RPC activities for the India-based Neutrino Observatory and Present RPC activities at Bose Institute

Saikat Biswas
Bose Institute
Kolkata, India

Outline of the talk

- *Neutrino oscillation and Physics motivations for India-based Neutrino Observatory (INO)*
- *INO Detector (ICAL) and Resistive plate chamber (RPC) for ICAL*
- *Development of bakelite RPC*
  - *Efficiency*
  - *Time resolution*
  - *Long term stability*
- *Summary*

Atmospheric Neutrinos

Production:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \pi^- \rightarrow \mu^- + \overline{\nu}_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu \qquad \mu^- \rightarrow e^- + \overline{\nu}_e + \nu_\mu$$

Expected ratio of ν_μ and ν_e:

$$\frac{N(\nu_\mu, \overline{\nu}_\mu)}{N(\nu_e, \overline{\nu}_e)} \equiv \frac{N_\mu}{N_e} \approx 2$$

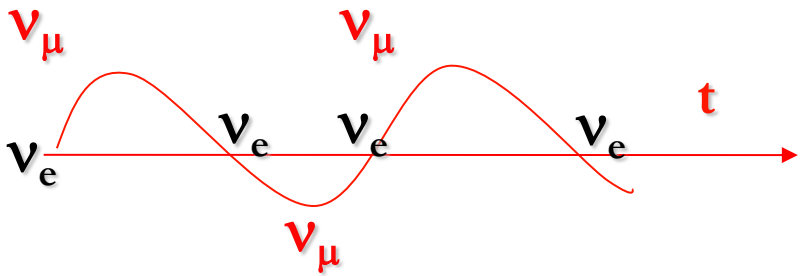
Result of Super-Kamiokande experiment:

$$\frac{N_\mu}{N_e} \approx 1.4$$

Deficit of ν_μ

Neutrino Oscillations

- Neutrinos come in more than one flavour or type. Consider, for simplicity, two flavours, ν_e and ν_μ.
- Neutrino oscillation is a quantum mechanical phenomena depending on the superposition principle.



- During travel, a ν_e becomes a ν_μ and then back again to a ν_e. This oscillation process continues.
- The oscillation wavelength depends on the neutrino energy (E) .

$$P(\nu_e \rightarrow \nu_\mu; L) = \sin^2 2\theta \ \ \sin^2 \frac{\Delta m^2 L}{4E}$$

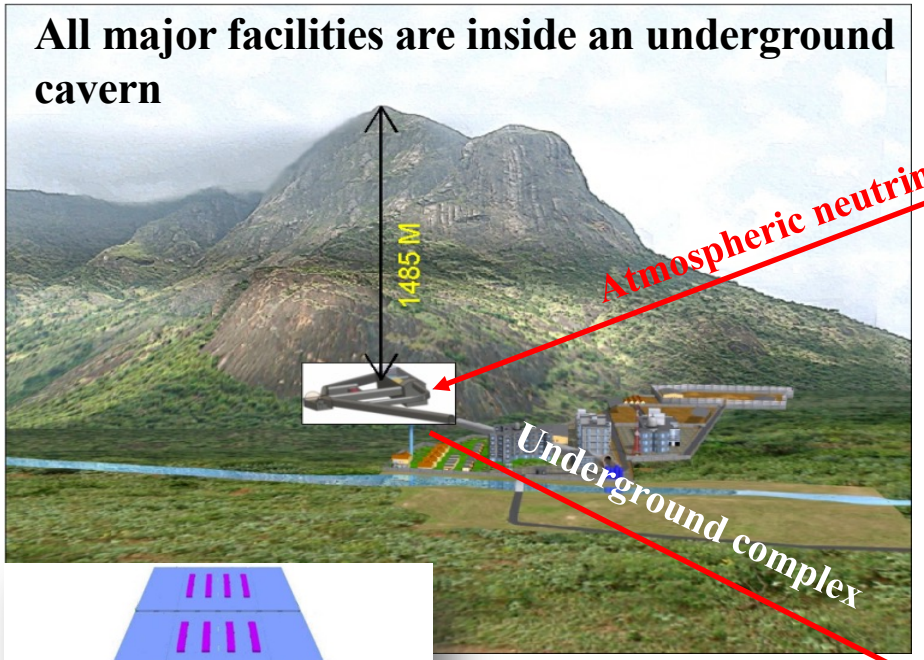
Physics Motivations for INO

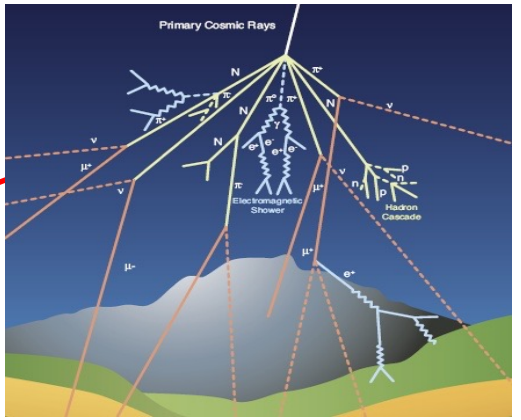
- It is a neutrino oscillation experiment.
- To reconfirm the oscillation through appearance and disappearance of neutrinos.
- To measure the neutrino oscillation parameters $|\Delta m^2_{31}|$, $\sin^2 2\theta_{23}$, θ_{13} more precisely.
- To determine neutrino mass hierarchy, whether normal ($m^2_3 > m^2_1$) or inverted ($m^2_3 < m^2_1$).

Oscillation parameters from other experiments

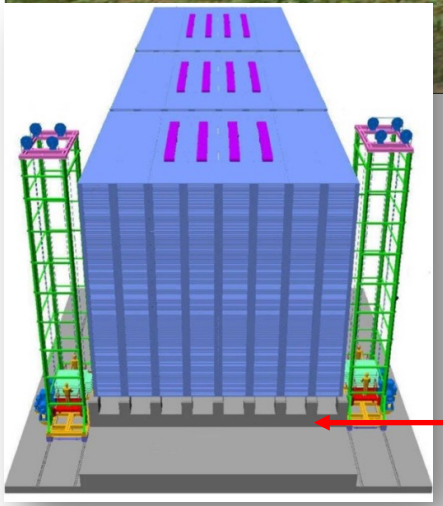
- **Solar $\nu \Rightarrow \Delta m^2_{21} = 7.9 \times 10^{-5}$ eV^2, $\theta_{12} = 36^o$**
- **Atmospheric $\nu \Rightarrow |\Delta m^2_{32}| = 2 \times 10^{-3}$ eV^2 , $\theta_{23} = 45^o$**
- **Reactor $\nu \Rightarrow$ KamLAND [$\Delta m^2_{21} = (7.2 - 9.2) \times 10^{-5}$ eV^2 , $\theta_{12} = 30^o - 39^o$] agrees with solar and CHOOZ constrain $\theta_{13} \leq 11^o$**
- **Accelerator $\nu \Rightarrow$ K2K confirms atmospheric results**

India-based neutrino Observatory (INO)-ICAL Project

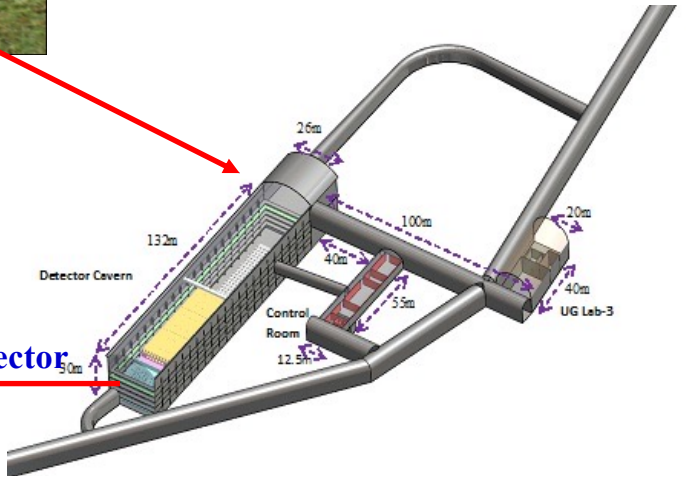




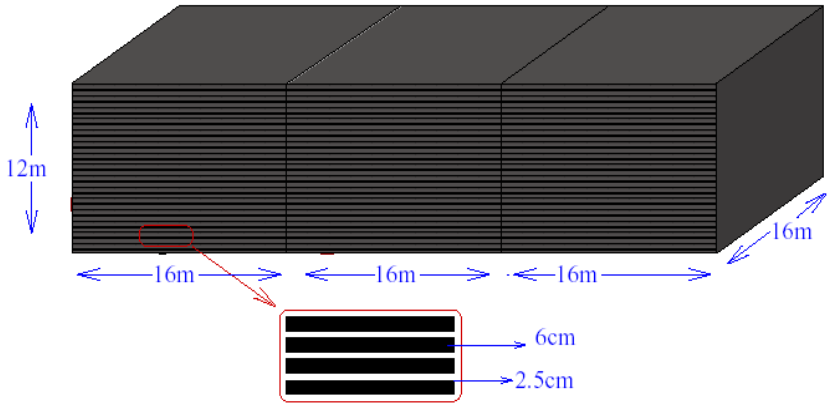
The magneised ICAL detector will study neutrinos naturally produced in Earth's atmosphere.

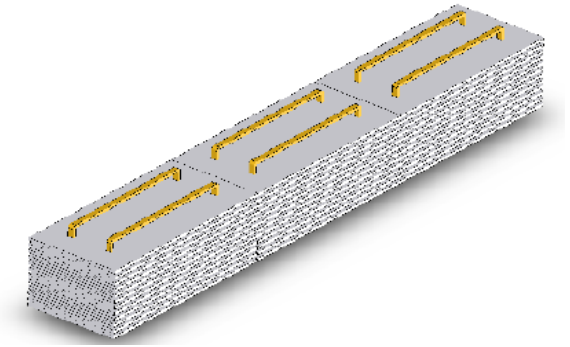


50Kton ICAL neutrino Detector



INO Detector
Iron Calorimeter (ICAL)





