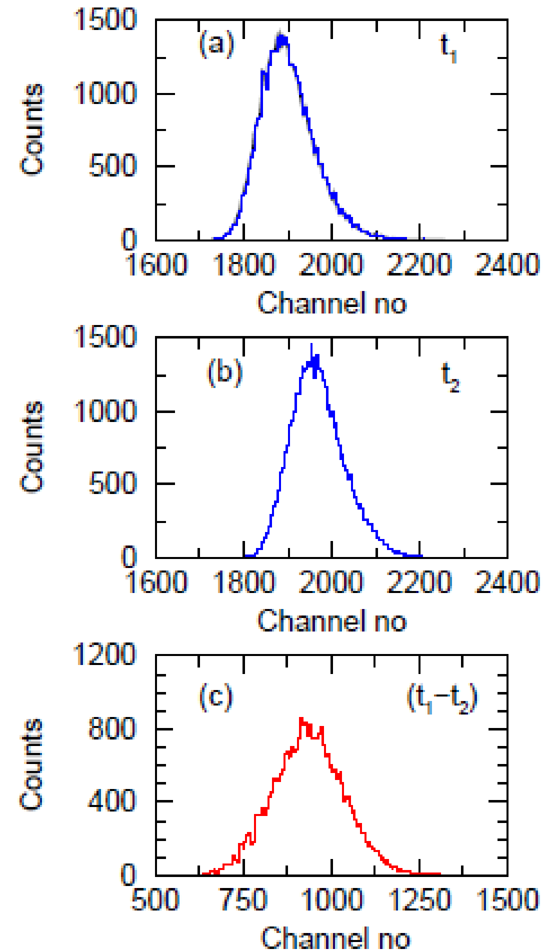
Angular correlations of the complimentary fission fragments



MWPC : Timing correlations

In-beam characteristics:





Mass distribution calculation

Difference in time of flight of complementary fragments gives mass:

$$m_1 = \frac{(t_1 - t_2) - \delta t_0 + m_{CN}\dfrac{d_2}{p_2}}{\left(\dfrac{d_1}{p_1} + \dfrac{d_2}{p_2}\right)}$$

$$m_2 = m_{CN} - m_1$$

$$p_1 = \frac{m_{CN}V_{CN}}{cos\theta_1 + sin\theta_1 cot\theta_2}$$

$$p_2 = \frac{p_1 sin\theta_1}{sin\theta_2}$$

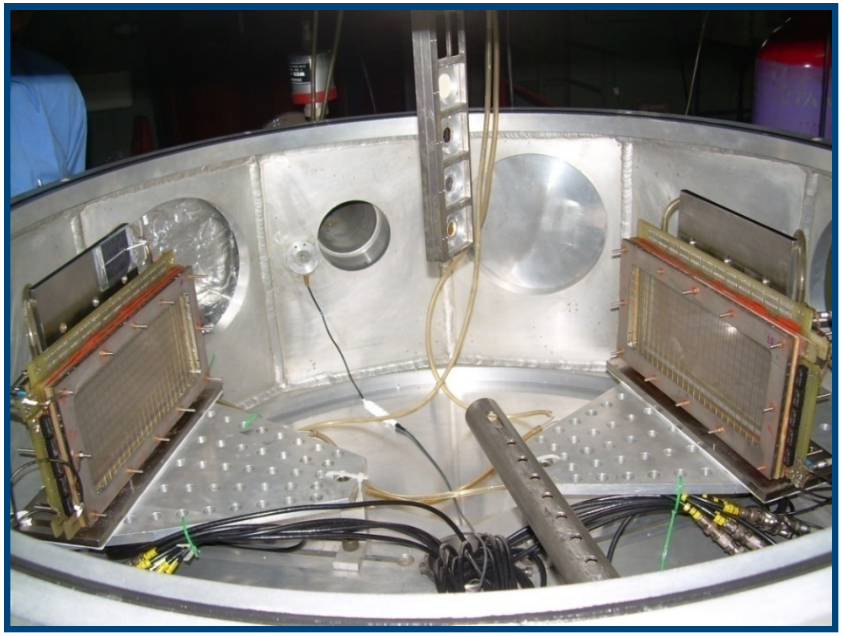
where m_1, $m_2 \Rightarrow$ *fragment masses*

t_1, $t_2 \Rightarrow$ *flight times of the fragments for distances* d_1, d_2

p_1, $p_2 \Rightarrow$ *linear momentum in the lab. Frame*

δt_0 = *difference of time zero*

MWPC : work horse for fission studies



Experiment @ VECC, Kolkata

Experiment @ TIFR, Mumbai

Experiment @ IUAC, Delhi

Exploring Fission Valleys

MWPC: work horse for fission studies

Shell effects: *help the survival of SHE*

Quasi-fission: *culprit; does not allow to form SHE*

Physics related to Super Heavy Elements (SHE)

Phys. Rev. C 94, 064617 (2016)
Phys. Rev. C 93, 064602 (2016)

Phys. Rev. C 92, 041601 (2015) (R)
Phys. Rev. C 91, 044620 (2015)

New hybrid detector development

At higher beam energy (~ 20 A MeV or more) the complete fusion scenario changes over to an incomplete fusion mechanism.

Depending upon the mass, excitation energy and angular momentum, the decay of the complex system is characterised by neutrons, LCP and fission, yielding fission fragments like events.

Higher beam energy

↓

Reactions may not be binary in nature

$$\frac{m_1}{m_2} = \frac{t_2}{t_1}, \quad \boldsymbol{m_1 + m_2 = m_{CN}}$$

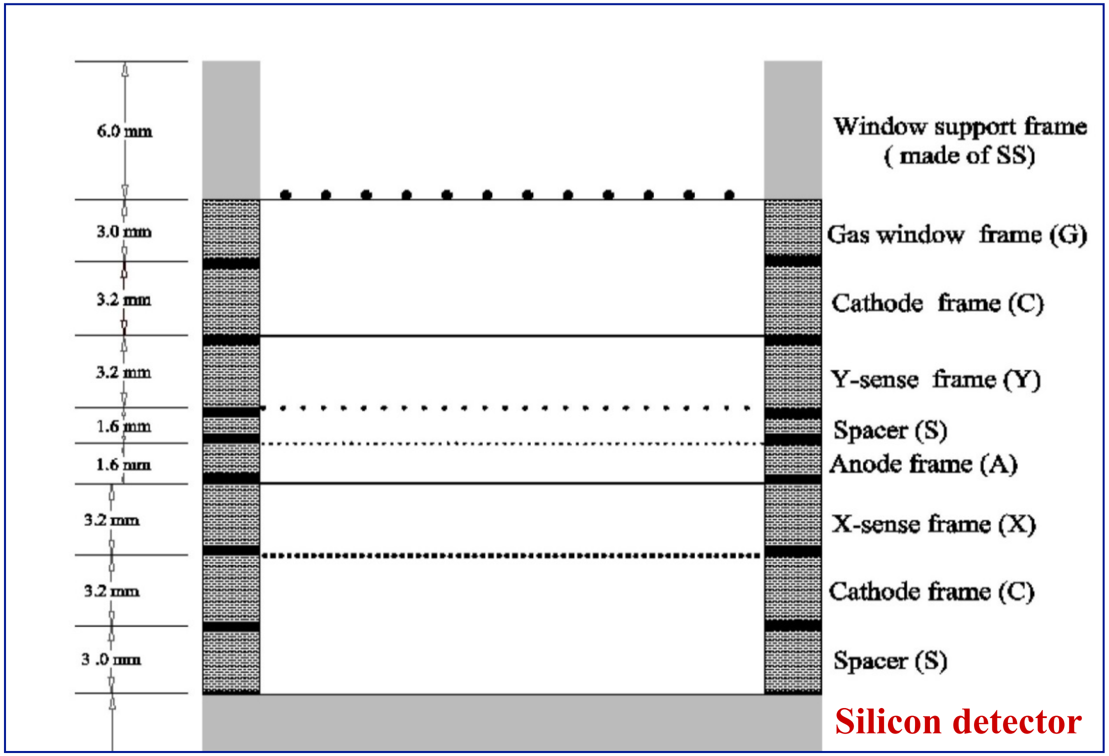
$$E = \frac{1}{2}mv^2$$

→

Requires detector that measure both energy and velocity

New hybrid detector development at VECC

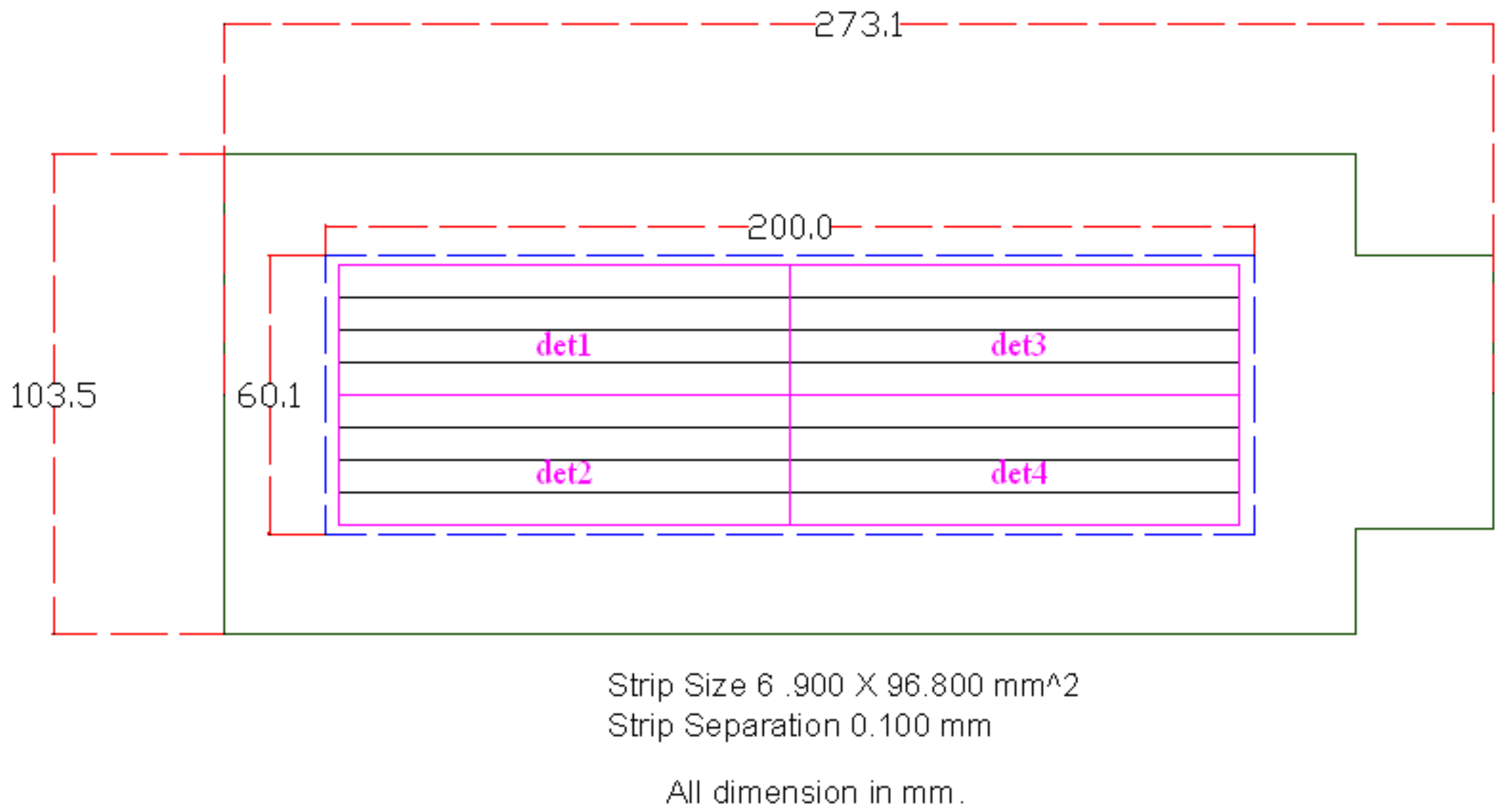
➢ As a spin off development of MWPC, we have designed and fabricated hybrid detectors



The detector provides

- *Time (t)*
- *Position (X,Y)*
- *Energy (E)*

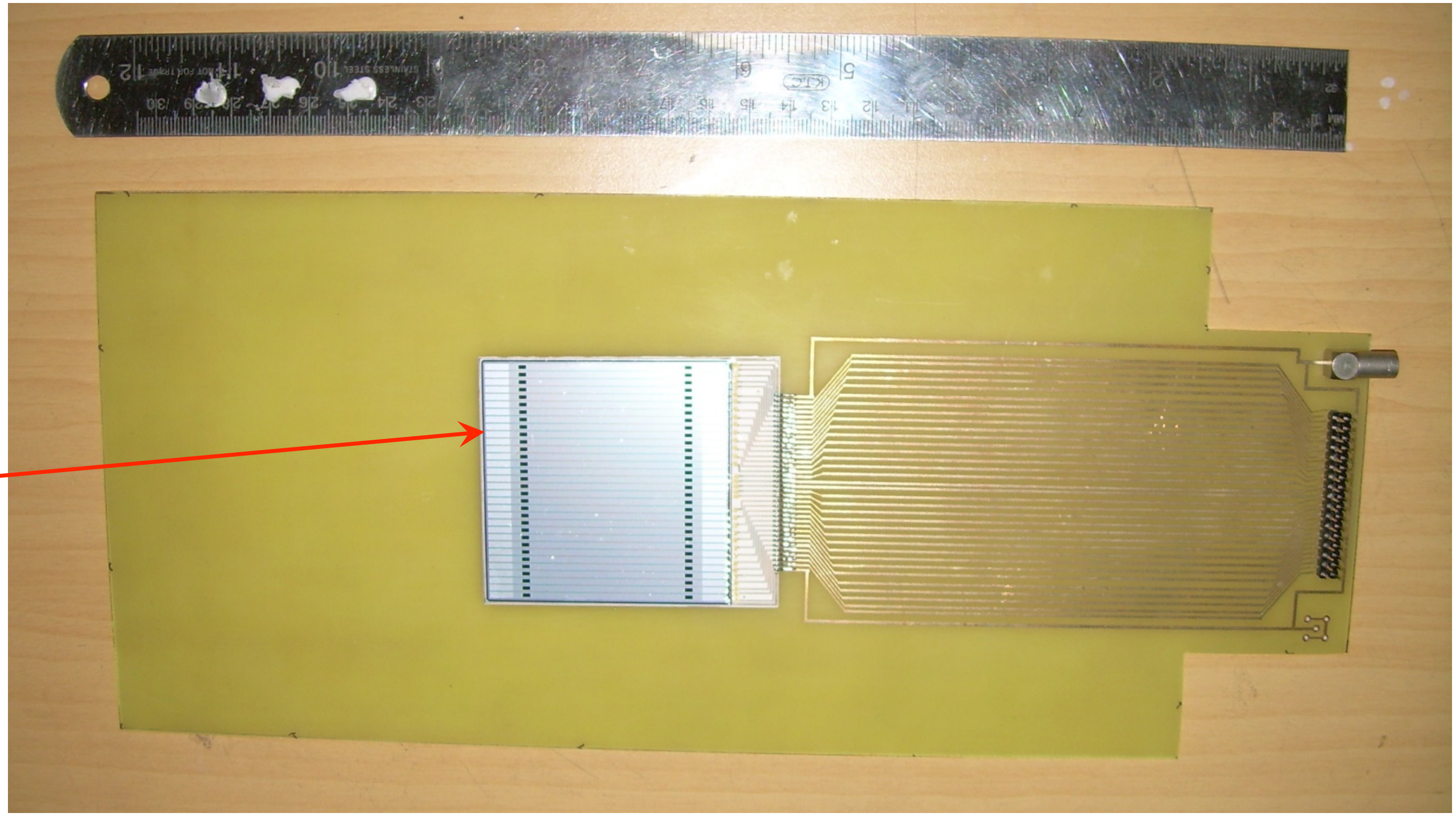
Assembly design of silicon detector



- 4 silicon detectors (300 μm) on a ceramic plate
- Active area of each detector = 27.6 mm x 96.8 mm
- Active area of the detector: 193.6 mm x 55.2 mm

Assembly of a prototype silicon detector

Si-detector from BARC

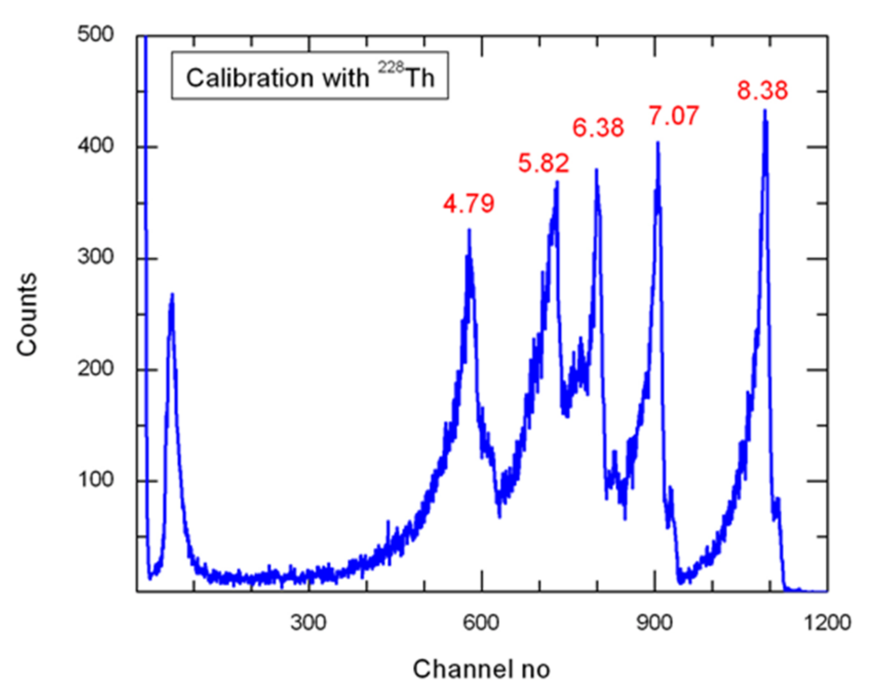


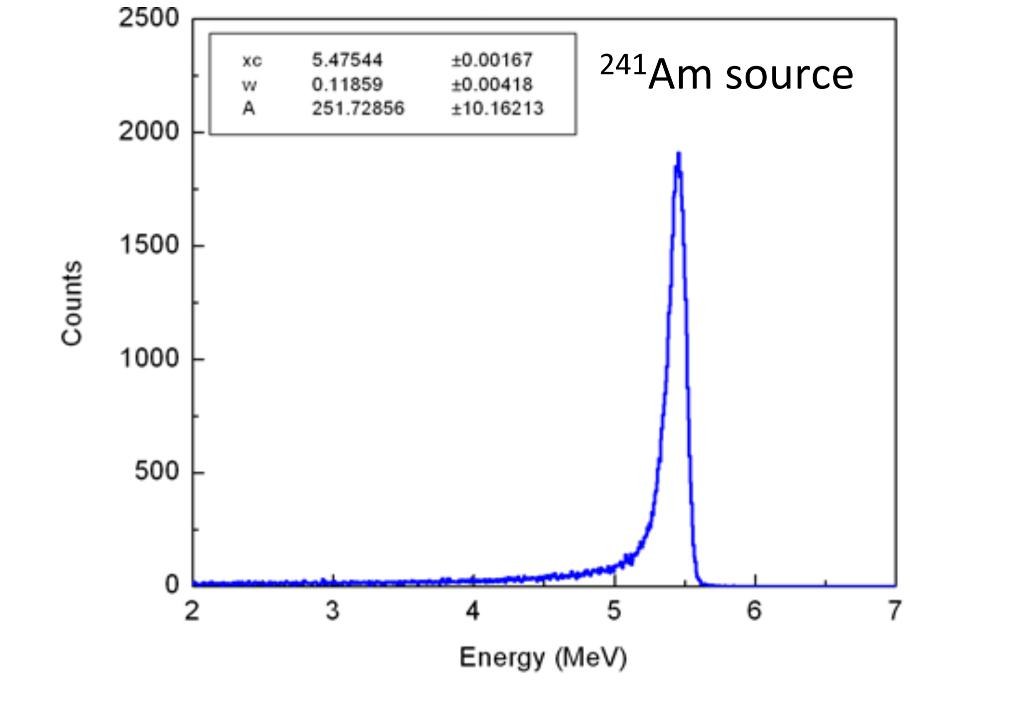
No of strips: 32
Thickness: 300 micron
Window thickness: 5 micron

Area: 6.3 cm x 6.3 cm
Pad width: 1.8 mm
Separation: 100 micron

Prototype characterisation

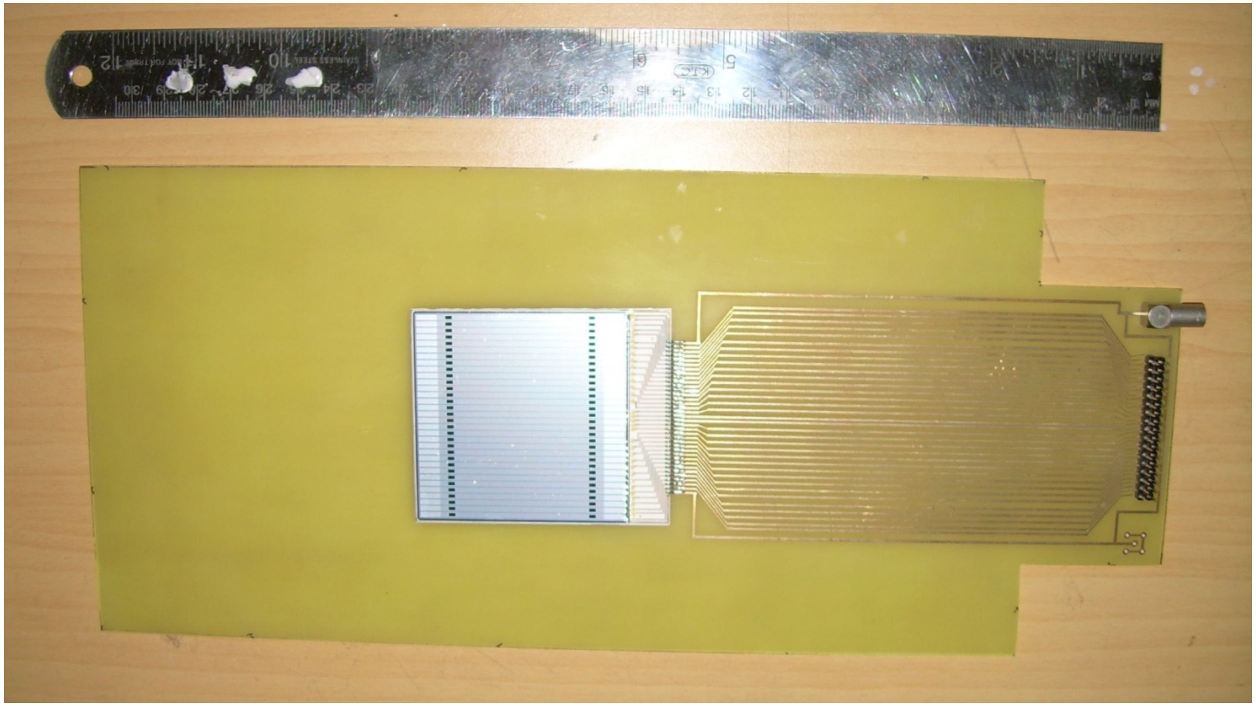
Bias: 100 Volt; Dark current: 140 nA





Energy resolution : 2.3 % .

Assembly of a prototype silicon detector

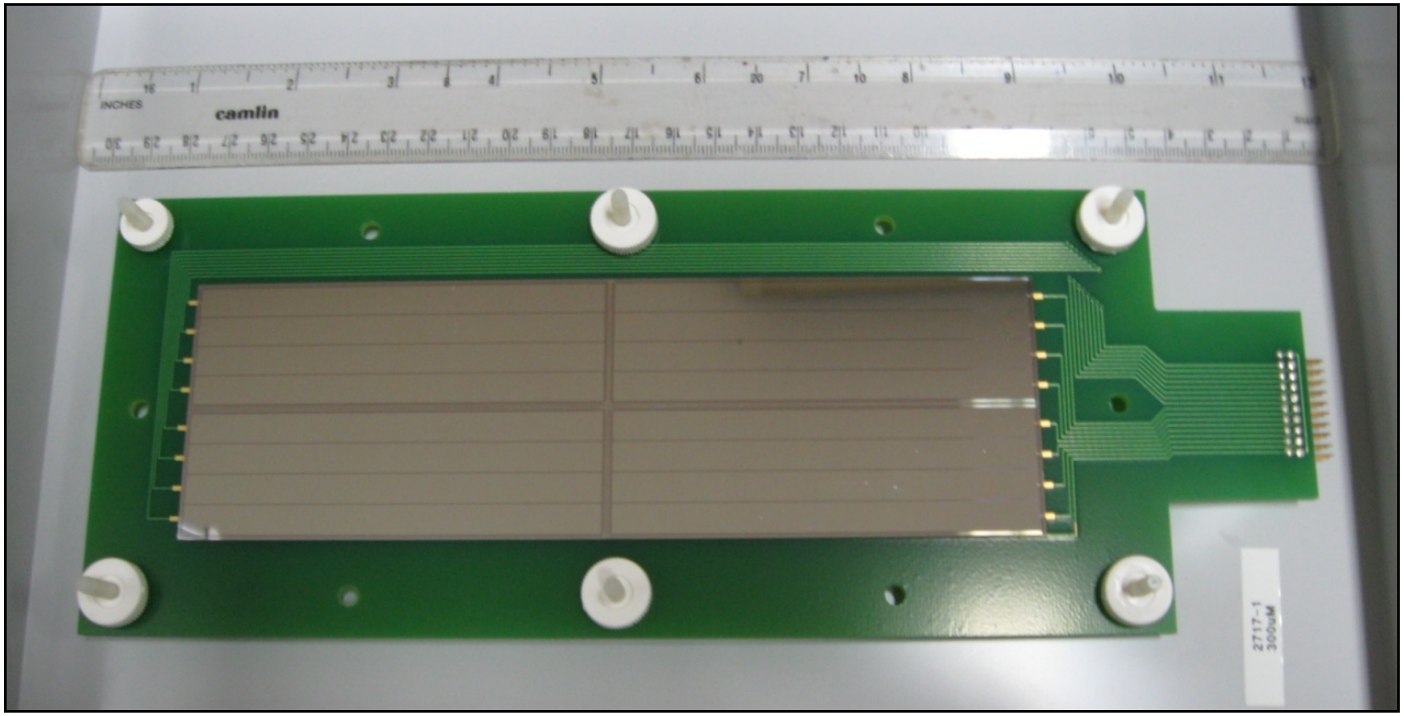


Window thickness: 5 micron

Energy loss of fission fragment in silicon 8 MeV/micron

New hybrid detector development

Segmented silicon detector



Thickness: 300 micron

Bias: 60 Volt,

Resolution: 55 KeV (^{241}Am)

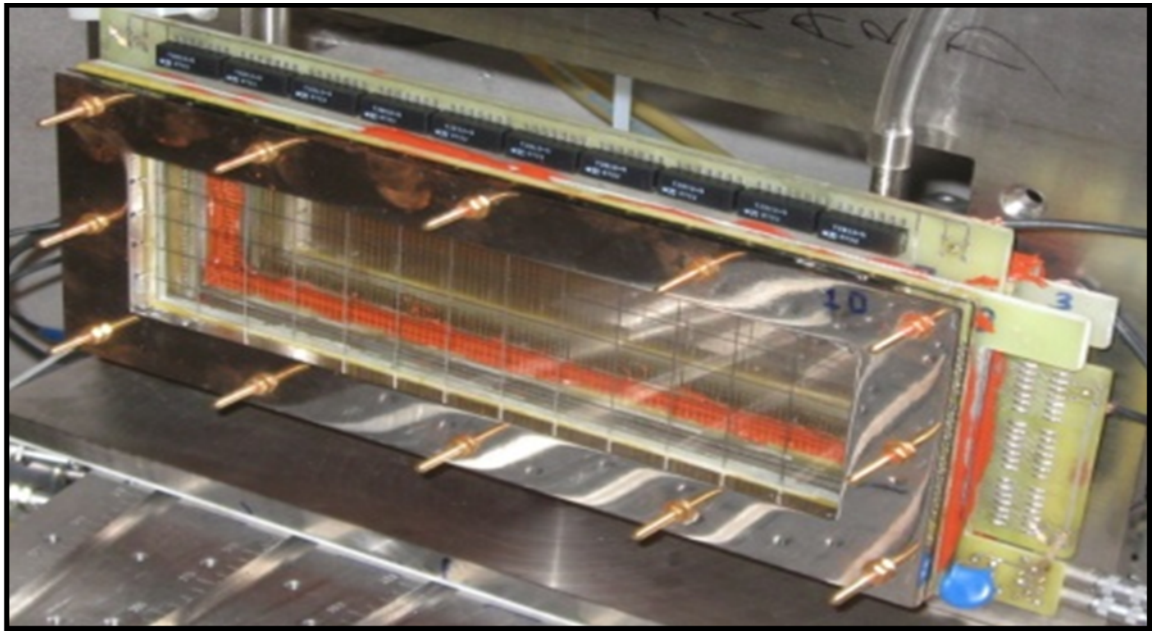
Chip dimension: 30 mm x 96.8 mm

Window thickness: 0.3 micron

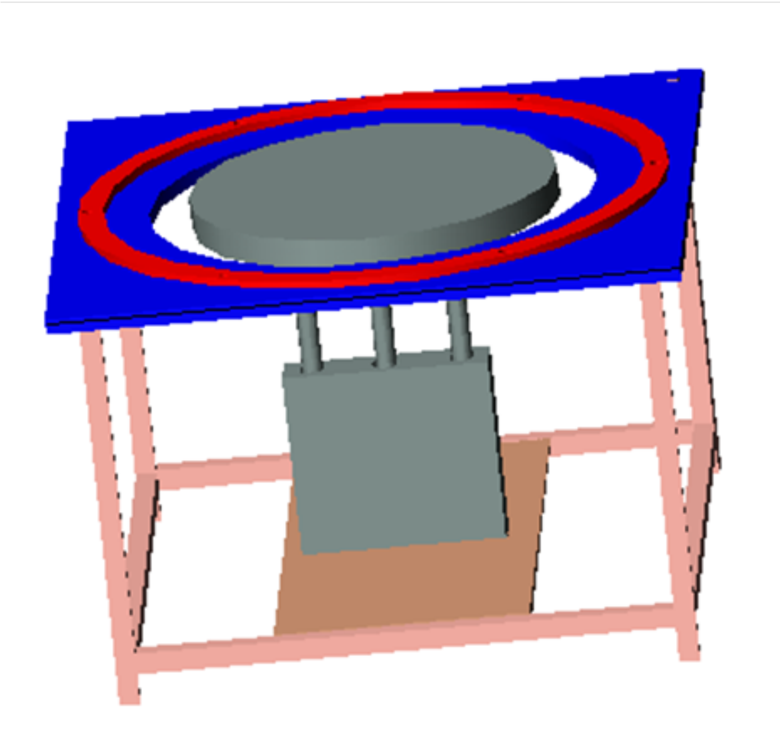
Silicon detectors designed by us, fabricated by Micron Semiconductor Ltd (UK)