Magnetic field ~ 1 Tesla along y-direction

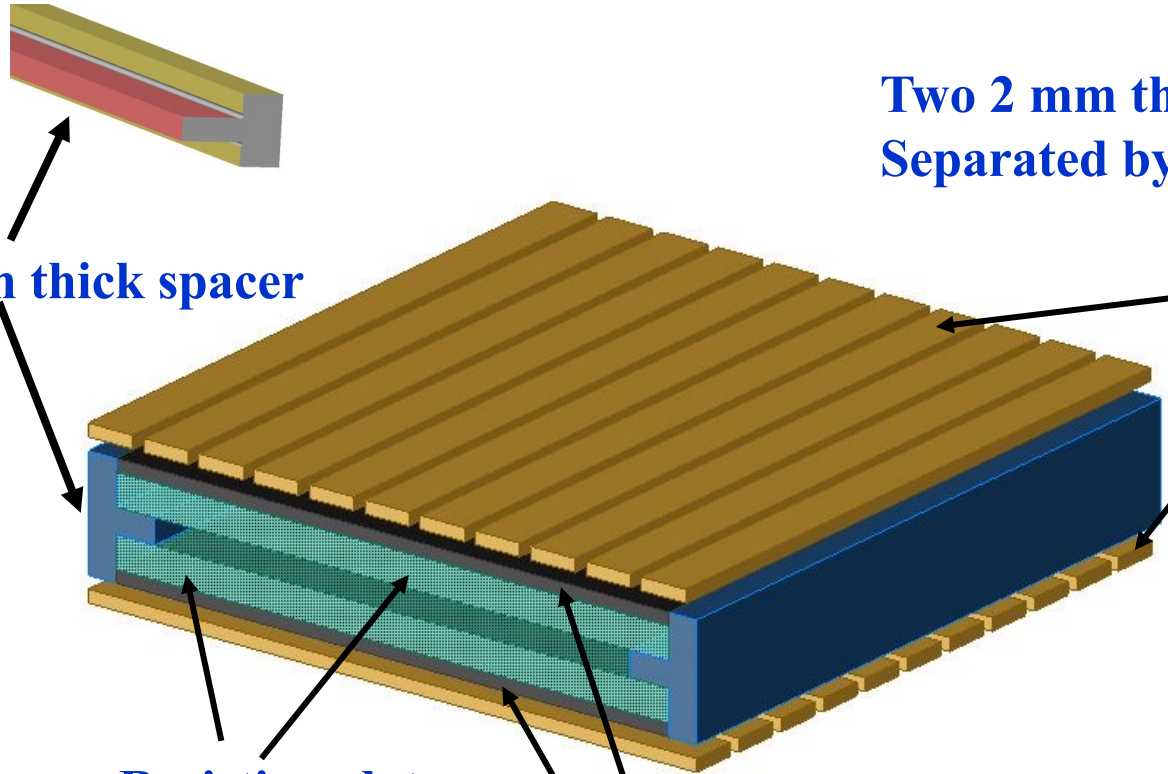
Mass: 50 kTon

Size : 48 m (x) ×16m (y) ×12 m (z)

140 layers of 6 cm thick iron

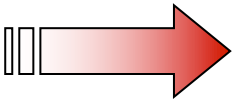
with 2.5 cm gap for active elements

Resistive Plate Chamber for INO



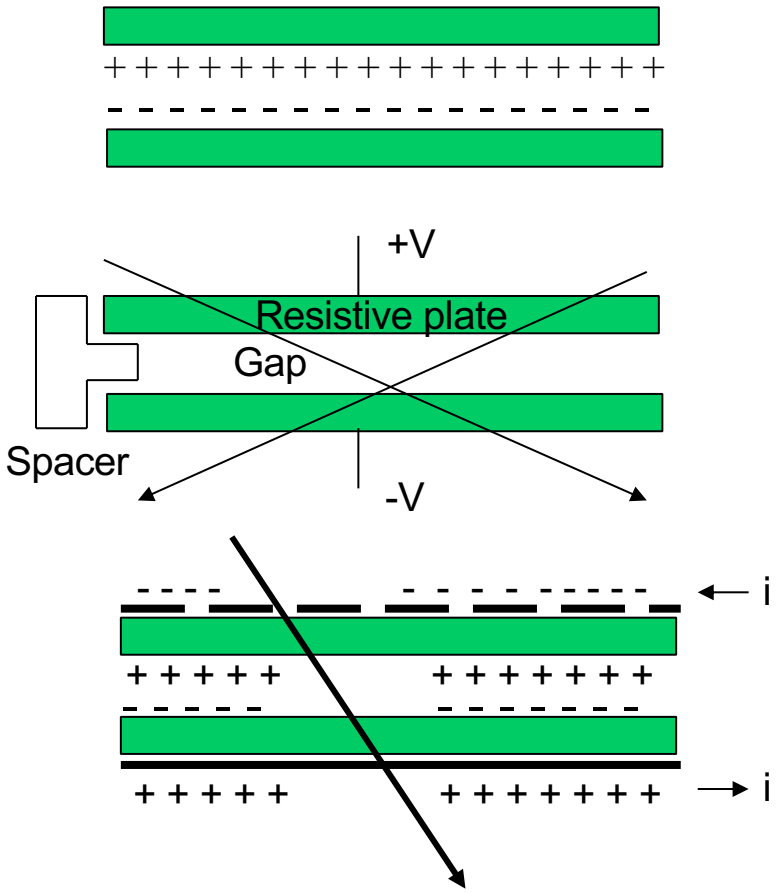
ICAL Detector Specifications

No of modules	*3*
Module dimension	*16 m X 16 m X 12 m*
Detector dimension	*48 m X 16 m X 12 m*
No of layers	*140*
Iron plate thickness	*6 cm*
Gap for RPC trays	*2.5 cm*
Magnetic field	*1.5 Tesla*
RPC unit dimension	*2 m X 2 m*
Readout strip width	*2 cm*
No. of RPCs/Road/Layer	*8*
No. of Roads/Layer/Module	*8*
No. of RPC units/Layer	*192*
Total no of RPC units	***27000***
No of Electronic channels	*$3.6 X 10^6$*

The active detector in INO  RPC

- Built from simple and common materials.
- Low fabrication cost per unit area.
- Easy to construct and operate.
- Simple signal pick up and readout system.
- Large detector area coverage.
- High efficiency (>90%) and time resolution (~2ns).
- Particle tracking capability and good position resolution.
- Two dimensional (x and y) readout from the same chamber.
- Long term stability.

Basic principle of RPC



Surface of resistive electrodes are charged from power supply. Charge-up process is slow due to high resistivity of the material.

A passing charged particle induces an avalanche, which develops into a spark. The discharge stops when local charge is used up. This region is dead until recharged through the bulk resistivity of the plates (10^{11} Ω cm.)

When readout strips are placed, induced charge is either drawn in or drawn out from the readout board, generating voltage signals of opposite polarities.

Bakelite based Resistive plate chambers have been developed and tested satisfactorily in the streamer mode

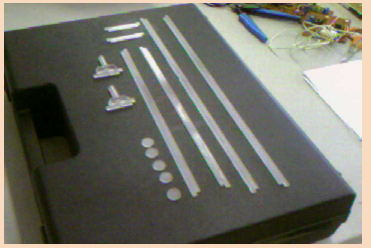
Bakelite : Produced in India

Trade Name	BS-2572 Grade	Density (g/cc)	Electrical strength (kV/mm)	Surface finish	Measured bulk resistivity (Ω cm)
P-1001	P1	1.38	3.5	Matt	6.13×10^{10}
Superhylam	P2	1.72	9.5	Glossy	1.25×10^{11}
P-120	P3	1.22	9.5	Matt	3.67×10^{12}

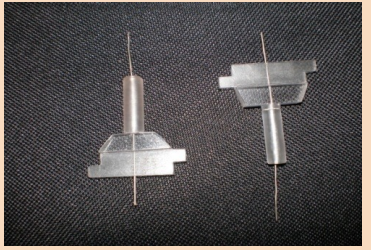
- Bulk resistivity of these bakelites are comparable to that of glass.
- Some samples can be used for high voltage operation under humid condition.
- **Cost is LOW.**
- **Leakage current of P-1001 was very high : ~10 μA at 6 kV (not acceptable for RPC)**

Fabrication Procedure

- Bulk resistivity measurement
- Cut in proper dimension
- Making of polycarbonate
  - Edge spacers
  - Button spacers
  - Gas nozzles
- Gluing
- Partially conducting graphite coating on the outer sides
- Surface resistivity measurement
- Electrical leads connection
- Leak test using Argon and Helium sniffer probes

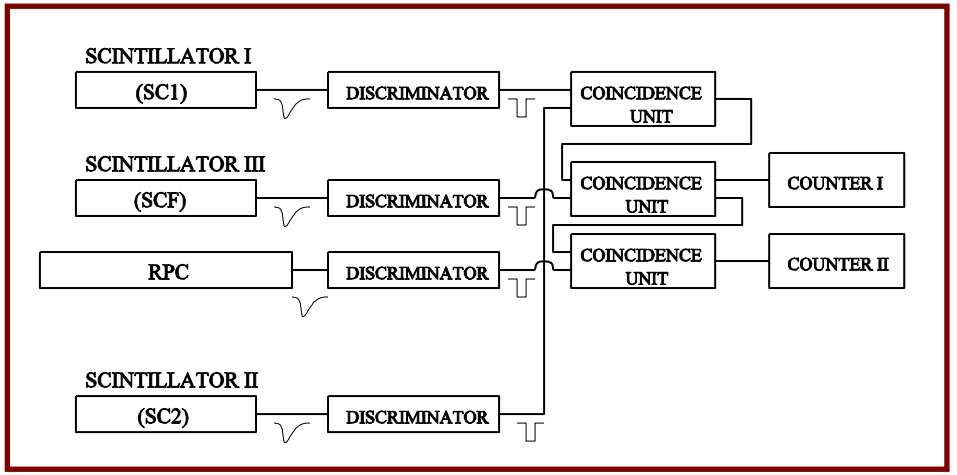


Edge spacers and button spacers



Polycarbonate gas nozzles

Schematic representation of cosmic ray setup



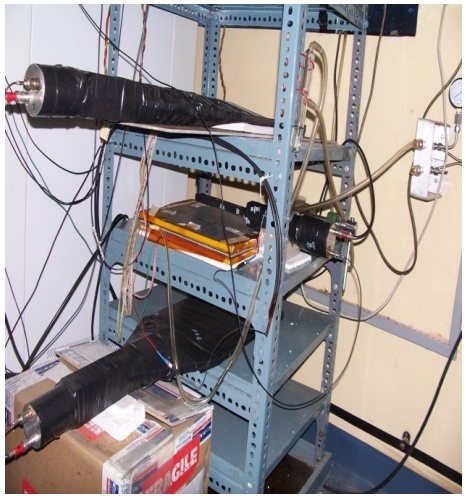
Complete RPC

All RPCs are tested in streamer mode.
Discriminator threshold for the RPC signal is set at -40 mV.

Master trigger signal = SC1 .AND. SC2 .AND. SCF

$$\text{Efficiency} = \frac{\text{(RPC signal in coincidence with master trigger)}}{\text{(Master trigger count)}}$$

Cosmic ray test bench



Arrangement of the scintillators and the RPC

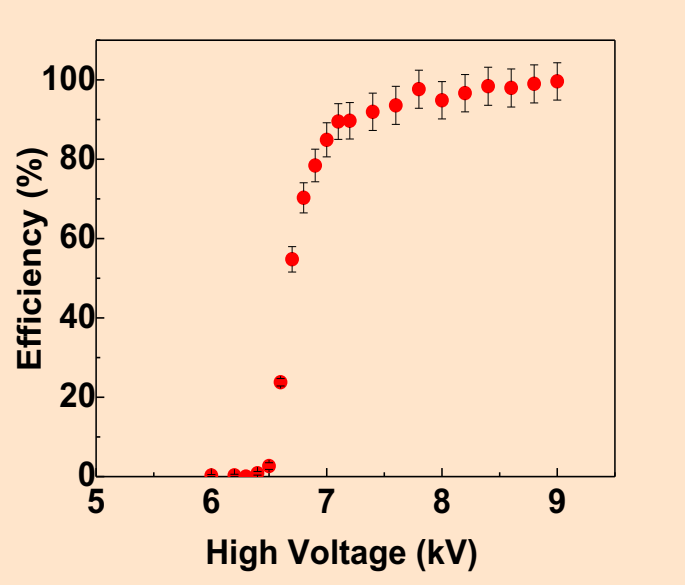
Power supply, front-end electronics and DAQ