New hybrid detector development

Hybrid gas detector

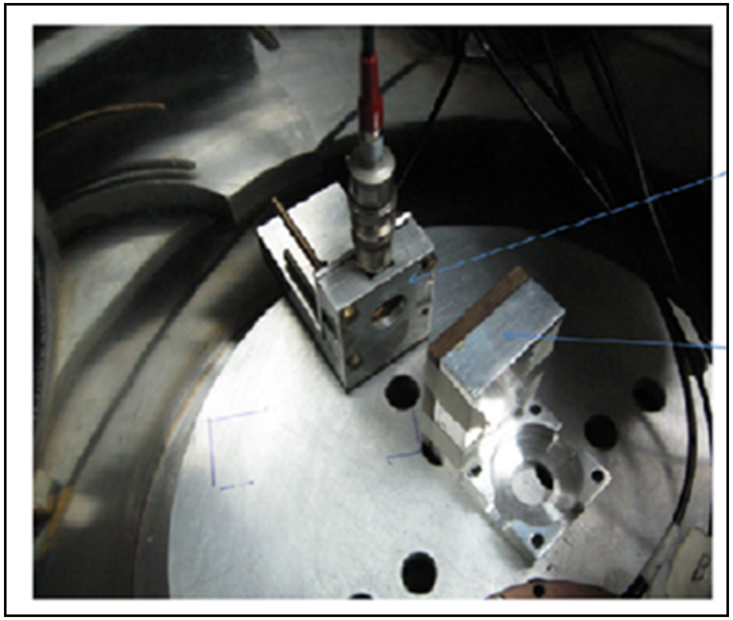


Auxiliary detector fabrication facilities at VECC



Custom made detector window film stretcher unit developed at VECC

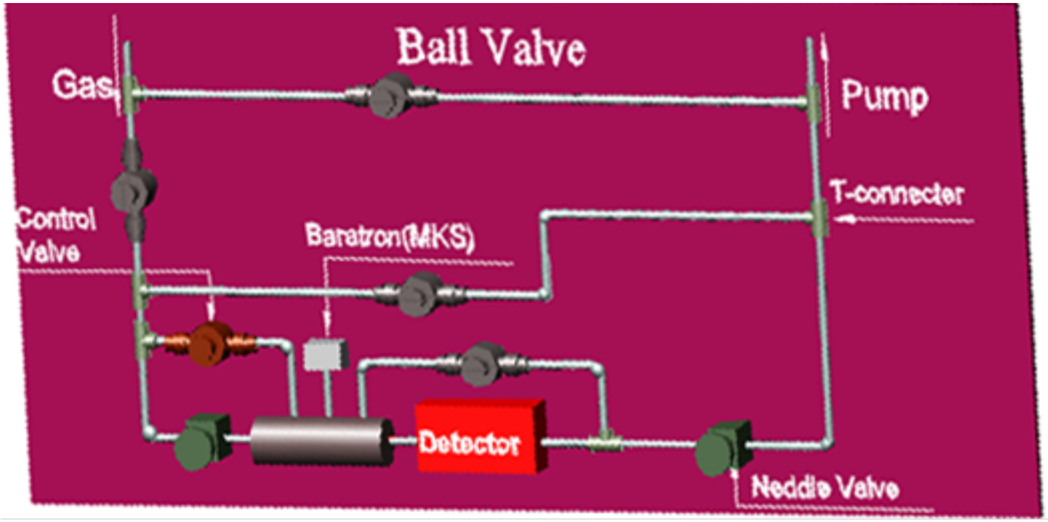
Auxiliary detector fabrication facilities at VECC



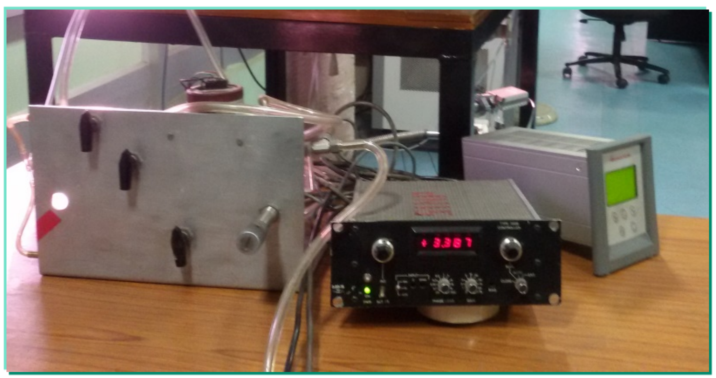
Measured thickness of the polypropylene film : 0.42 μm.

Thickness of a un-stretched polypropylene film : 33.8 μm.

Auxiliary detector fabrication facilities at VECC

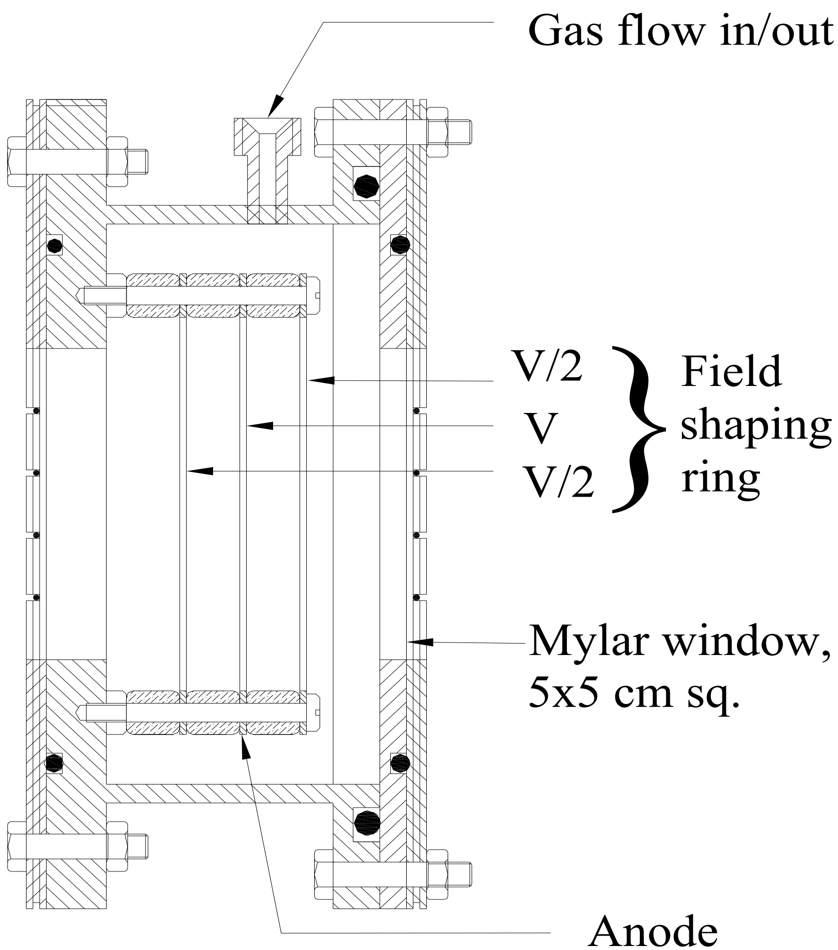


Gas handling system for precise monitoring of gas pressure



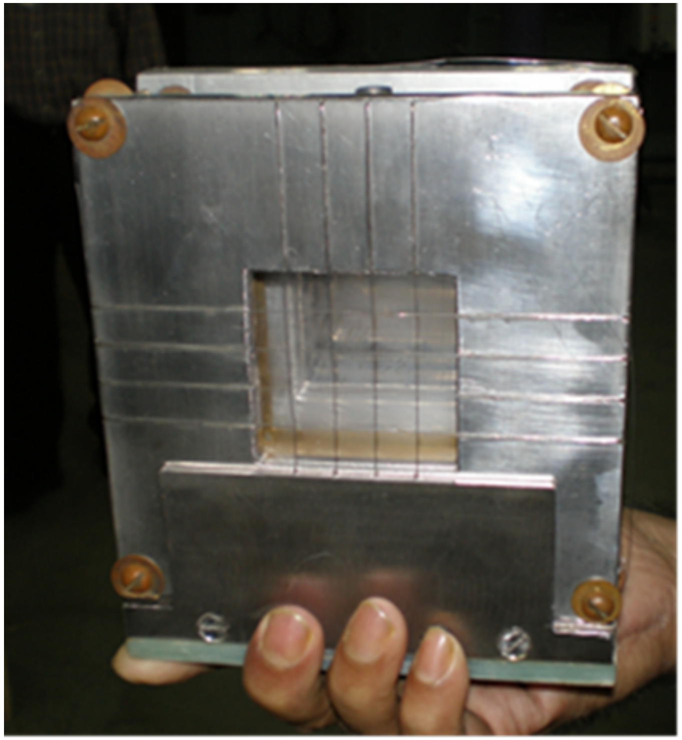
Ionization chamber

For detection of heavy fragments, because of the non availability of large area silicon detector of sufficiently smaller thickness.



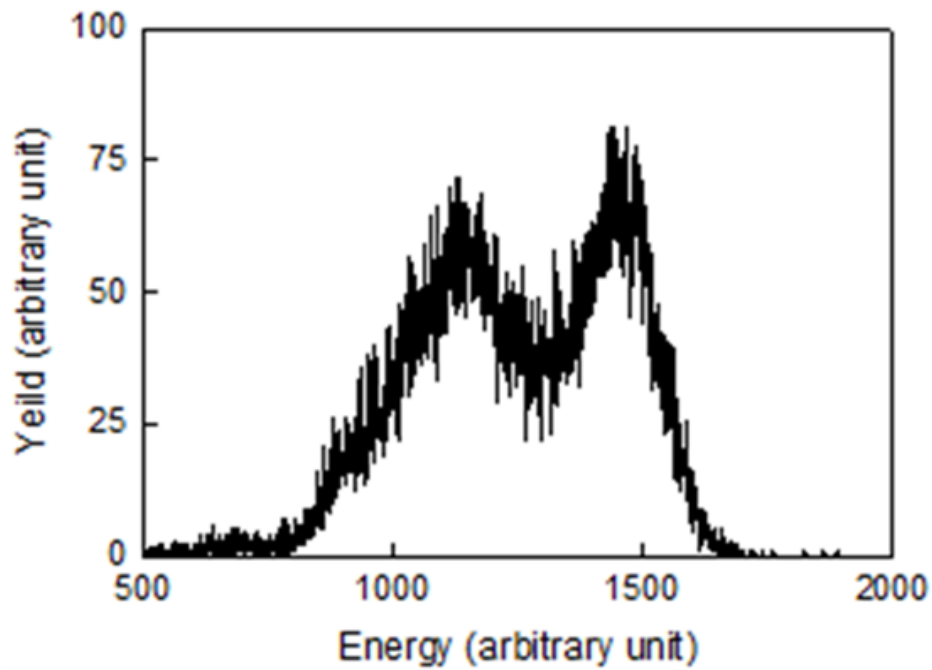
- Active area: 5 cm X 5 cm
- Three square shaped field-shaping ring separated by 10 mm
- A nichrome wire mesh of 98% transparency attached with the middle field-shaping ring as an anode

Axial field ionization chamber



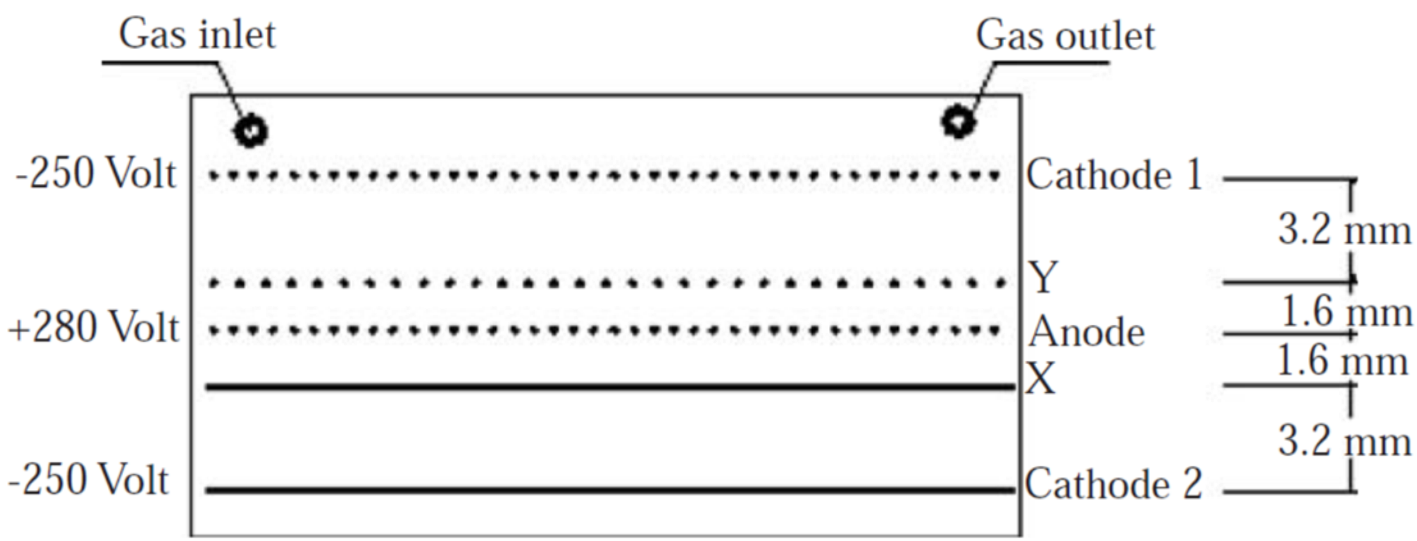
Ionization chamber

- Testing with ^{252}Cf source
- P-10 gas at a pressure of 60 torr
- E/p : 1 Volt/cm/torr



Possibility to use GEM in MWPC?

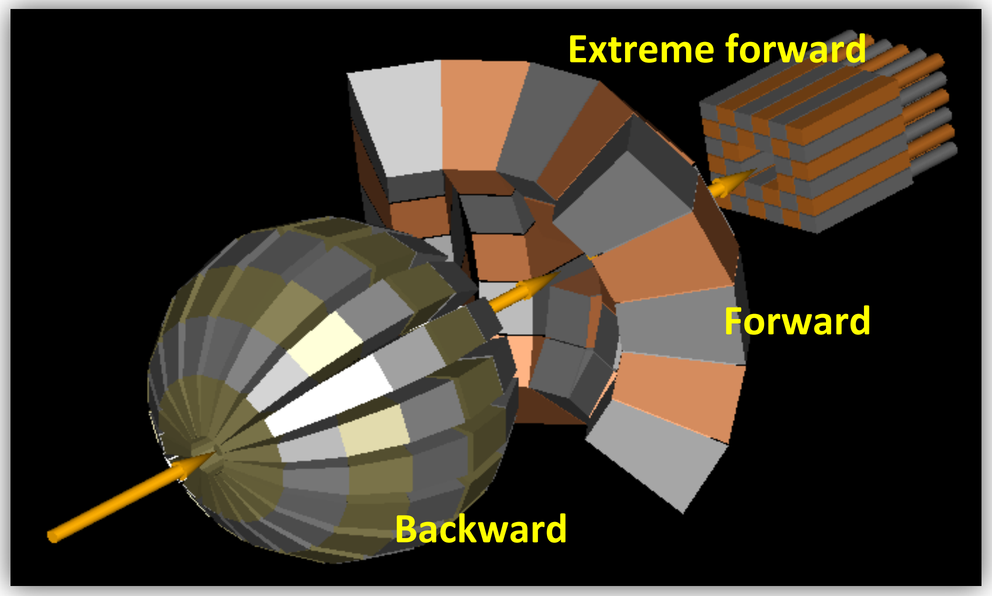
We are exploring the possibility for the replacement of fragile anode wire plane by GEM foil



Thick GEM at low pressure

Charged Particle Detector Array (CPDA) @ VECC

Charged Particle Detector Array (CPDA)

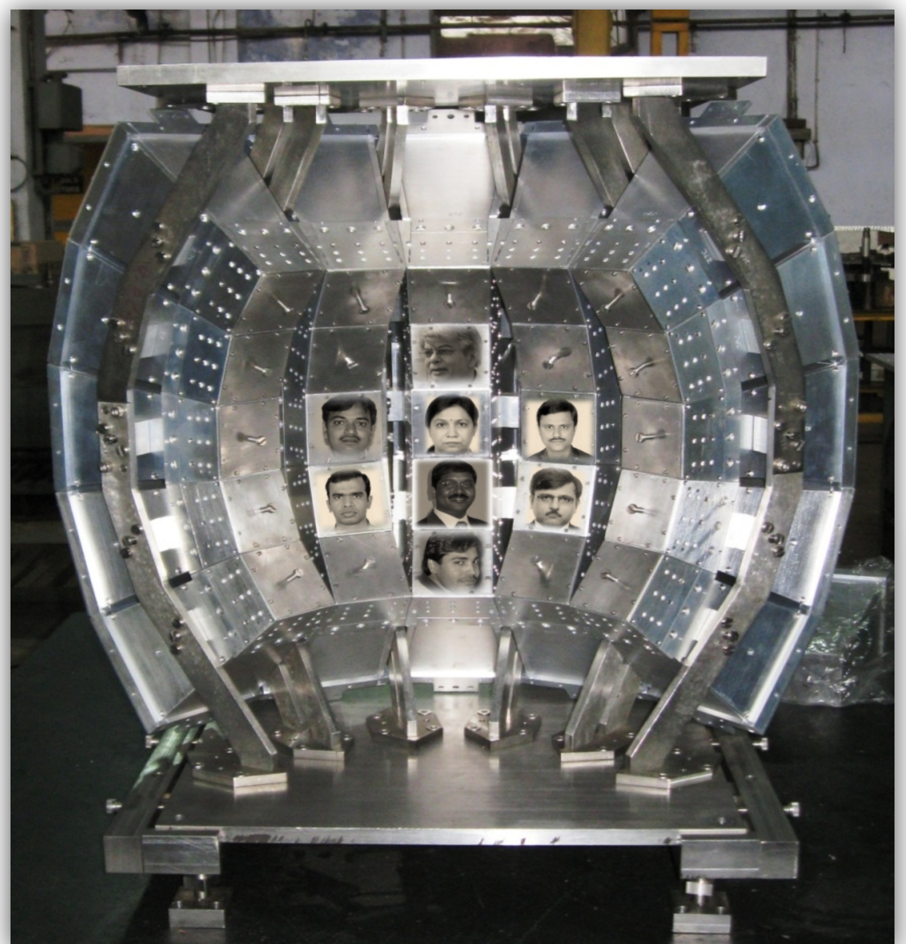


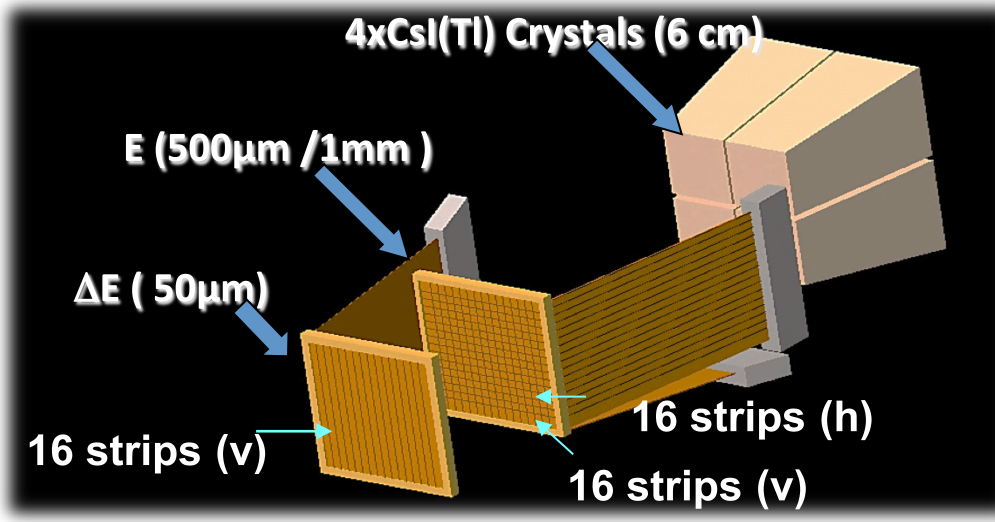
A high-resolution, high-granularity 4-pi array for complete charged particle spectroscopy

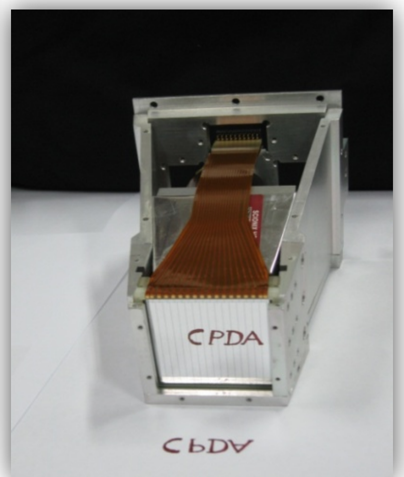
Unique tool for study of multi-particle correlation, resonance spectroscopy, complete calorimetry etc.

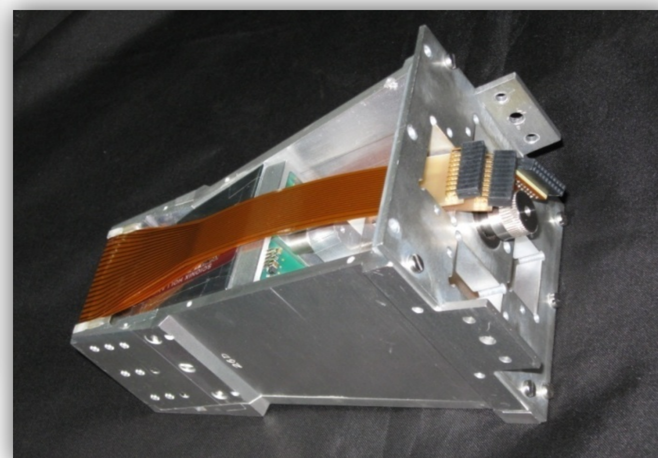
	Extreme Forward Array	Forward Array	Backward Array
Detectors	Plastic slow (10 cm) - fast (200 μm) phoswich	Si (50 μm) + Si – (500 /1000 μm) + CsI(Tl) (6 cm)	CsI(Tl) (2- 4 cm)
Number	32	24 telescopes	114
Ang. Cov.	3^0 -7^0	7^0 - 45^0	45^0 -170^0
Channel	~ 64	~1248	~ 228
Status	Completed	Completed	Partially completed

Forward array



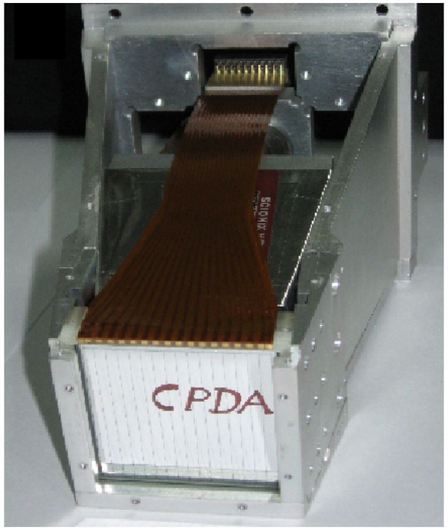


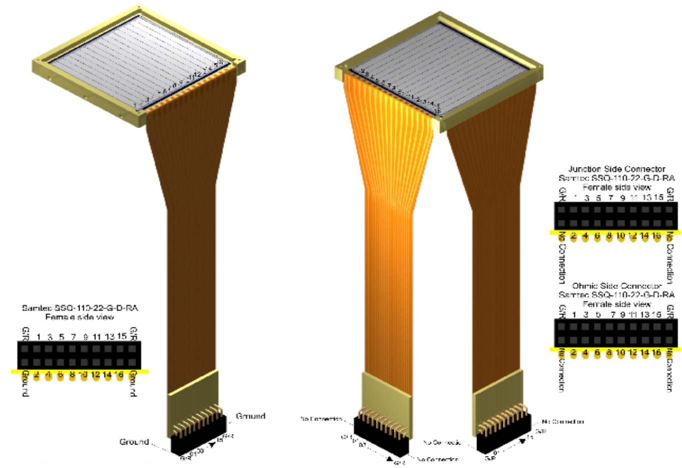




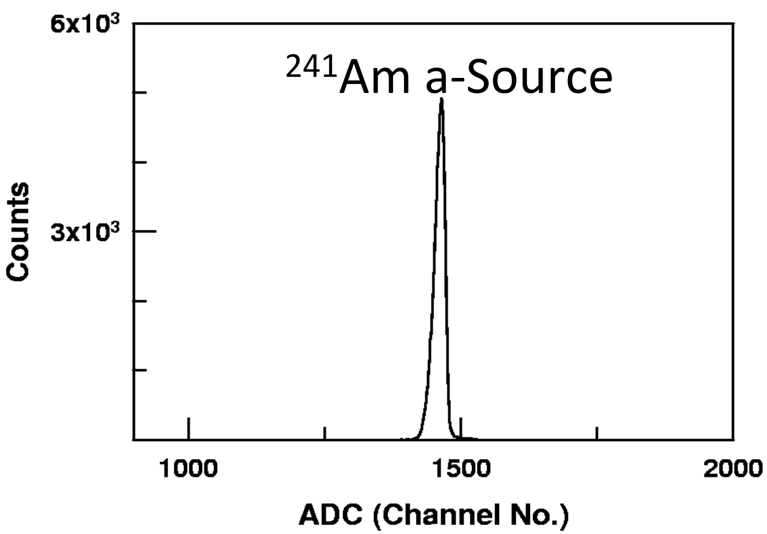
24 telescopes ready with detectors and electronics