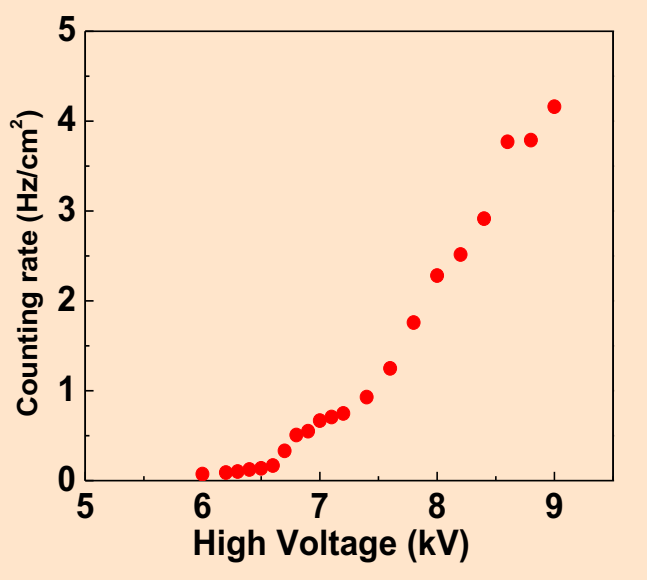
- Used gas: Argon, Isobutane, R-134a (34:7:59).
- Flow rate: 0.4 ml/min (3 detector volume/day)

4 gas mixing unit

S. Bose et al., Nucl. Instr. and Meth. A 602 (2009) 839.

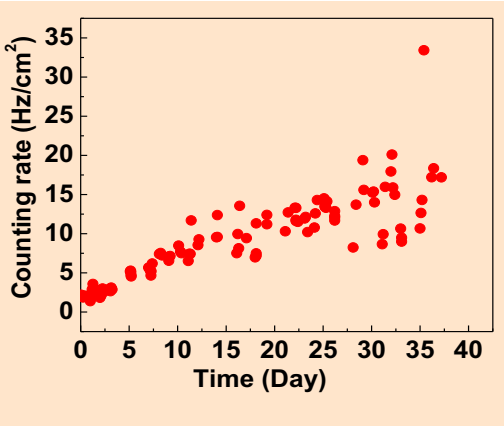
Characteristics of Superhylam grade bakelite RPC

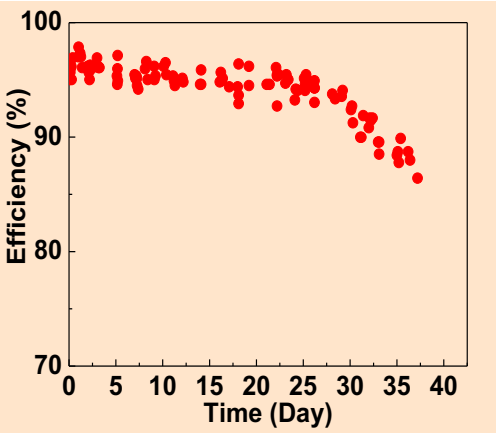


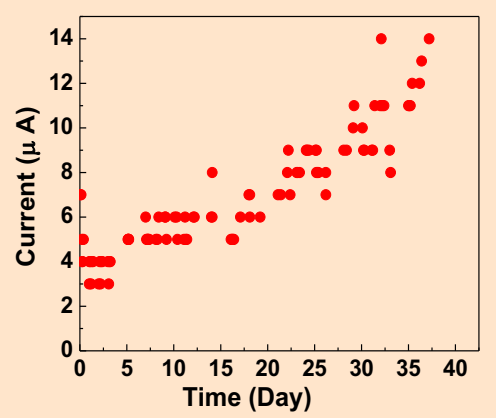


- The RPC is tested in streamer mode using premixed gas.
- The Trigger rate is around 0.005 Hz/cm^2.
- Plateau region has been found from voltage 7.5 kV onwards at efficiency >95%.
- At 9 kV leakage current of the RPC ~ 5 μA.

Problems in long term operation

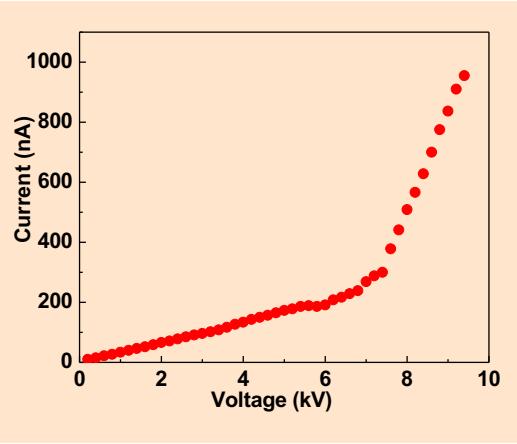


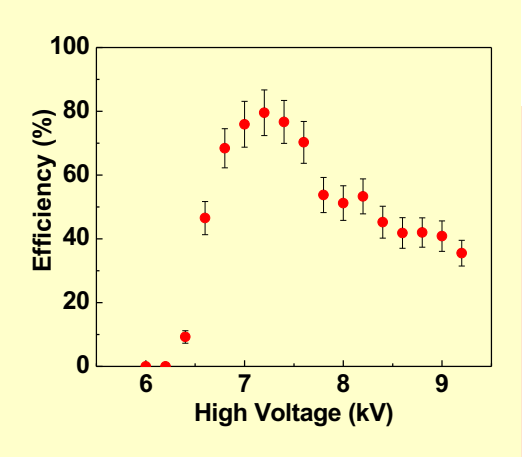


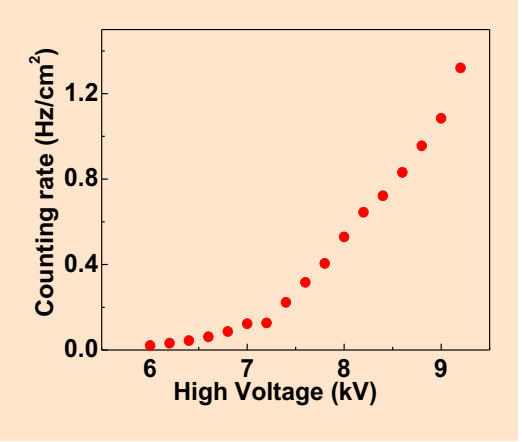


- RPC is tested at 8 kV.
- Long term stability test for 38 days.
- Counting rate increases with time.
- RPC operated continuously for 25 days without change in efficiency.
- Efficiency decreases from a value ~ 95% to 85% within next 13 days.
- Current increases with time.
- Retested after 2 months. Efficiency saturates at ~ 82%.

Characteristics of P-120 grade bakelite RPC



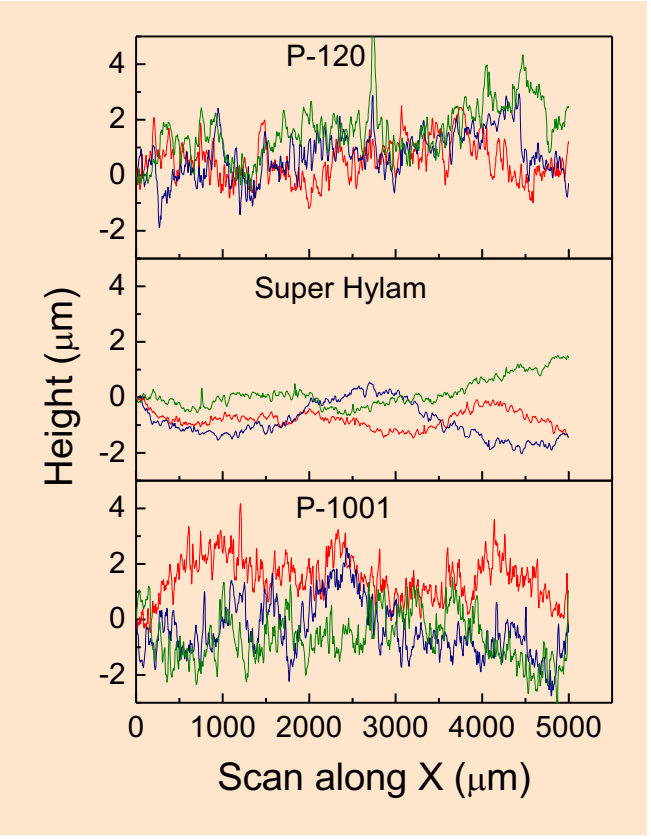




- Leakage current ~ 950 nA at 9 kV.
- Efficiency starts to decrease from a HV ~ 7.5 kV.
- Conditioned for a few days with HV.
- No improvement is observed.

Surface profile study

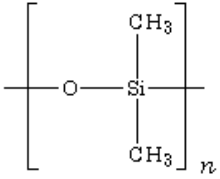
Surface profile scan by DekTak 117 Profilometer



Grade	Long range variation (μm)	Short range variation (μm)
P-120	0.84 ± 0.12	0.64 ± 0.06
Superhylam	0.49 ± 0.17	0.17 ± 0.02
P-1001	0.88 ± 0.09	0.63 ± 0.13

Inner-side of P-120 grade RPC is coated with **silicone** to make the surface smooth.

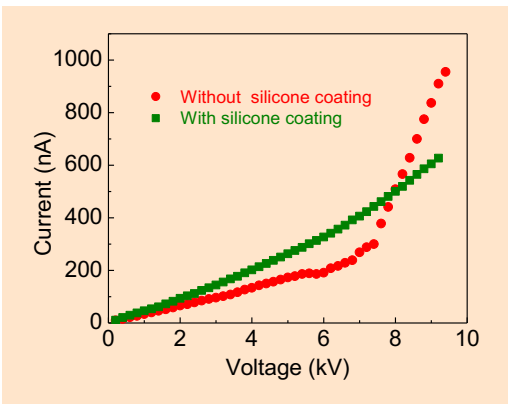
Chemical structure of polydimethylsiloxane (PDMS) or silicone:



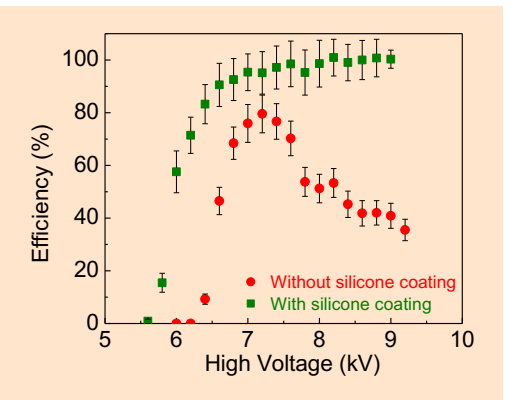
Utilities of Silicone

- Very low chemical reactivity with the gas used
- Good thermal stability over a wide temperature range (from -100 to 250°C)
- Electrically insulator
- Low vapour pressure
- High viscosity ~ 5500 cP at 23°C
- Density 1.02 g/cc at 23°C