Characterization of strip detectors



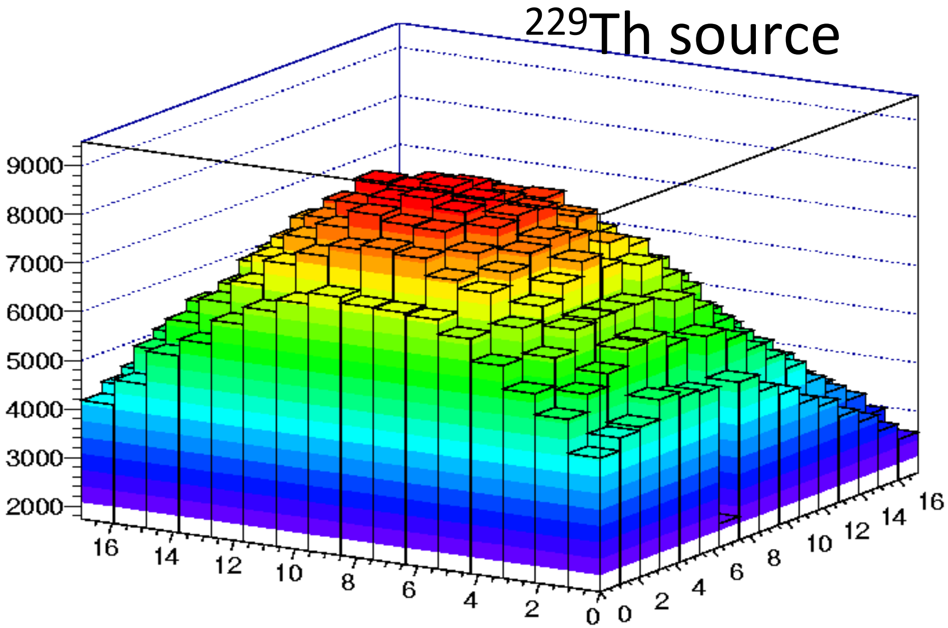


Silicon-strip detectors

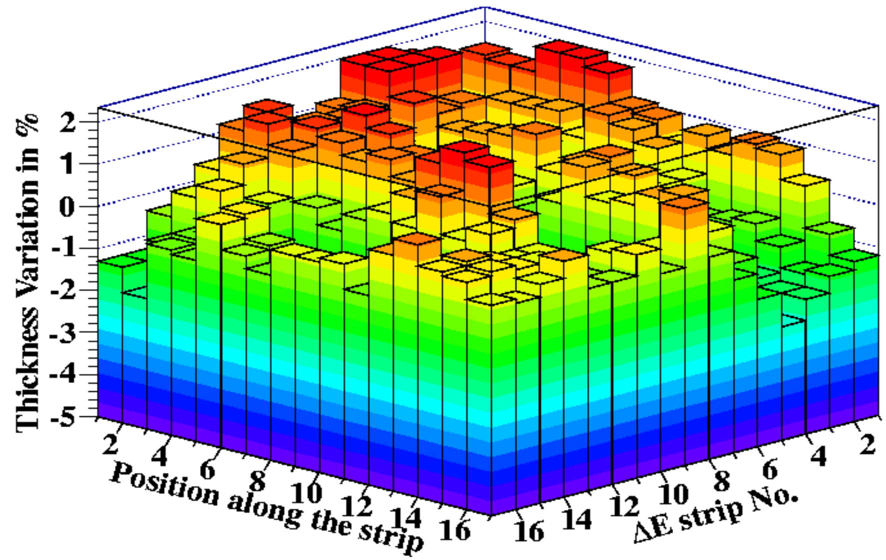


Energy resolution < 50 keV

Characterization of strip detectors



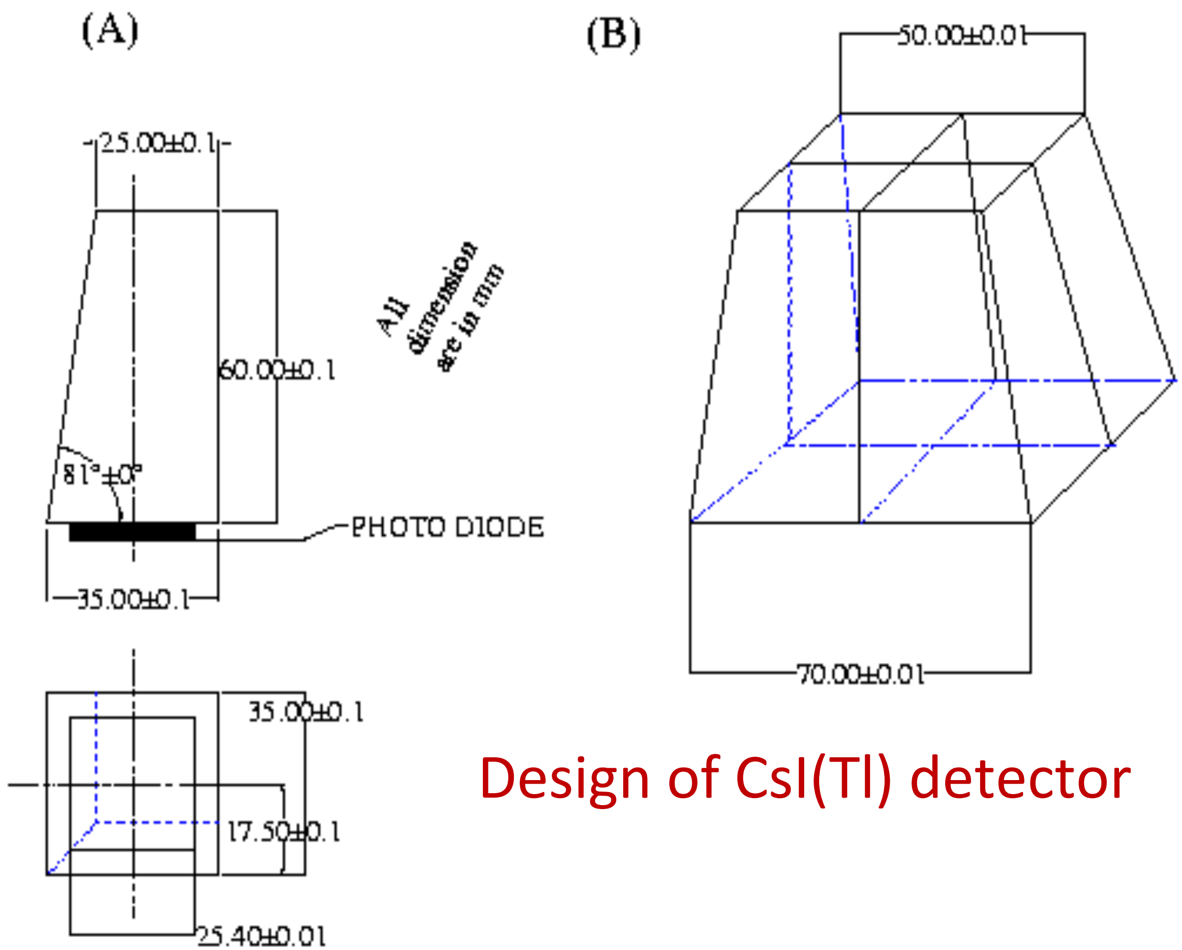
Position identification in DSSD



Non uniformity of SSSD

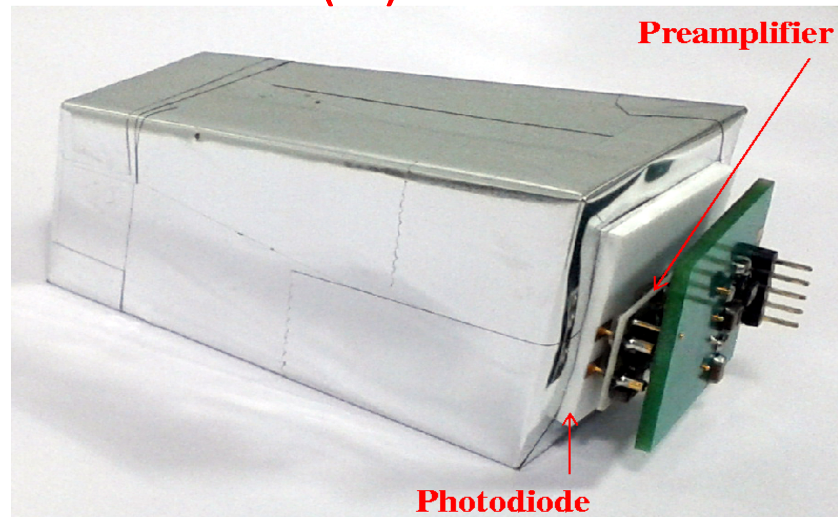
- Thickness at different position along the strip have been estimated and the variation with respect to mean thickness of strip.
- Thickness variation is found to be < 3 % of 50 micron detector.

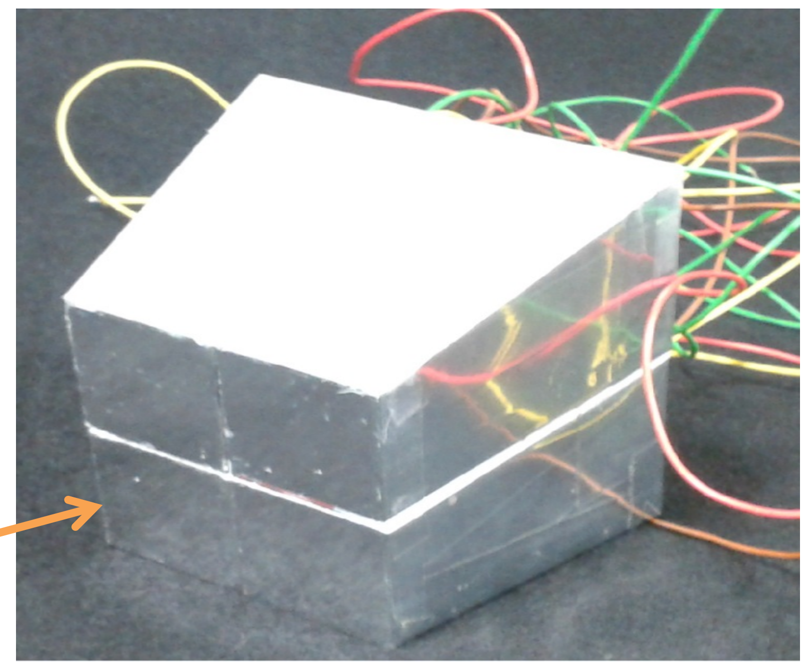
CsI (Tl) detectors for forward array



Design of CsI(Tl) detector

CsI(Tl) detector

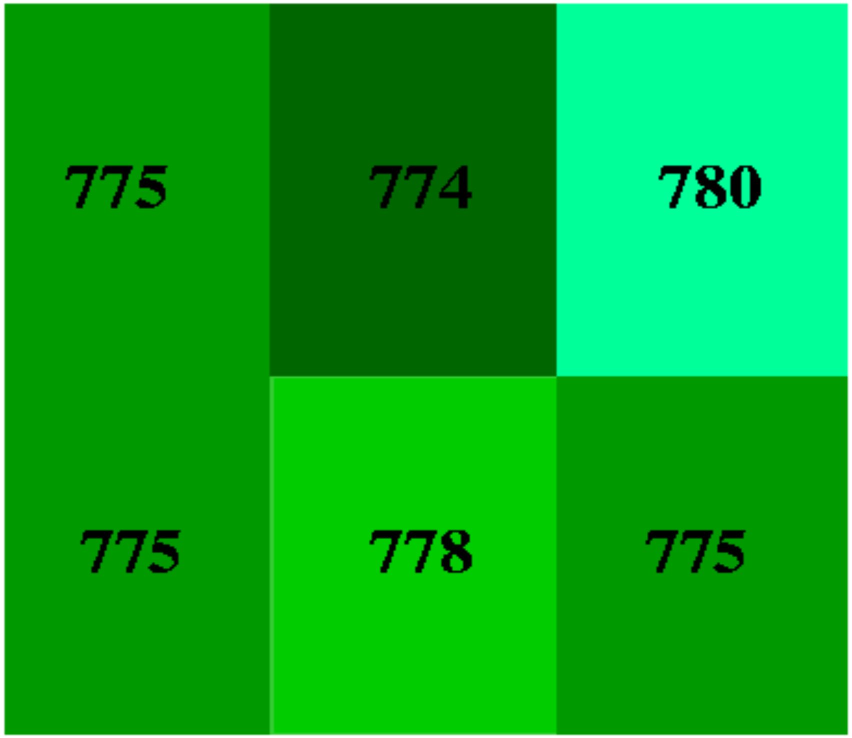




Assembly of four CsI(Tl) detectors

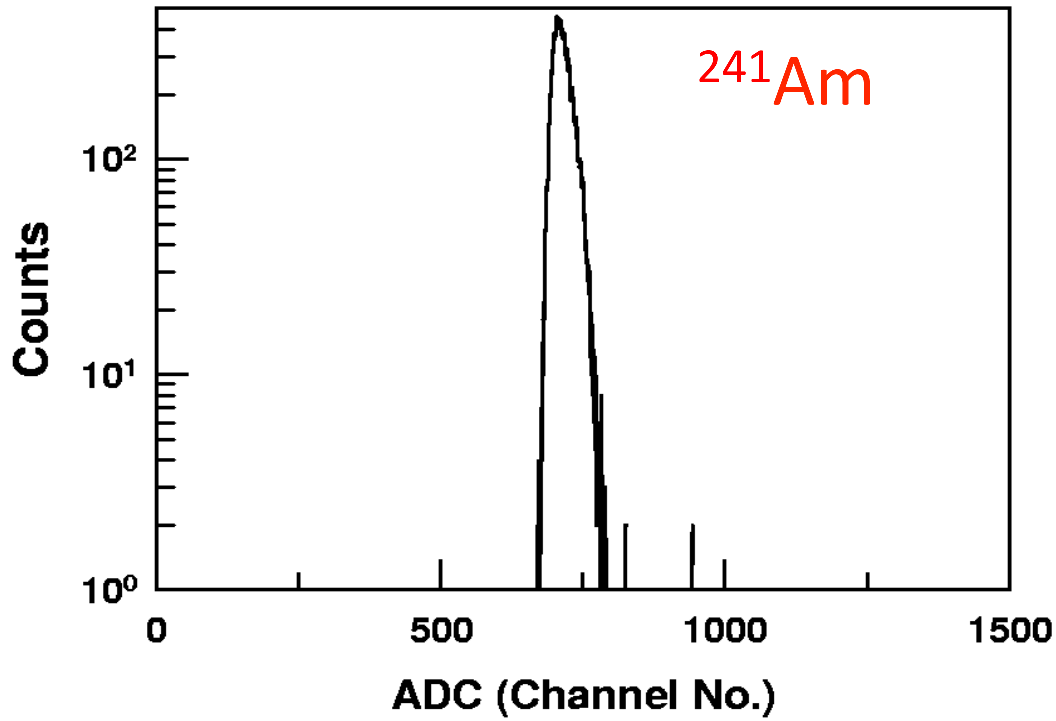
Truncated pyramid shape

Characterization of CsI(Tl) detectors



Non-uniformity measurement of CsI(Tl) detector

Max non-uniformity < 0.49 %



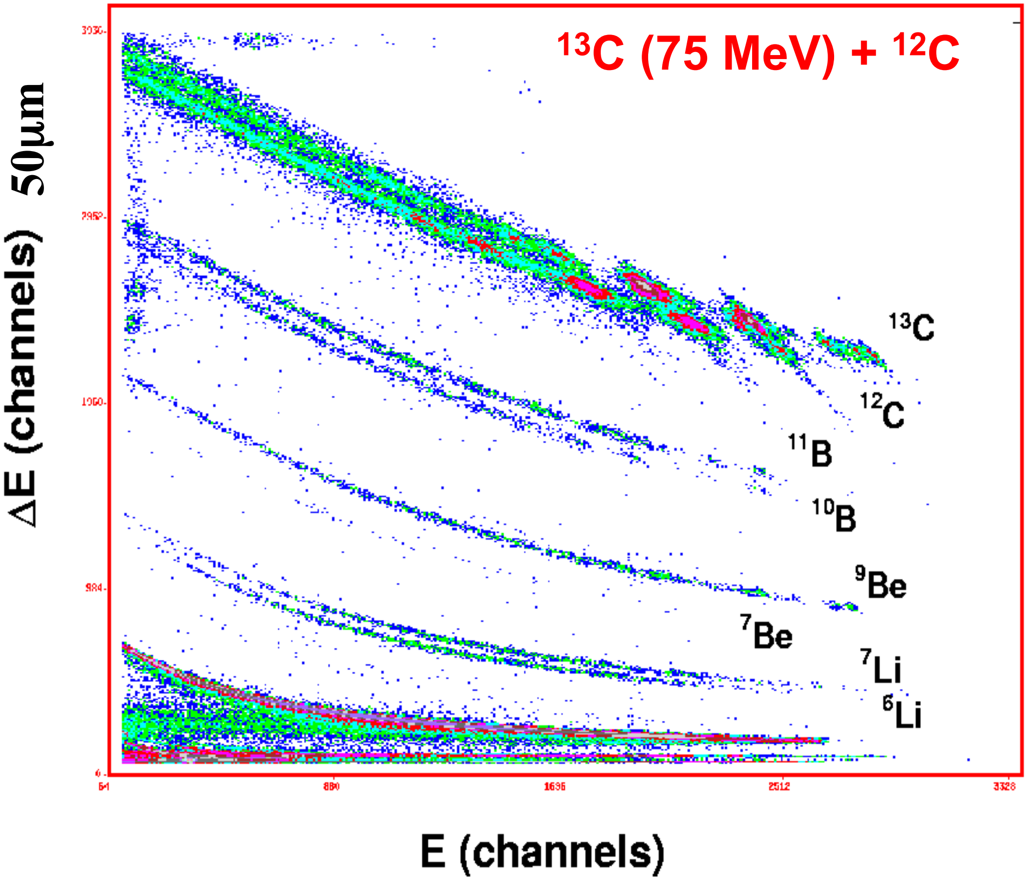
Energy resolution using α-source

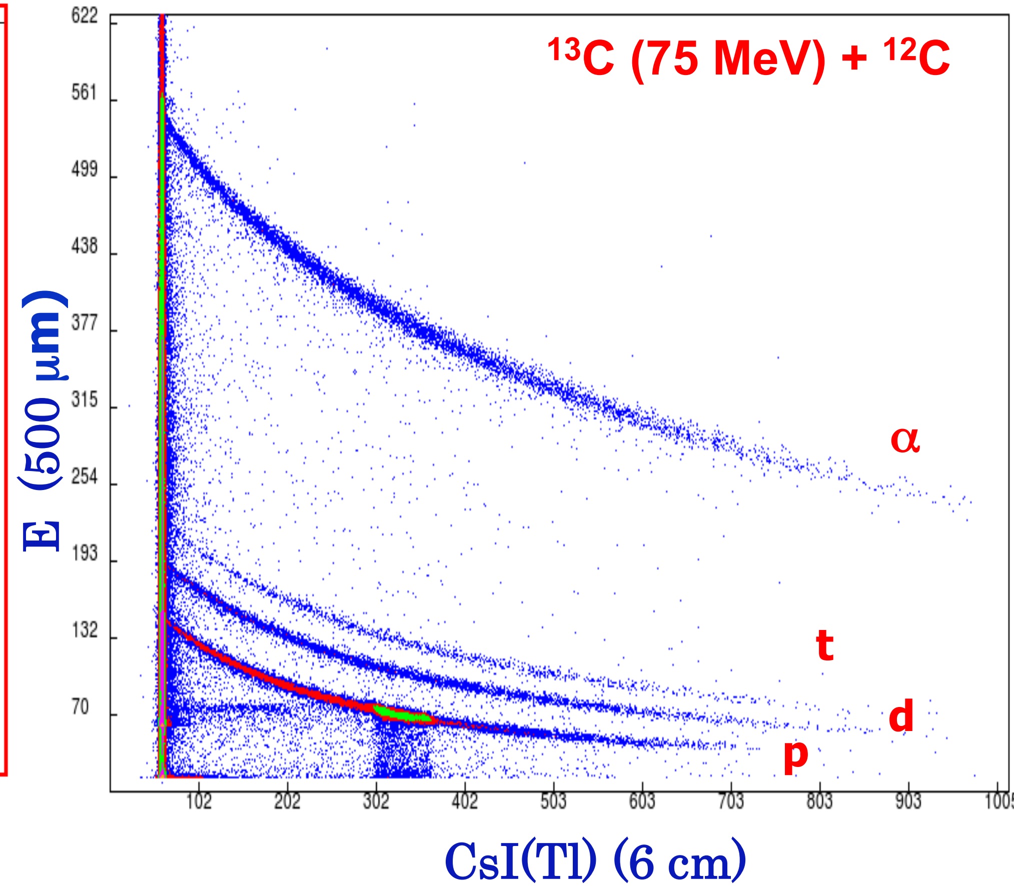
Resolution < 5 %

Non-uniformity and the energy resolution are found to be consistent with our requirement

Forward part of CPDA with electronics

Characterization of telescopes



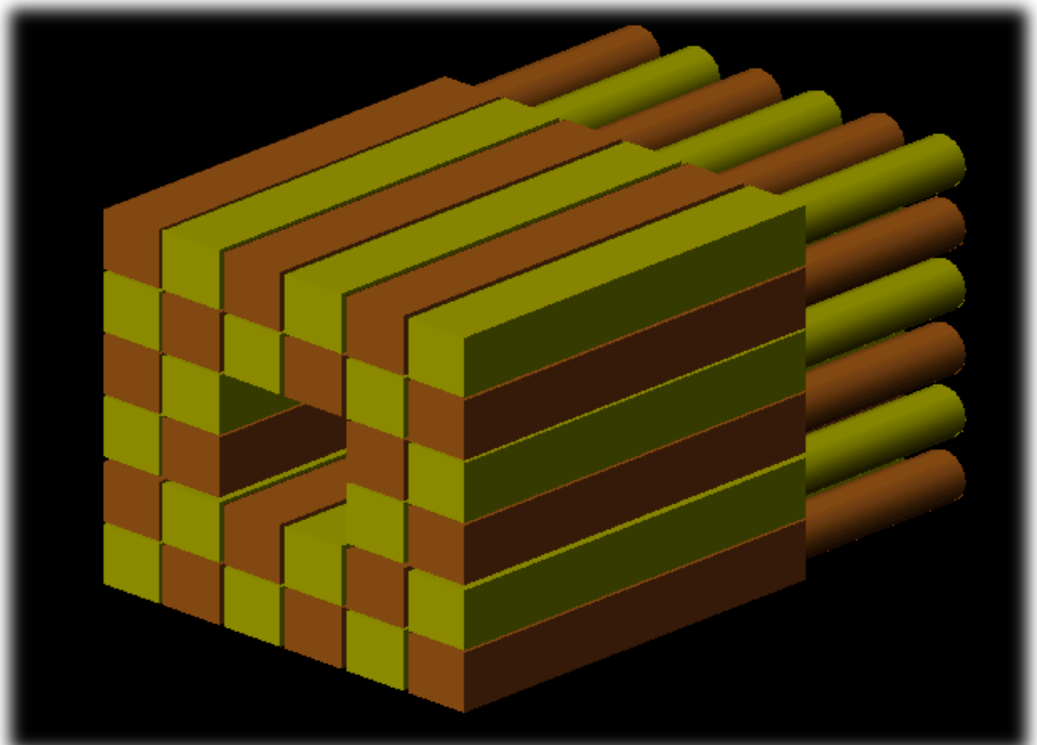


Particle identification by ΔE – E Methods

Good isotopic separation for all fragments has been observed

Extreme forward part of the array ($\pm 3^0$ - $\pm 7^0$)

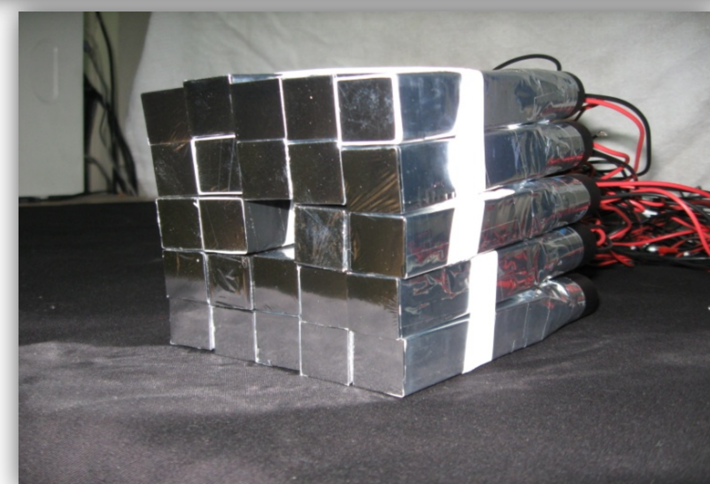
32 Plastic phoswich detectors



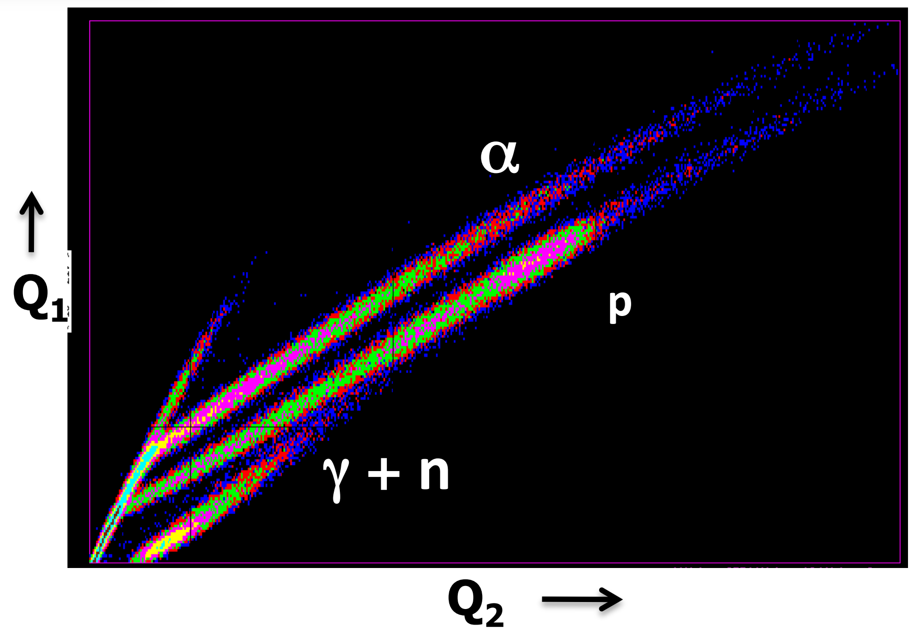
- Mostly LCP, elastic scattering and direct reactions products
- High count rate with higher energy
- Detector: Plastic phoswich detector
- Low radiation damage, high count rate handling capability.
- Element : Slow (100 mm, 280 ns, BC444)/fast (200 μm, 2ns, BC408) organic plastic (PVT based) scintillator
- No. of Detectors : 32 (area 20 mm x 20 mm)
- Typical low energy threshold :
  2 MeV/A for proton and alpha
  5 MeV/A for ^{16}O
  11 MeV/A for ^{40}Ca
- Angular resolution < 1^0
- Distance from target : 40 cm

Extreme forward part

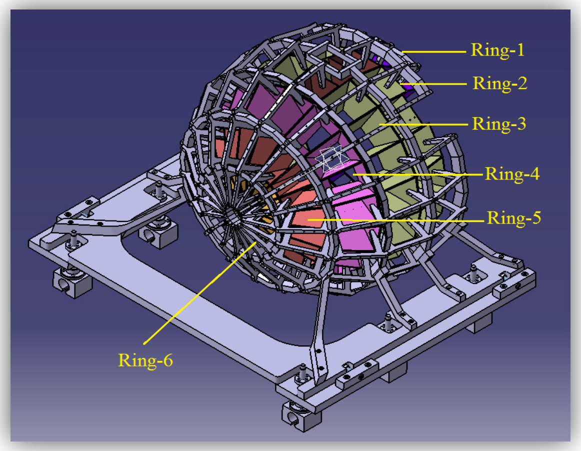
Entrance face with thin aluminized mylar and body with thick aluminized mylar

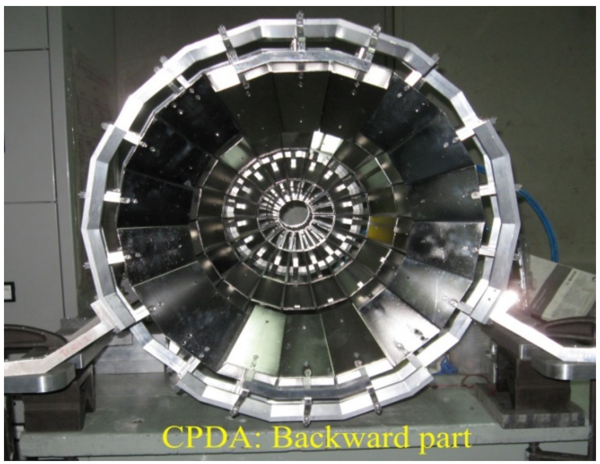


Extreme forward array detectors after fabrication



Backward array





- This part of the array will detect only LCP (Z=1,2)
- LCP will be identified using single CsI(Tl) crystal by pulse shape discrimination (PSD) technique .
- 114 CsI(Tl) detectors will be used.
- Geometry of this part of array is such that front face of the detectors form a part of sphere of radius 150 mm and it should not clash with the other part of the array.

Detectors arrived
Support structure ready

Effective utilization CPDA

What are we made up of?

The life on the earth would not have existed without the presence of the element Carbon !