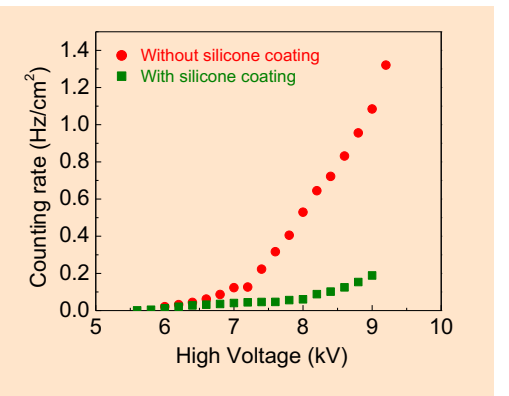
After silicone coating



Current reduces

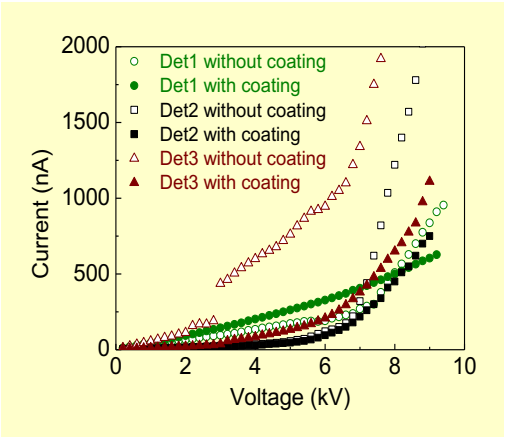


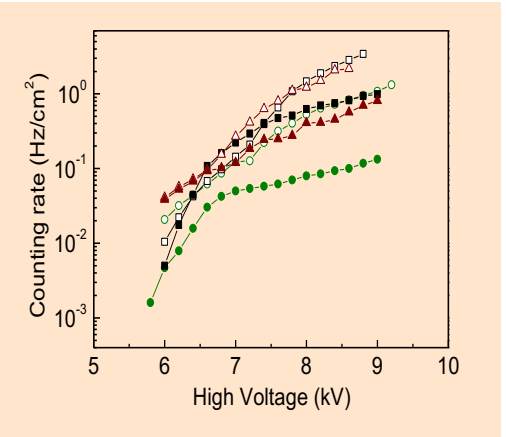
Efficiency plateau obtained

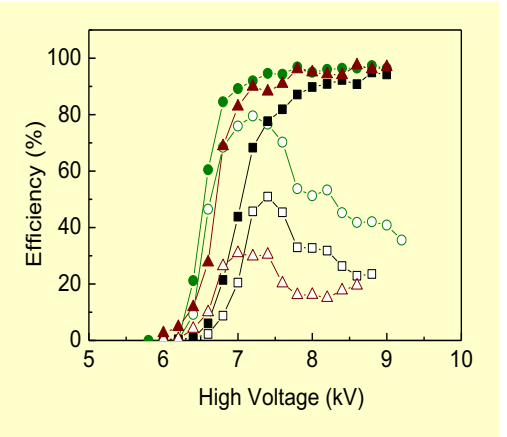


Counting rate decreases

Repetition of results







A few small prototypes have been tested.

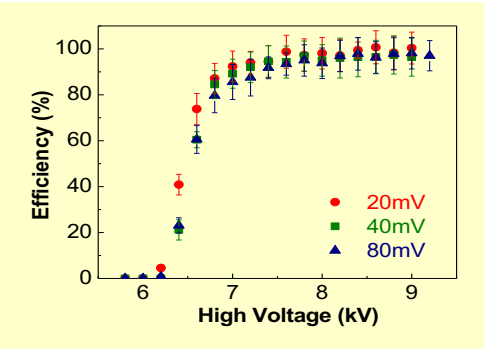
Without silicone coating

- **Current increases rapidly.**
- **After a certain voltage efficiency decreases in all cases.**

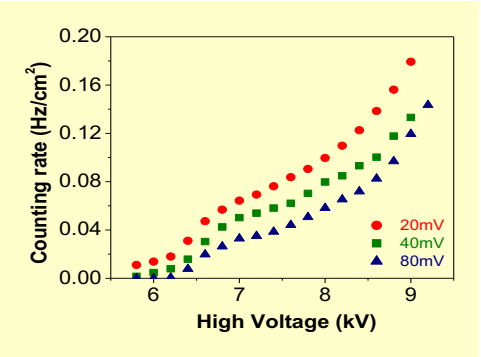
With silicone coating

- **Efficiency plateau >90% obtained.**
- **Counting rate decreased.**
- **Current decreased.**

Effect of RPC threshold

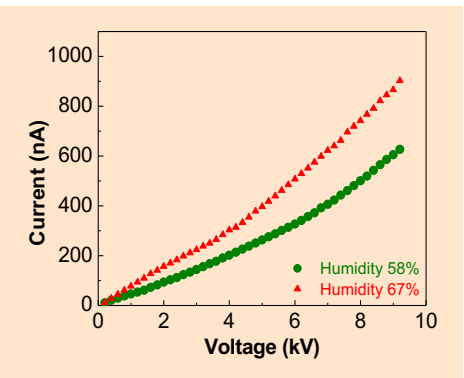


Efficiency curve does not depend on RPC threshold

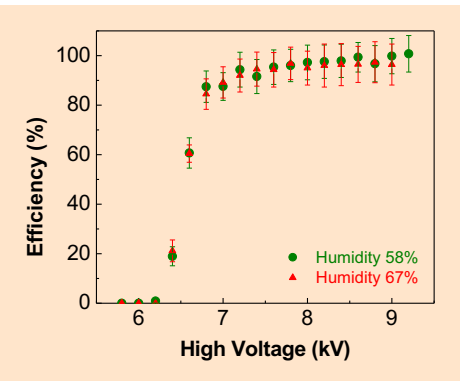


Counting rate is larger for lower RPC threshold

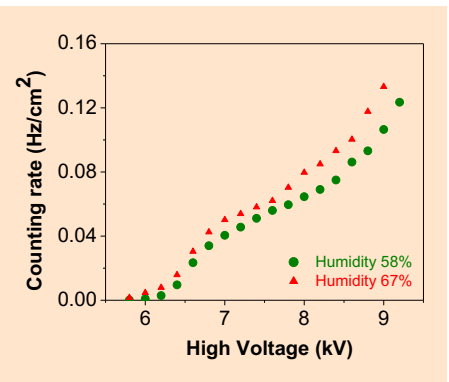
Effect of humidity



Leakage current is larger in higher humidity

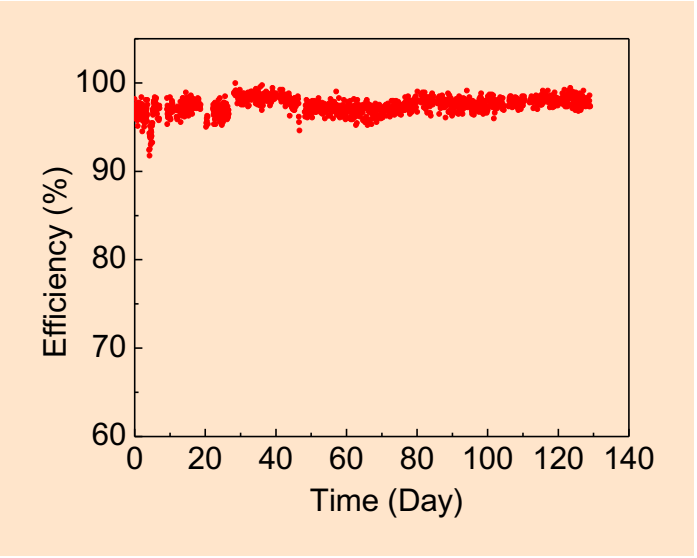


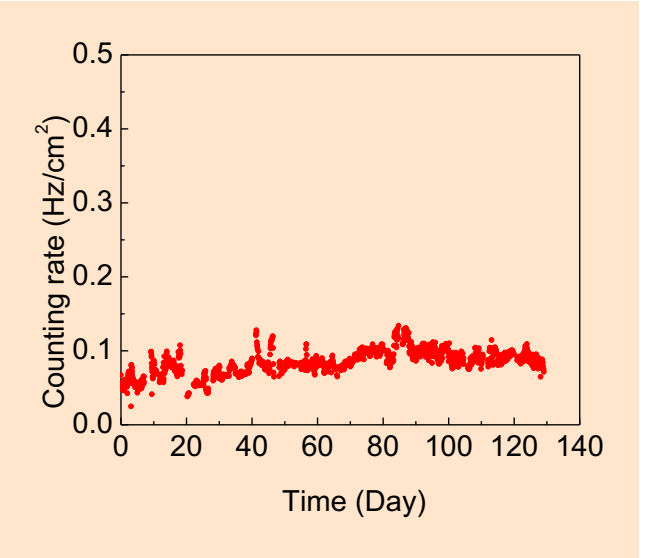
No effect of humidity on efficiency curve



Counting rate is larger in higher humidity

Results of long-term test

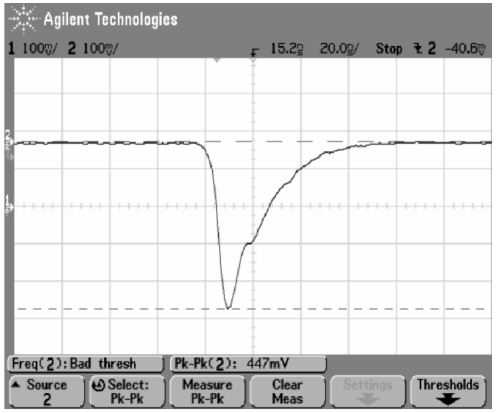




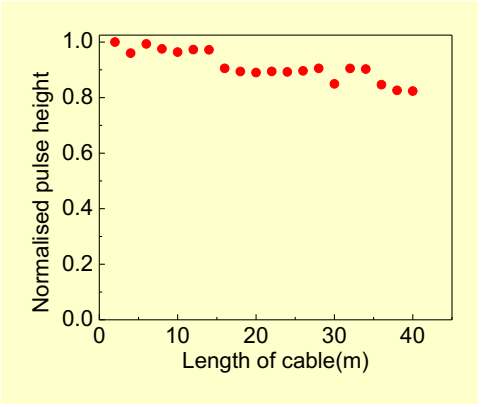
- RPC is tested at 8 kV.
- Efficiency remains constant > 90% for more than 130 days operation.
- Counting rate is constant and ~ 0.1Hz/cm^2.
- Current < 600 nA.