- Estimation of direct component of Hoyle state

PhD thesis Tapan Kumar Rana (HBNI)

Phys. Rev. C 88, 021601 (R) (2013)

- Survival of cluster correlation in dissipative binary breakup of $^{24,25}Mg^*$

Phys. Rev. C 94, 051601 (2016) (R)

- Spectroscopic information about different excited states of ^{26}Al and ^{26}Mg populated through the $^{27}Al(d, t)$ and $^{27}Al(d, ^{3}He)$ reactions

PhD thesis Vishal Srivastava (HBNI)

Phys. Rev. C 93, 044601 (2016)
Phys. Rev. C 91, 054611 (2015)

Neutron detector development @ VECC

Neutron TOF detector array @ VECC

Development of a neutron detector array at the K500 beam hall

- 50 detectors: dimension 5 inch X 5 inch

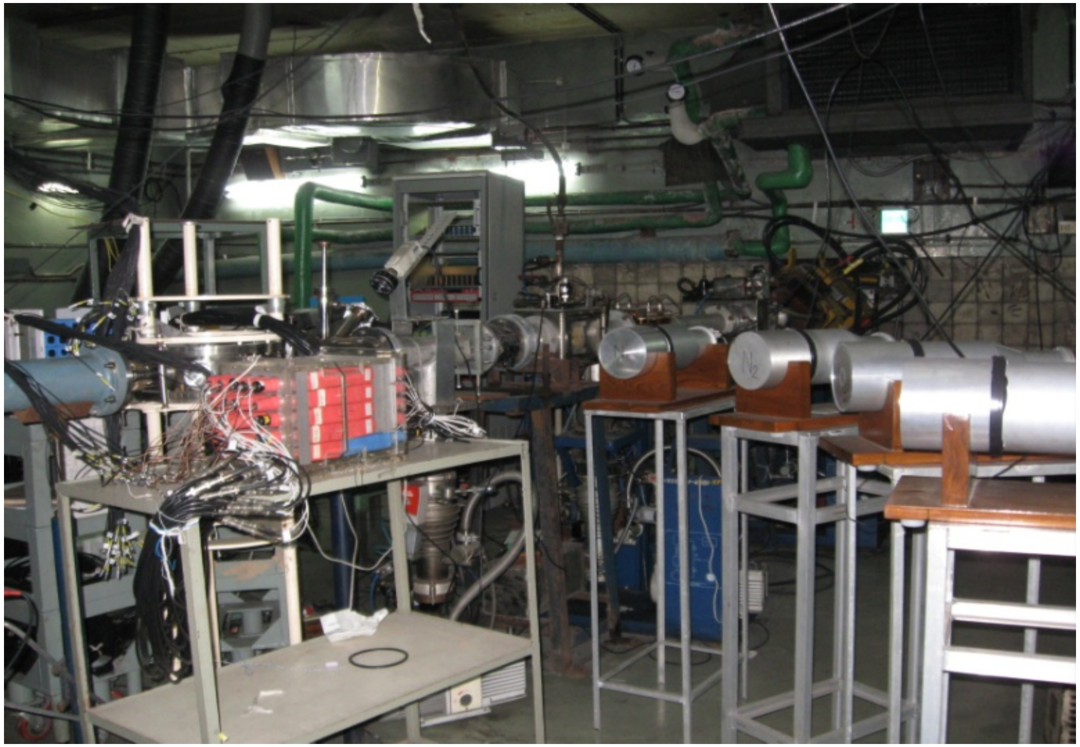
Liquid Scintillator : BC501A

Photo-multiplier tube : XP4512B (5")

- Flight path : 2 meter

Thin wall scattering chamber of wall thickness 3 mm to place the ancillary detectors

Utilization of TOF detectors @ VECC



These detectors are routinely used in in-beam experiments performed at K130 Cyclotron in VECC

PhD thesis (HBNI):
Pratap Roy (to be submitted)
Manish R Gohil (2014)
Kaushik Banerjee (2013)

- Angular momentum dependence of nuclear level density
- Fade out of collectivity in nuclear level density
- Shell effect in nuclear level density in ^{208}Pb region

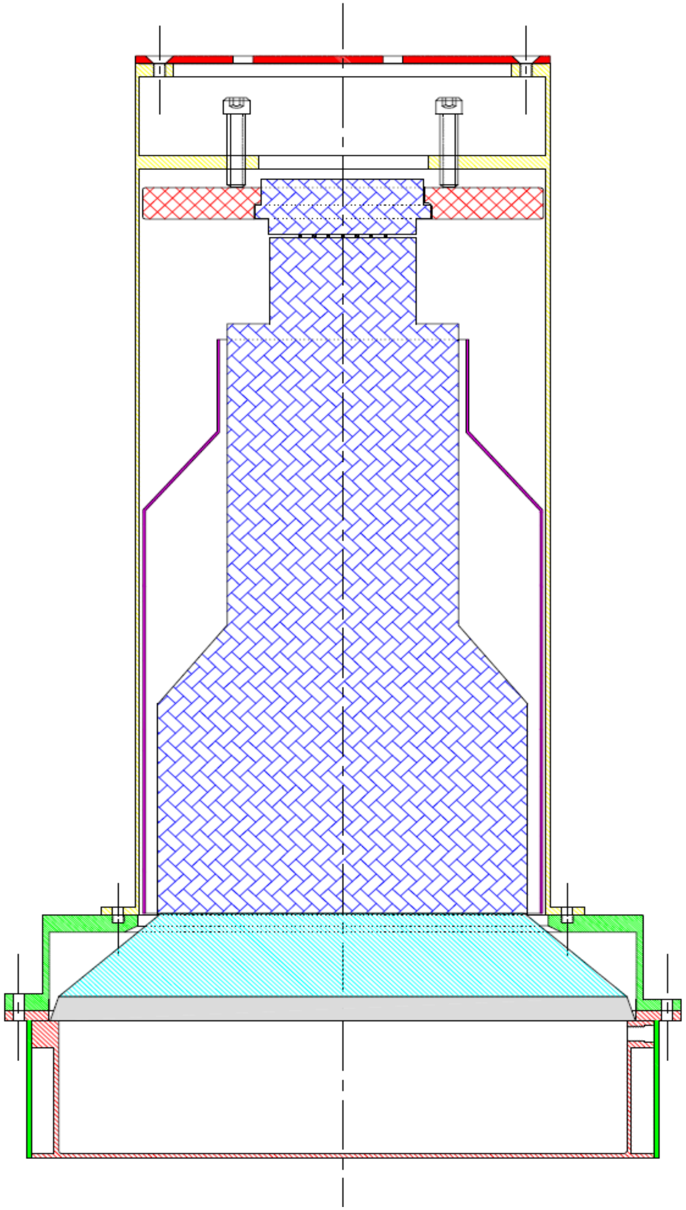
Phys. Rev. C 88, 031601 (2013) (R)
Phys. Rev. C 86, 044622 (2012)

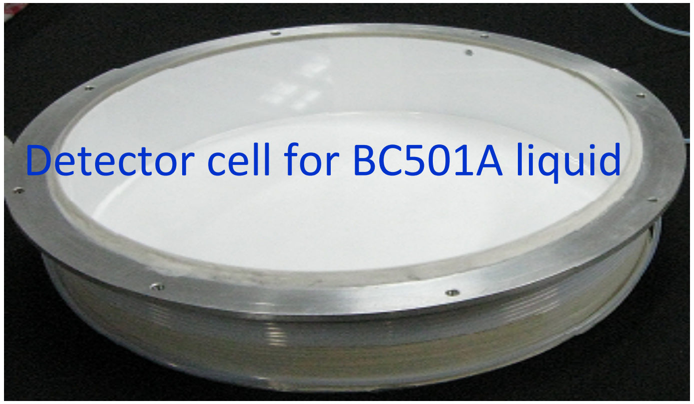
Phys. Rev. C 91, 014609 (2015)
Phys. Rev. C 94, 064607 (2016)

Neutron detector for DESPEC at FAIR

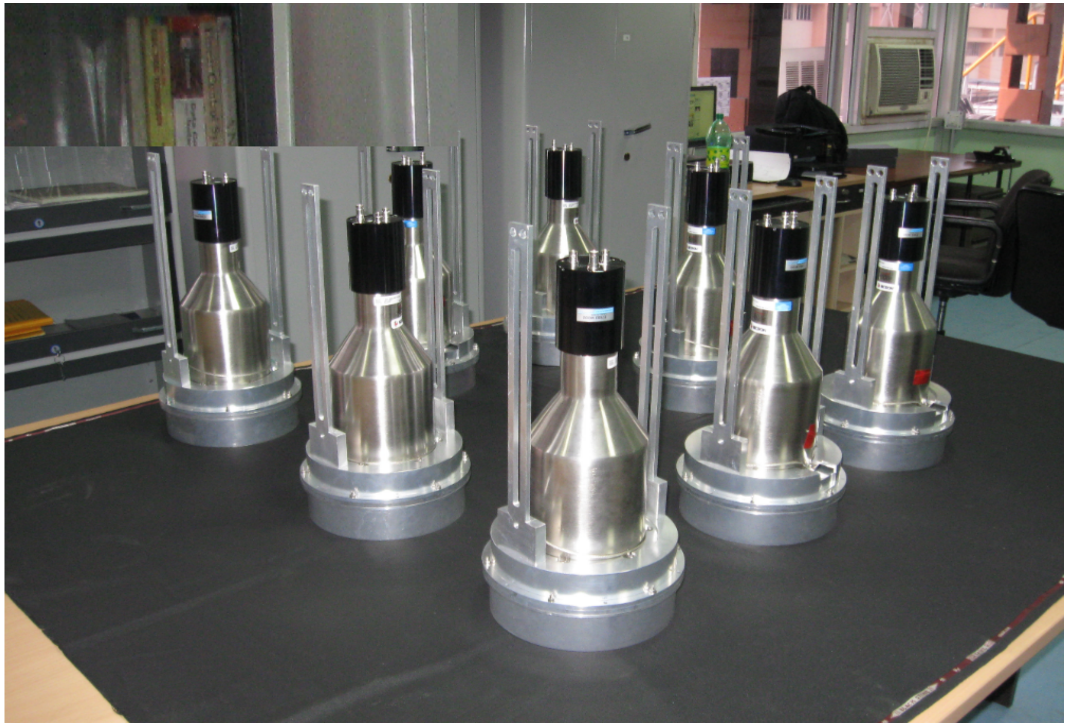
8 inch diameter and 2 inch thick

Typical energy resolution at 2 m flight path = 5%





Neutron detector for MONSTER@FAIR

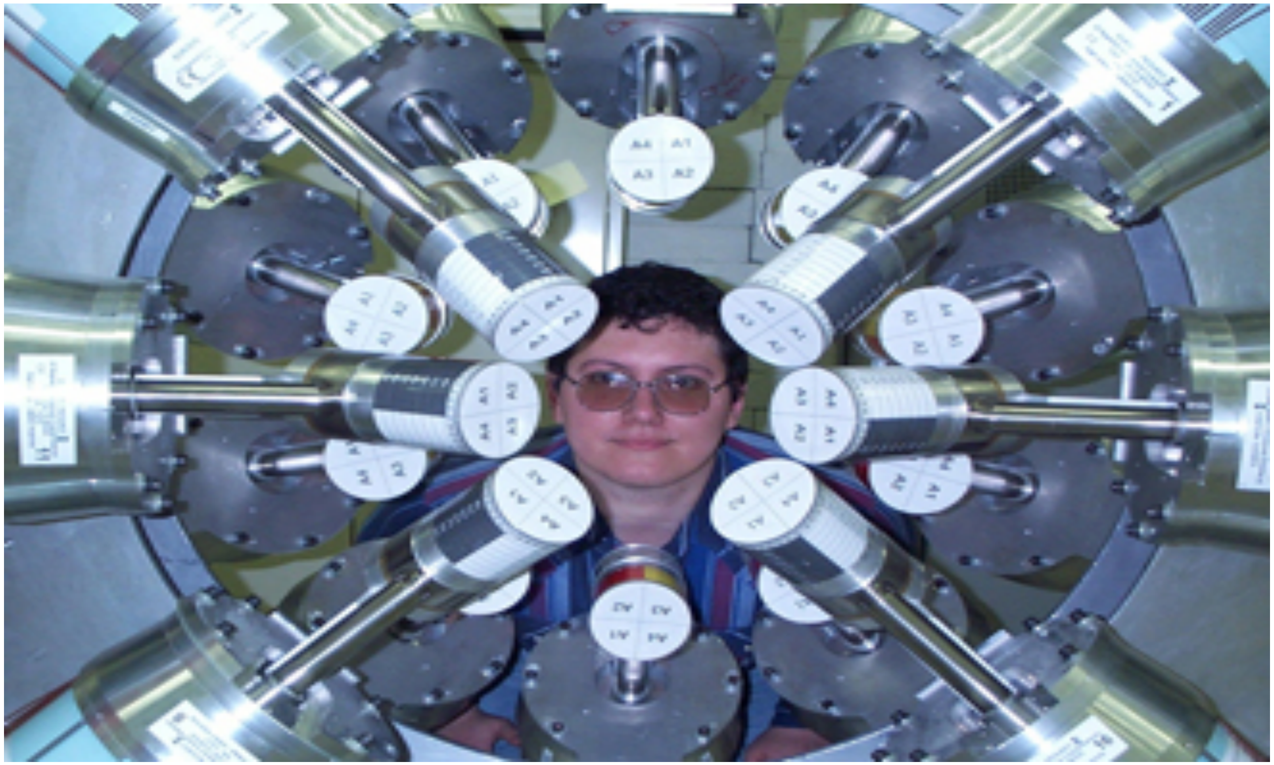


Detector housing of 10 neutron detectors have recently completed.

Housing made up of Al 6061-T6

Gamma detectors @ VECC

If you want to "see" the structure of a nucleus, look through the "window" of g-ray spectroscopy



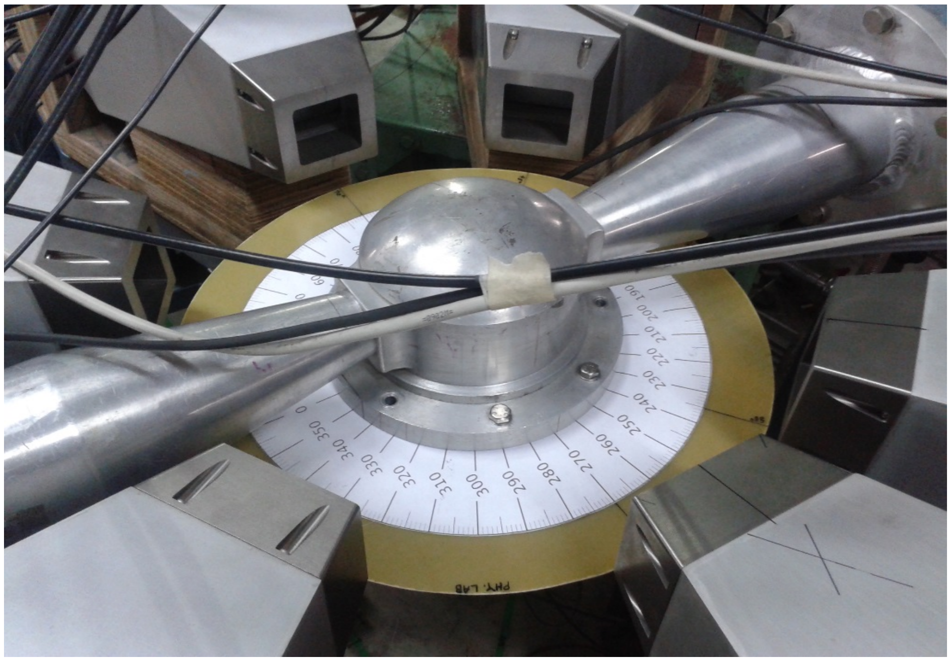
The heart of the γ-ray spectroscopy is the high-resolution γ-detectors

VENUS

VENUS (VECC Array for Nuclear Spectroscopy) at VECC

VENUS

VENUS (VECC Array for Nuclear Spectroscopy) at VECC

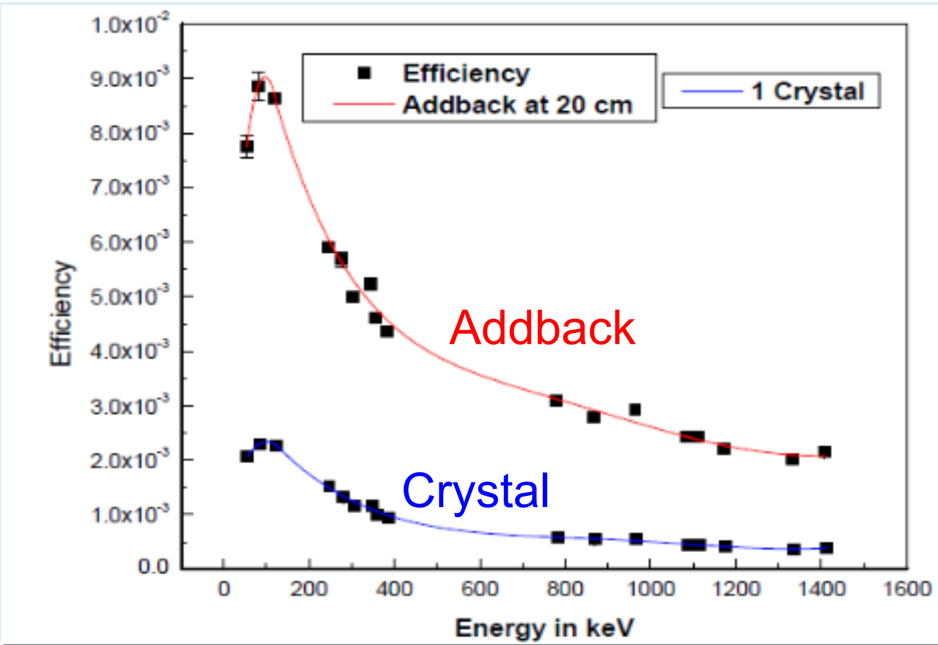


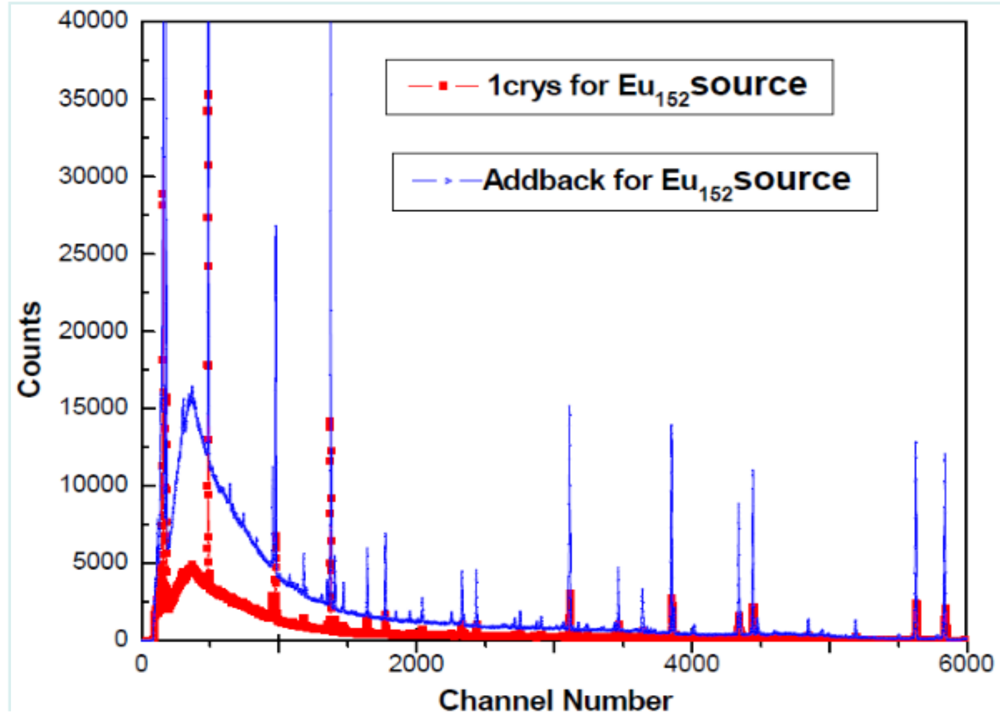
- VENUS consists of 6 Compton-suppressed clover HPGe detectors arranged in horizontal plane.
- Each detector placed in an individual platform so that one can arrange the detectors in any suitable angle.
- Typical target to detector distance is about 26 cm.
- The efficiency of the array at this distance is about 1%.

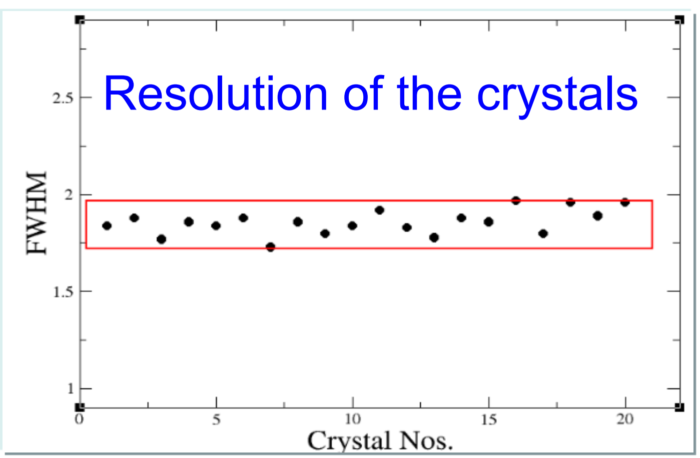
Possibility to use the array in conjunction with other detectors, like LaBr3(Ce) detectors, charged particle, neutron, fragment detectors etc.

Characterization of individual detectors of VENUS array

Measured absolute efficiency

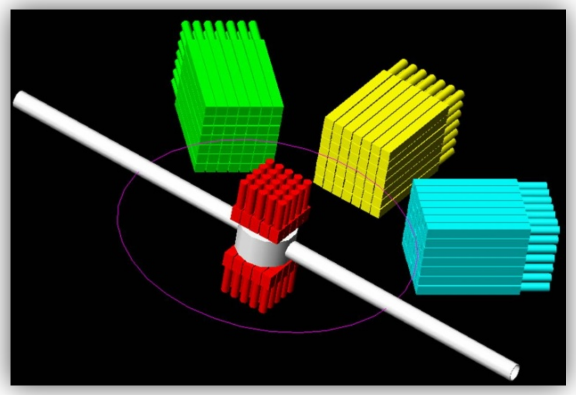




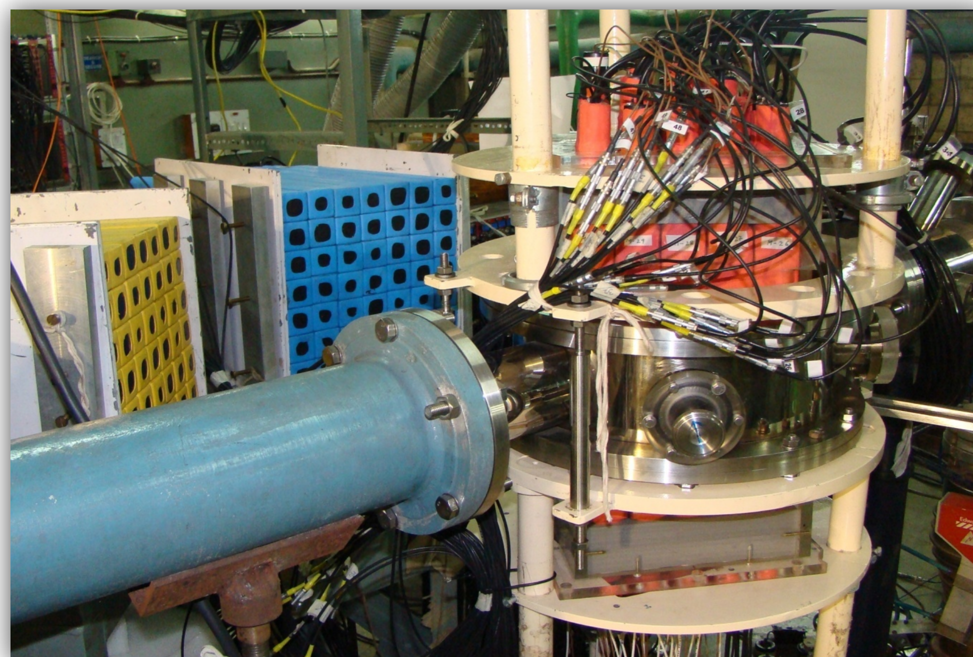


All 6 clover detectors are in good shape
Resolution of the HPGe crystals are < 2.0 keV at E_g = 1.33 MeV
Addback efficiency is satisfactory

Large Area Modular BaF2 Detector Array (LAMBDA)



162 BaF2 detectors & 50 BaF2 multiplicity filter Array



- Systematic study of the GDR width at low temperature
- Signature of clustering in atomic nuclei probed by giant dipole resonance

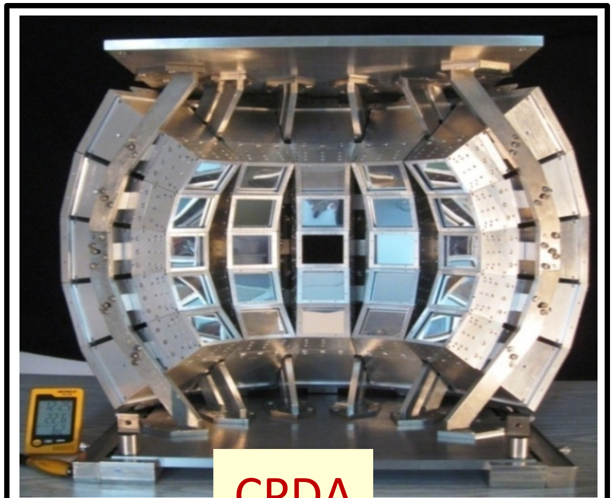
Physics Letters B 763 (2016) 422
Physics Letters B 731 (2014) 92
Physics Letters B 713 (2012) 434
Physics Letters B 709 (2012) 9

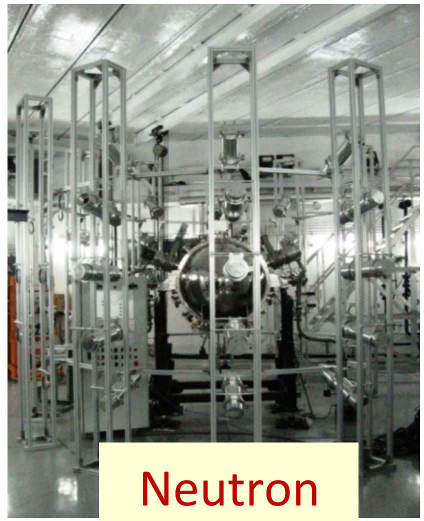
Each main detector : 35 x 35 x 350 mm^3
Each mult. detector : 35 x 35 x 35 mm^3

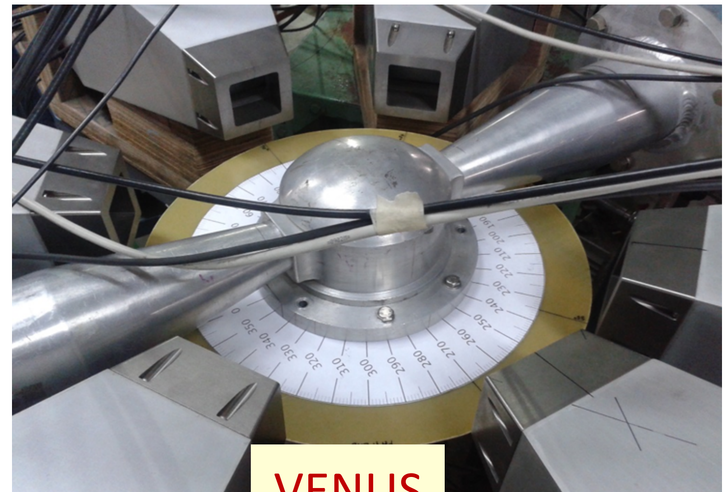
NIM A 727 (2013) 7; NIM A 624 (2010) 148

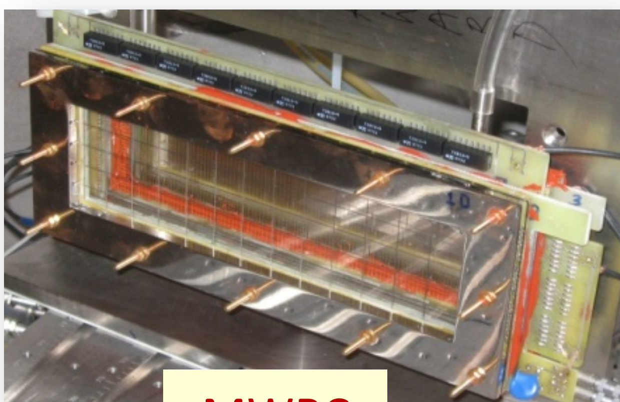
Summary

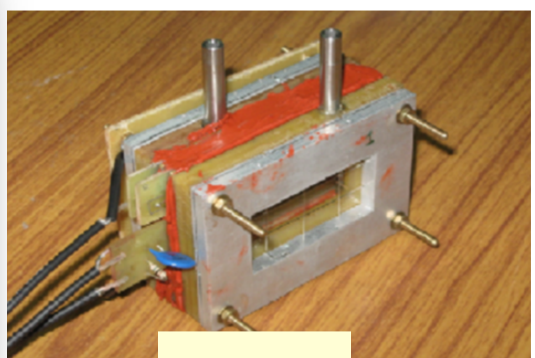
Several state of the art detectors are being developed at VECC and effectively utilised to study fundamental Nuclear Physics

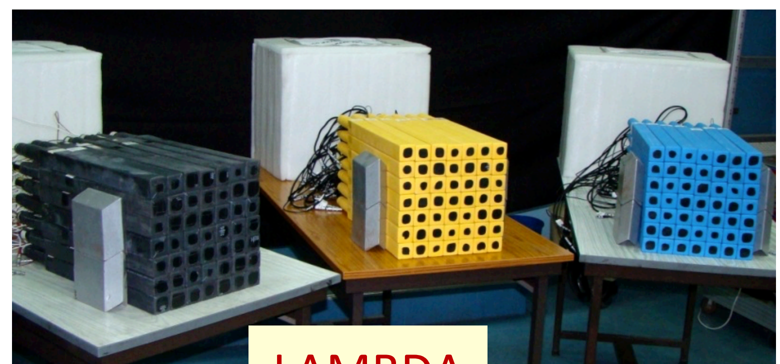

CPDA


Neutron


VENUS


MWPC


PPAC


LAMBDA

CPDA Group

Ruchi, Tapan, Kaushik, Gopal, Rathin, Saila, Samir, Jai, Ratnesh (standing, from left),
Arijit, Santu, Chandana, Tilak, Amiya, Jaynta (seating)
& Pratap (photographer/invisible ☺)