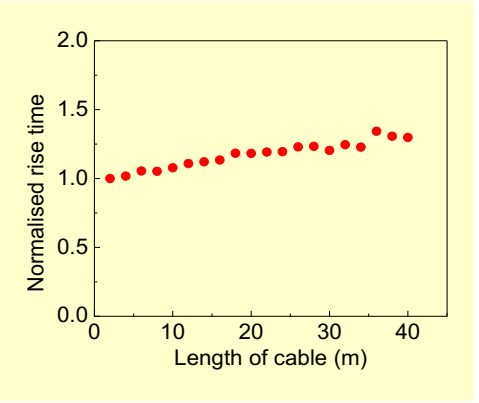
S.Biswas, et al., Nucl. Instr. and Meth. A 602 (2009) 749

Test of signal attenuation



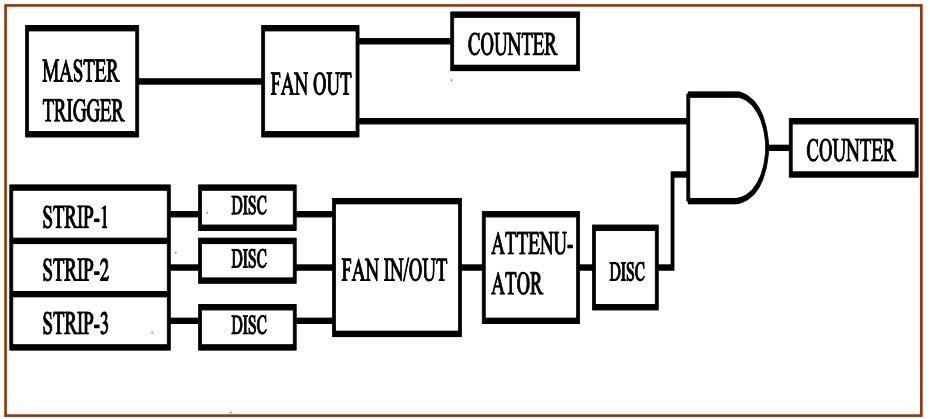
Streamer pulse



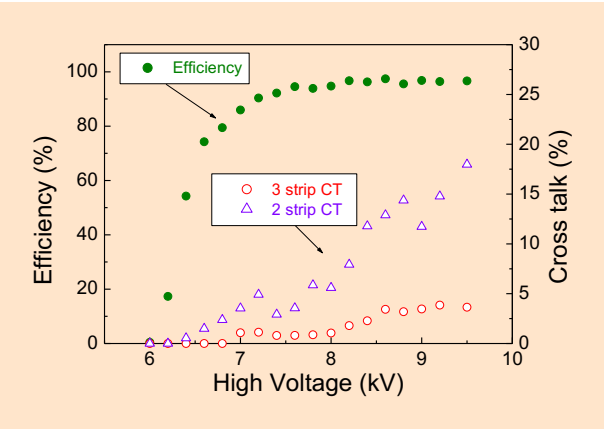


- Typical RPC streamer pulse height: ~ 300 – 500 mV
- Long cable drive has been tested
- Pulse height reduces to ~ 80% of the maximum

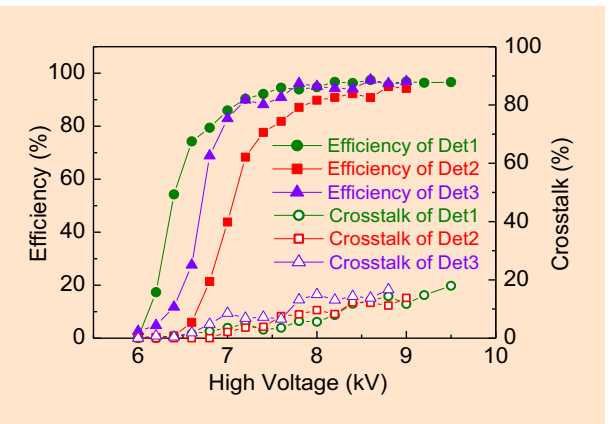
Crosstalk



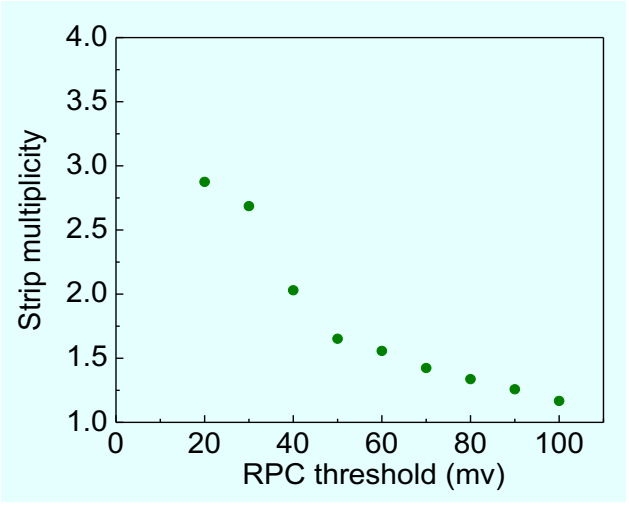
Circuit diagram for crosstalk measurement

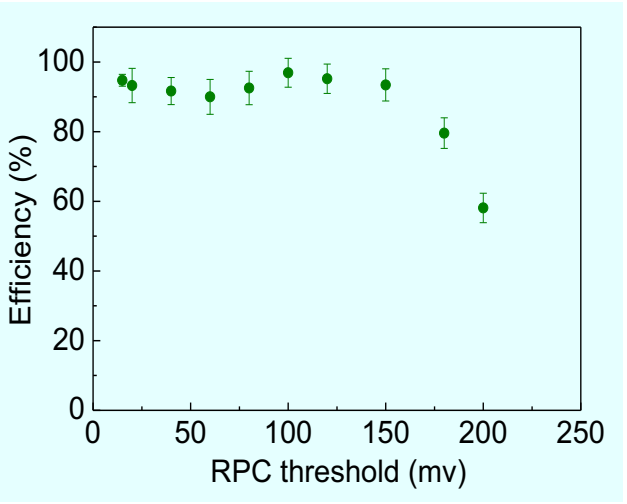


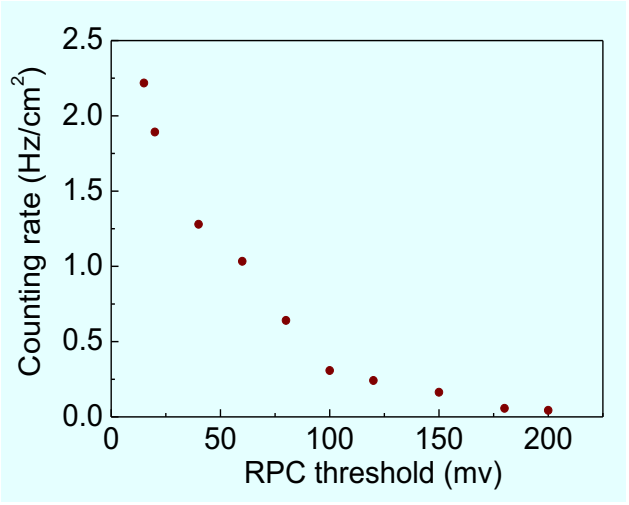
- Foam and G10 based copper pick-up strip has been used
- Crosstalk between two adjacent strip may come from some event
- Crosstalk between two adjacent strips is < 20%
- Crosstalk between three adjacent strips is < 5%



S.Biswas, et al., Nucl. Instr. and Meth. A 604 (2009) 310

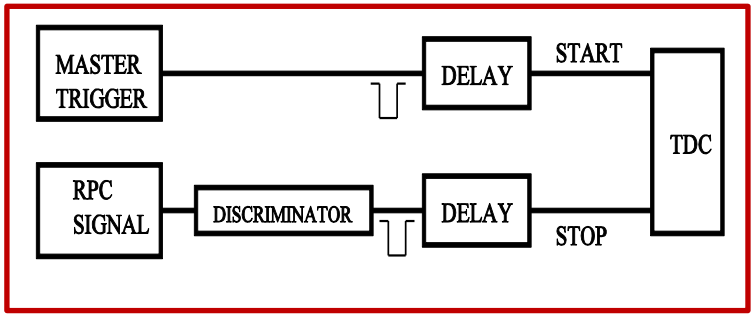




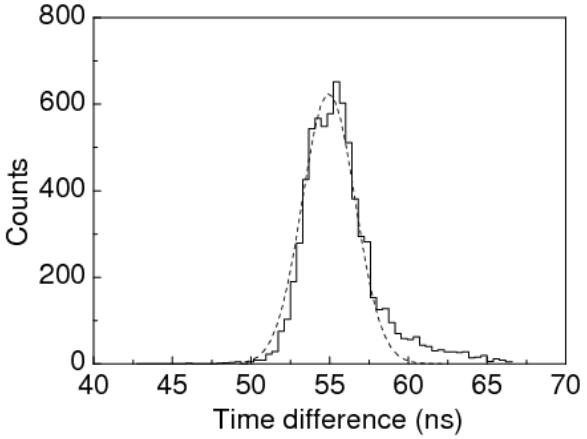


- **Strip multiplicity decreases with the increase of the RPC threshold**
- **Efficiency remains over 90% for wide range of RPC threshold**
- **Counting rate decreases with threshold**

Time resolution of RPC

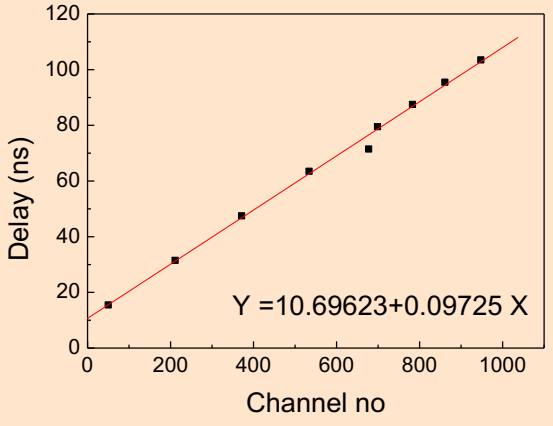


Block diagram for Time Resolution measurement



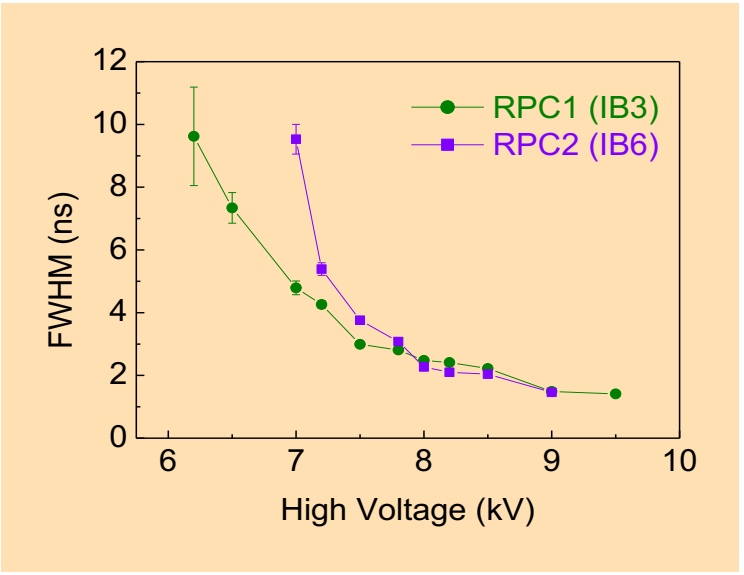
Time spectra of RPC

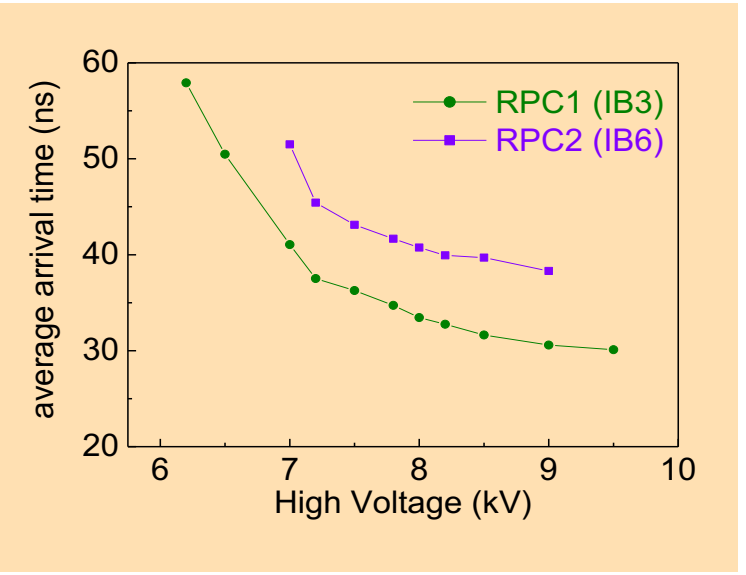
- P/S 7186 TDC is used
- Offset delay ~ 10 ns
- 1 ch of TDC = 0.097 ns
- $FWHM_{SCF}$ = 1.98 ± 0.02 ns
- $FWHM_{SC1}$ = 3.20 ± 0.07 ns
- $FWHM_{SC2}$ = 3.39 ± 0.08 ns



Calibration curve

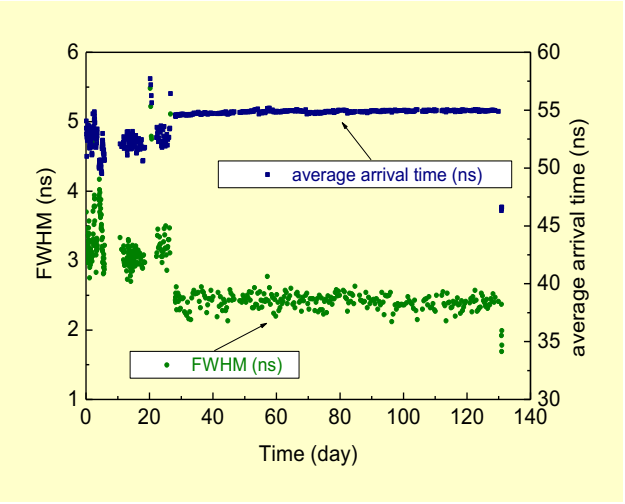
Results of time resolution measurement

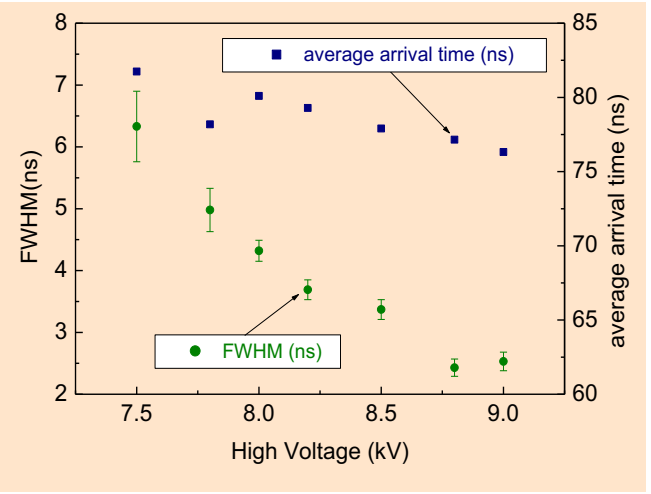




- RPC dimension: 30 cm × 30 cm
- TDC Start: Master trigger (3-fold scintillator)
- TDC Stop: Signal from RPC
- Time resolution of RPC at plateau region ~ 2 ns
- Average arrival time decreases with increasing high voltage

Long term test and RPC-RPC time resolution



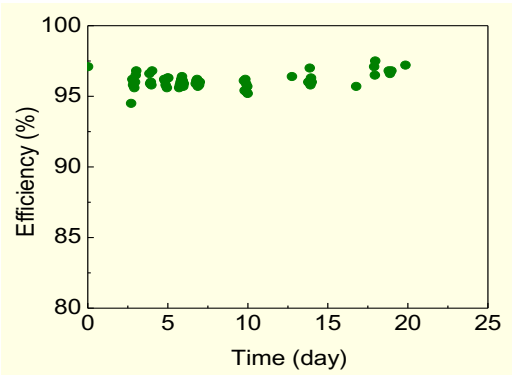


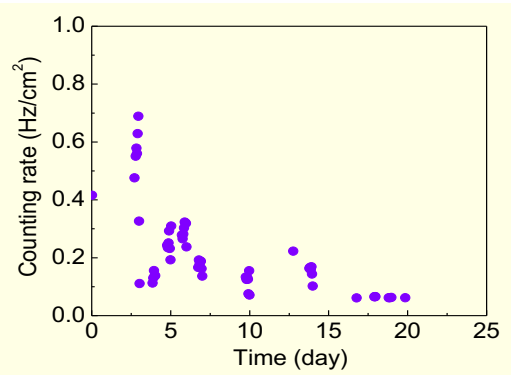
- RPC was tested at 8 kV for more than 130 days
- Time resolution remains constant ~ 2-3 ns
- Average signal arrival time remains constant

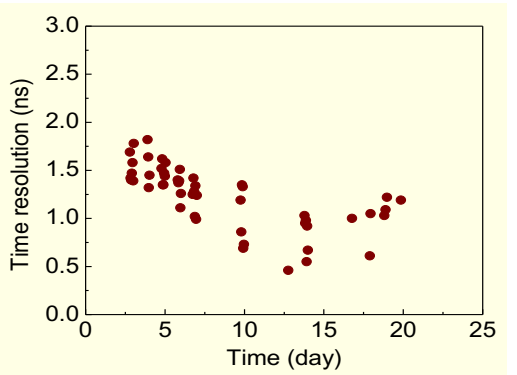
- Average time resolution ~ 3 ns
- TDC start: RPC 1
- TDC stop: RPC 2

S.Biswas, et al., Nucl. Instr. and Meth. A 617 (2010) 138

Long-term operation with higher voltage





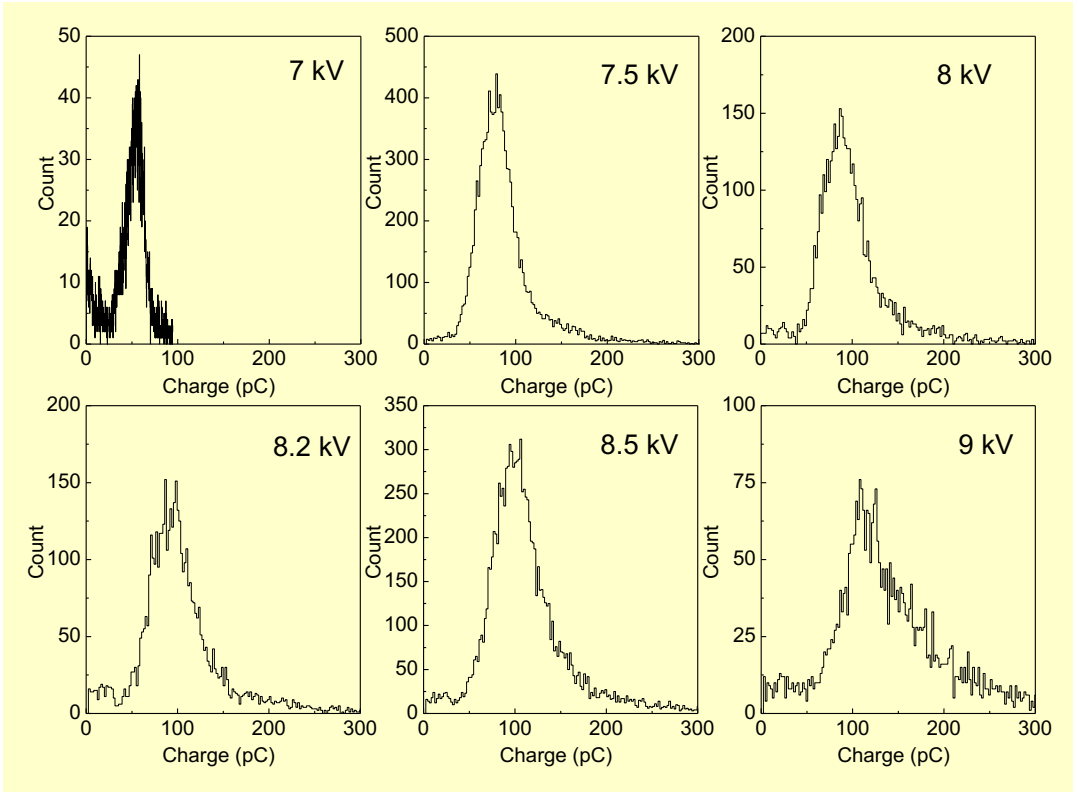


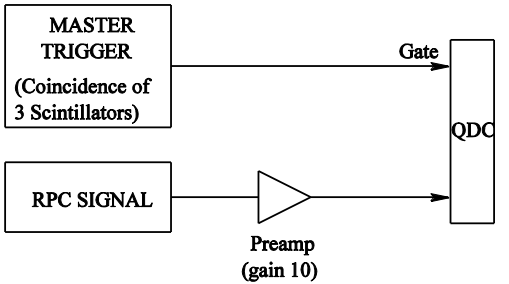
- The RPC is tested at 9.5 kV continuously for 21 days.
- Efficiency was found to be stable over 95%.
- Initially count rate was high. It decreased to ~ 0.1-0.2 Hz/cm^2 within 5 days.
- Leakage current ~ 1.5 μA.
- Time resolution < 2 ns.
- Sustained Operation over four months with and without high flux of radiation in CERN GIF.

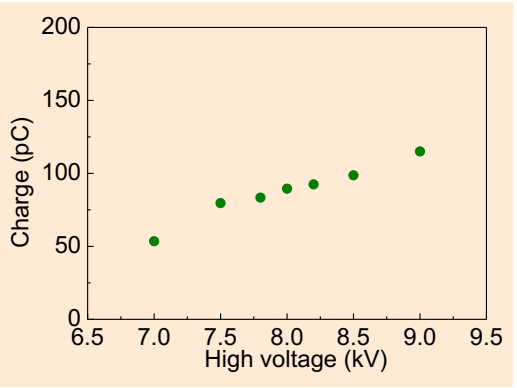
A. Sharma, IEEE Nuclear Science Symposium, Florida, USA,2009.

Charge spectra in streamer mode

Detector dimension: 30cm × 30cm, Pick-up strip width: 2.5 cm





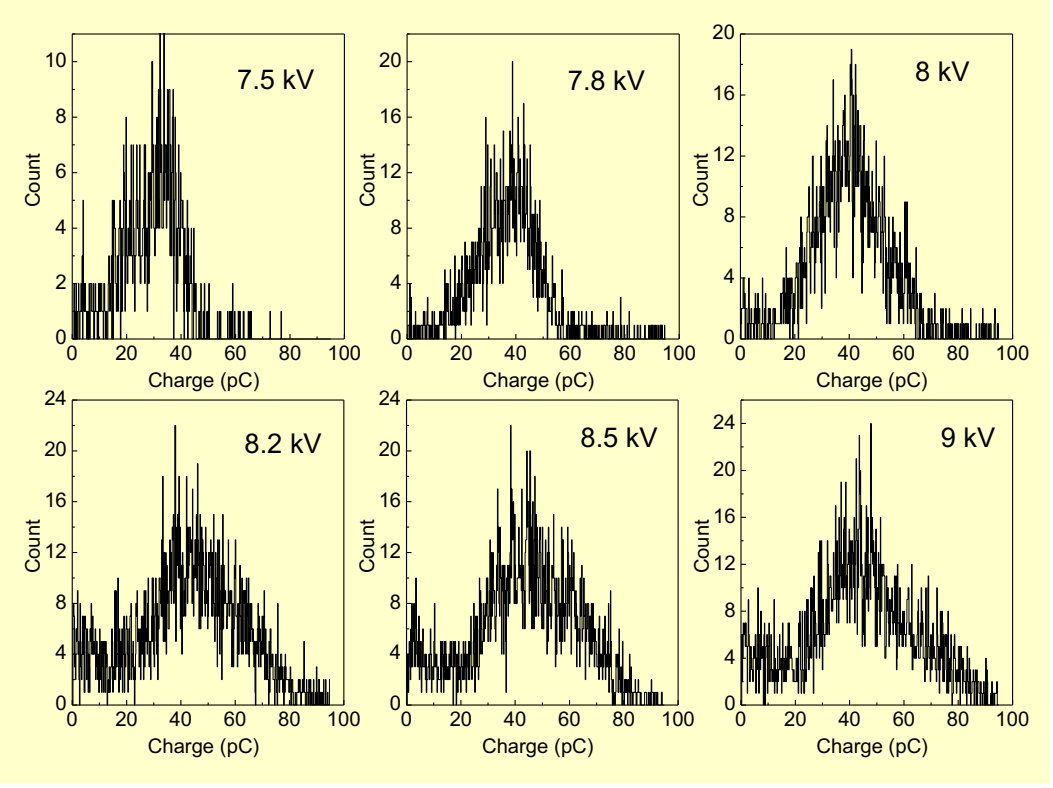


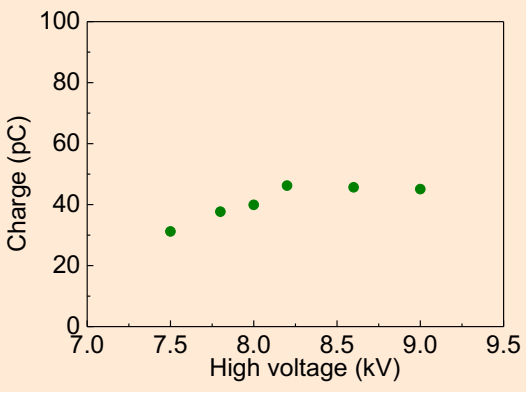
Gas mixture:
Argon/Iso-butane/R-134a : 34/7/59
Charge ~ 100 pC

C. Lu, SNIC Symposium, California, 2006

Charge spectra in streamer mode

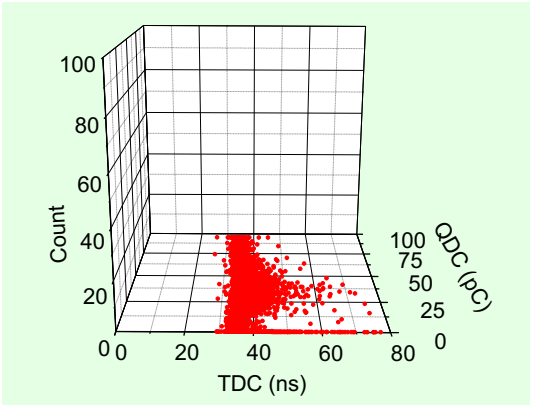
Detector dimension: 10cm × 10cm, Pick-up strip width: 5 mm

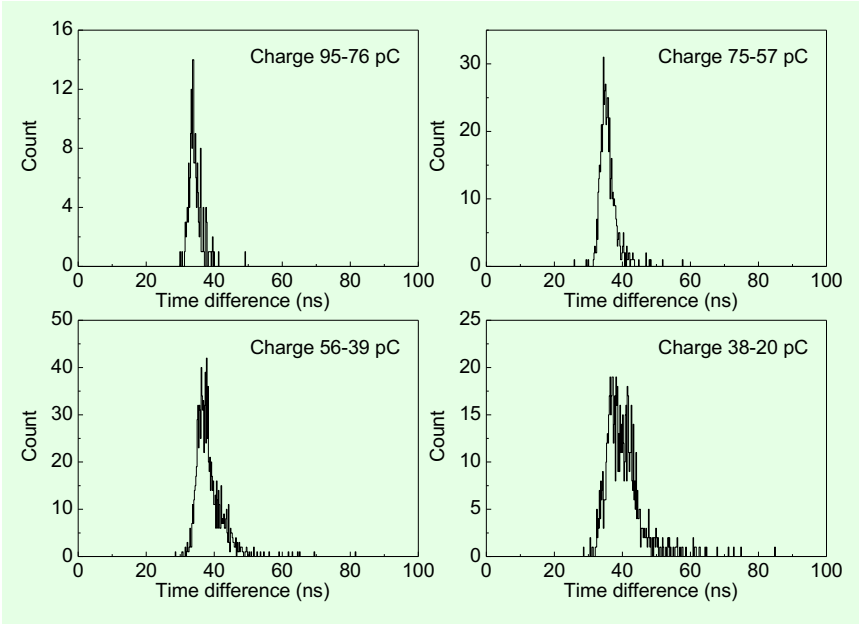


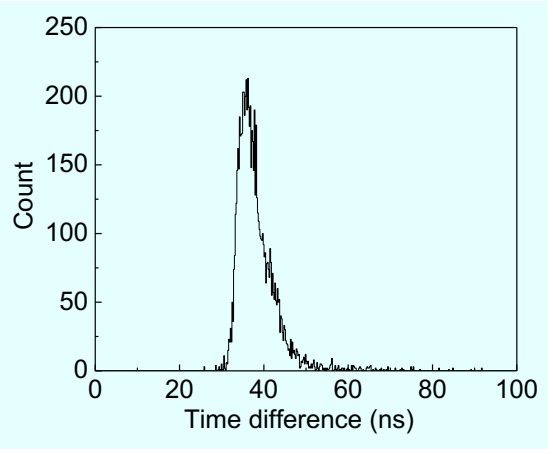


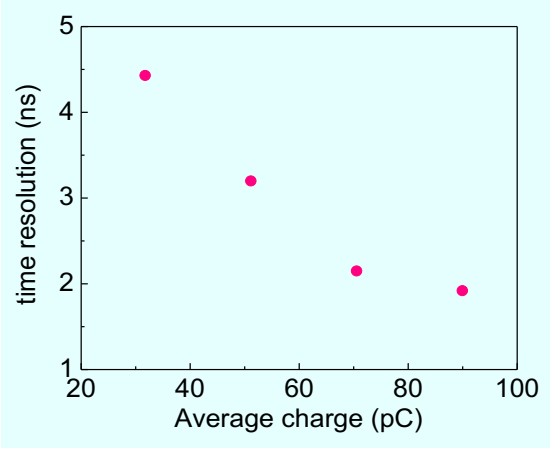
Gas mixture:
Argon/Iso-butane/R-134a : 34/7/59
Charge ~ 45 pC

Charge correlated time spectra in streamer mode

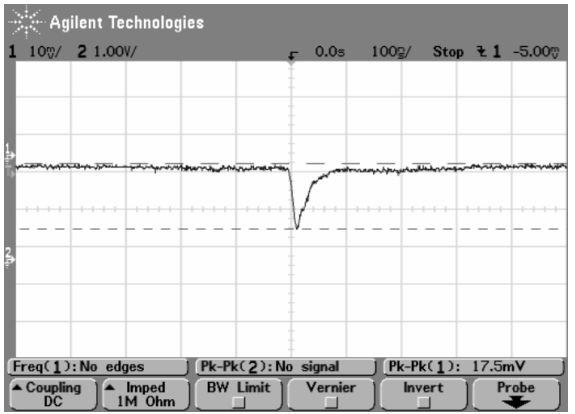


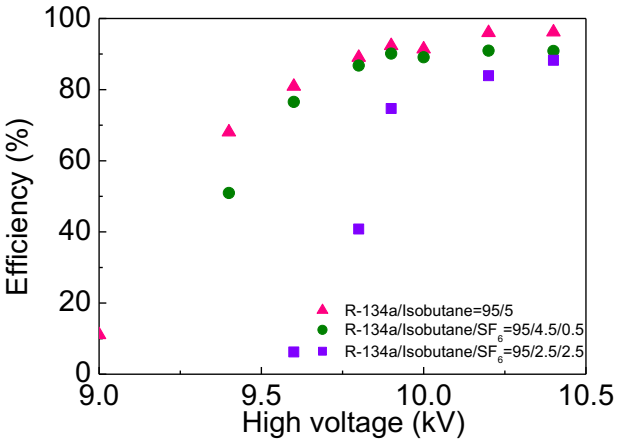


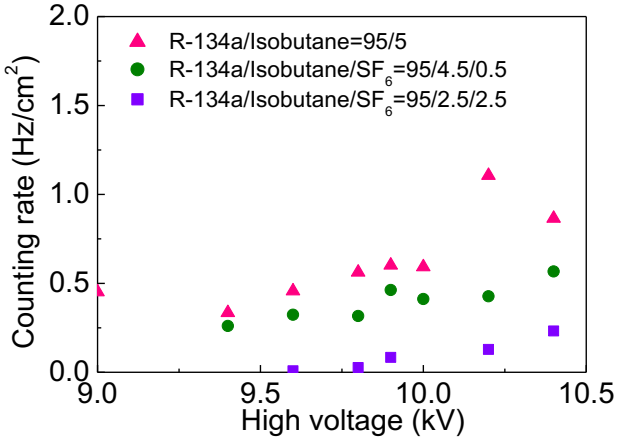


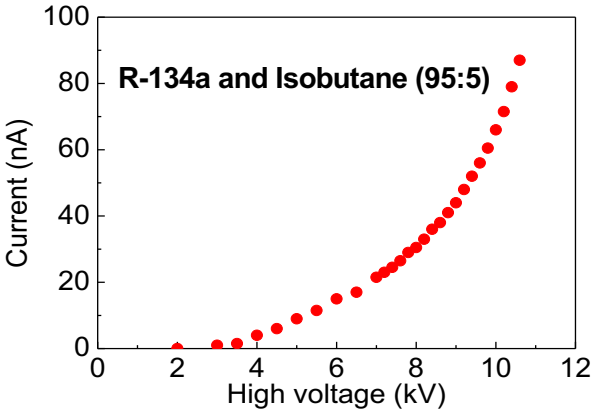


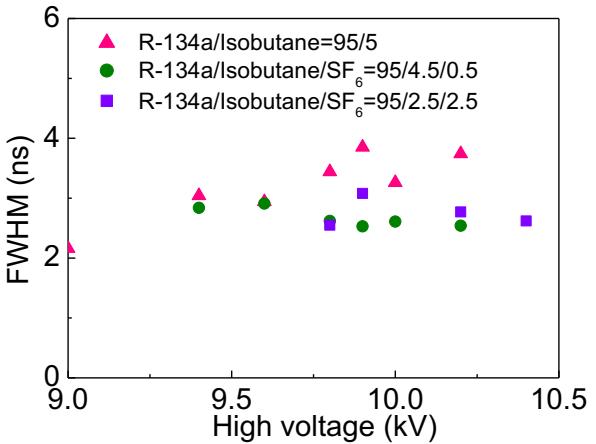
Efficiency and time resolution in avalanche mode

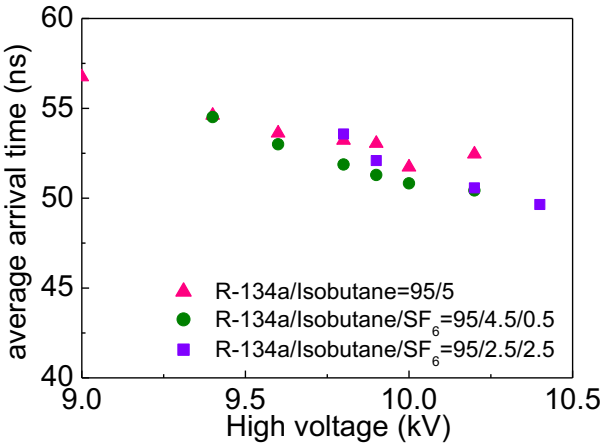








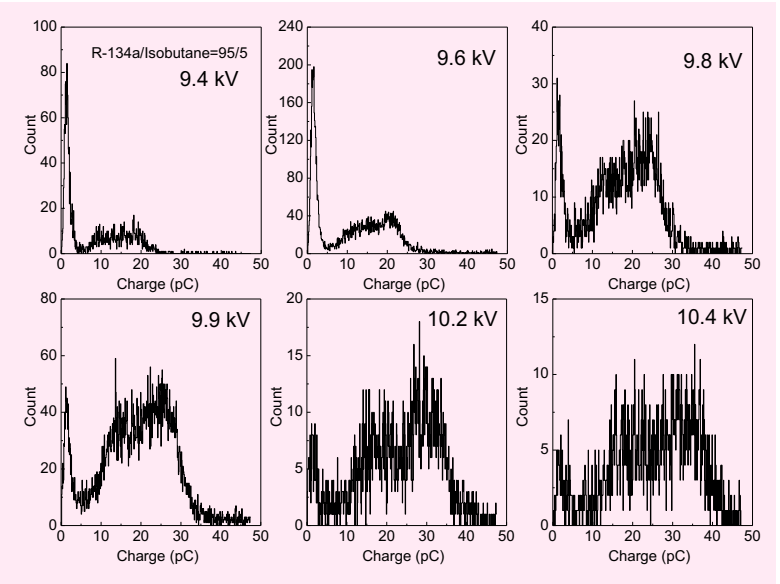


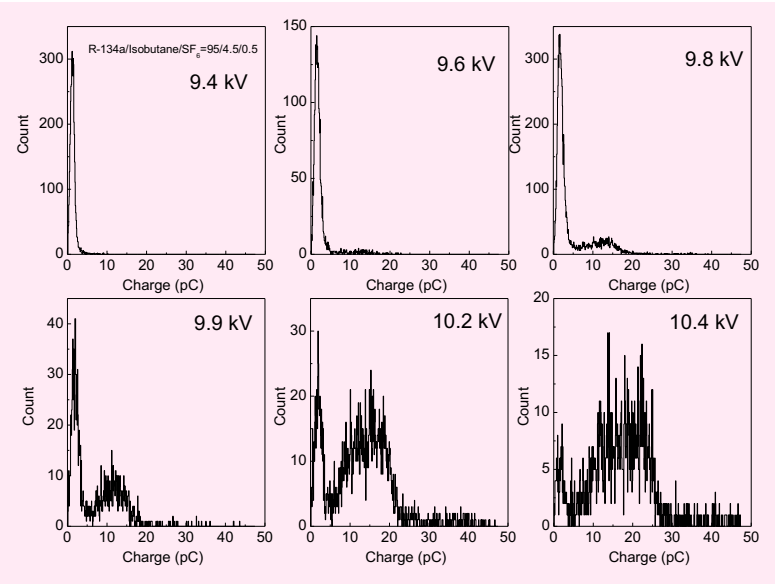


CMS FEE board has been used

Charge spectra in avalanche mode

Detector dimension: 30cm × 30cm, Pick-up strip width: 2.5 cm





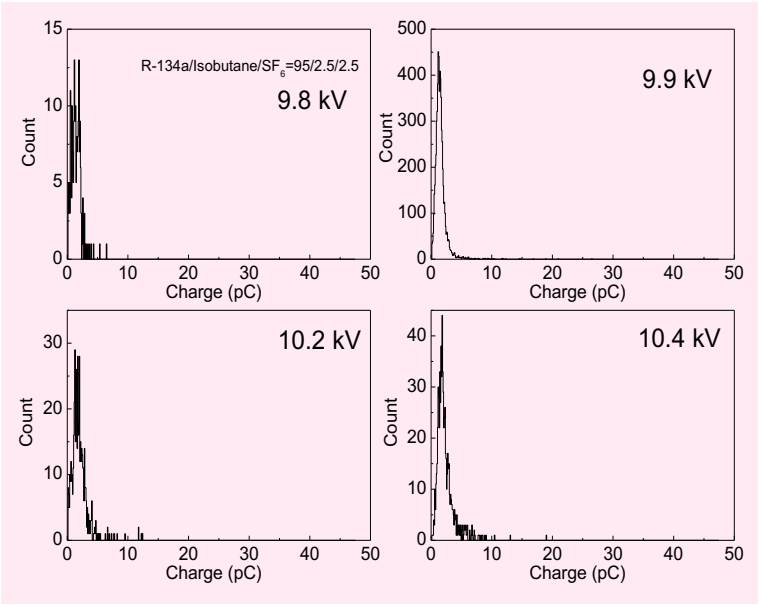
R-134a / Iso-butane = 95/5

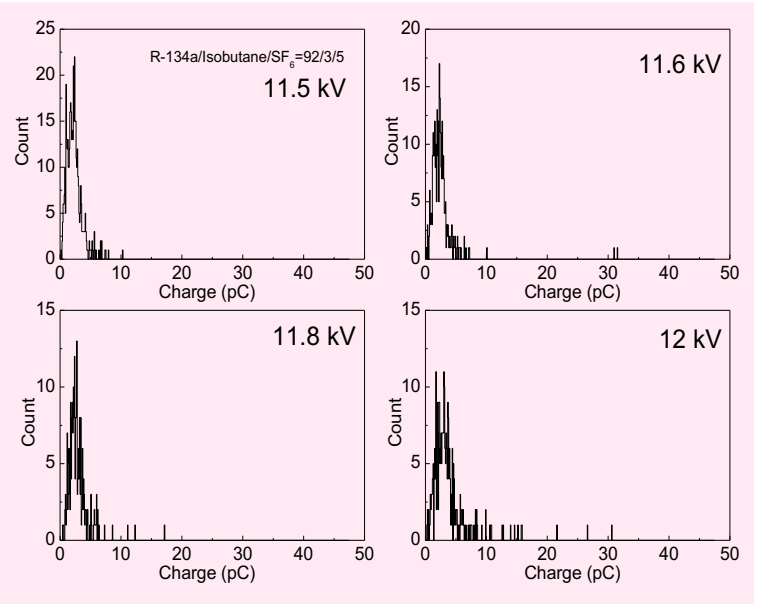
R-134a / Iso-butane/SF_6 = 95/4.5/0.5

Charge ~ 1.5 pC

A few streamer pulse after avalanche pulse

Charge spectra in avalanche mode





R-134a / Iso-butane/SF_6 = 95/2.5/2.5

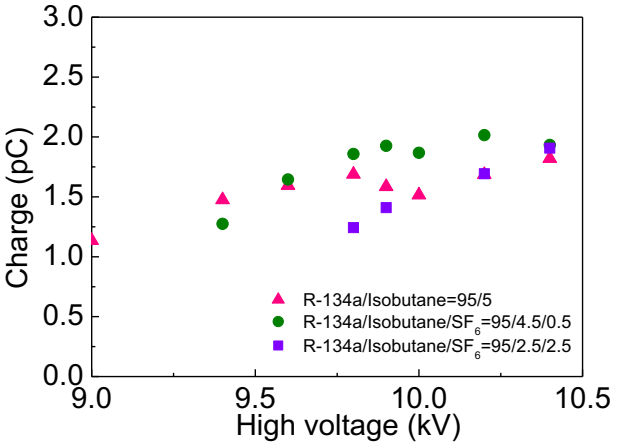
R-134a / Iso-butane/SF_6 = 92/3/5

Charge ~ 1.5 pC

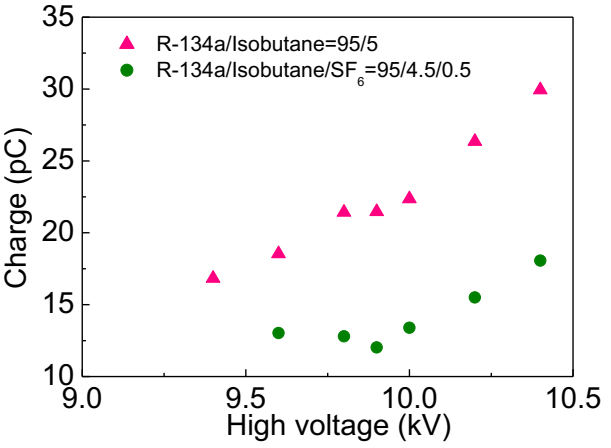
Increase of SF_6 suppress the streamer

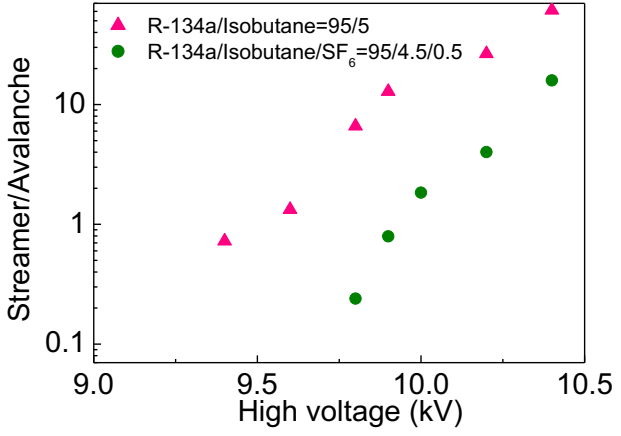
Charge Vs High Voltage in avalanche mode

Avalanche charge Vs HV



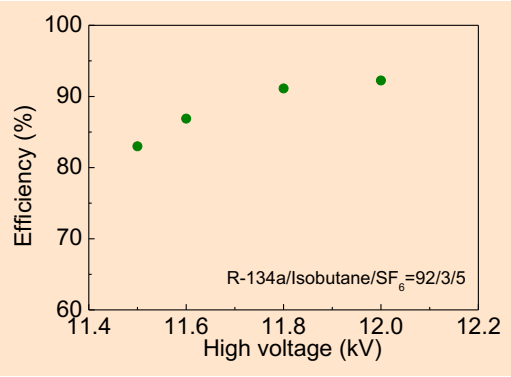
Streamer fraction Vs HV

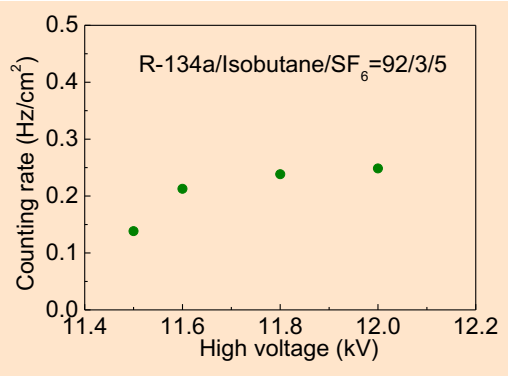




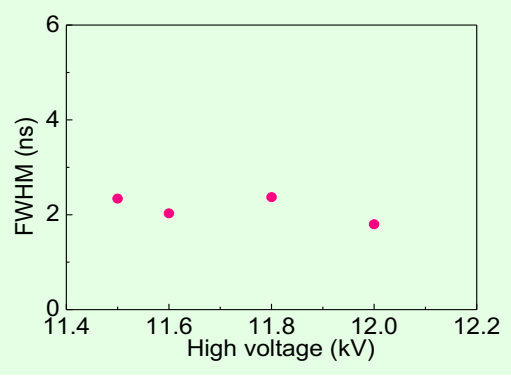
Ratio of area under the streamer and avalanche peak

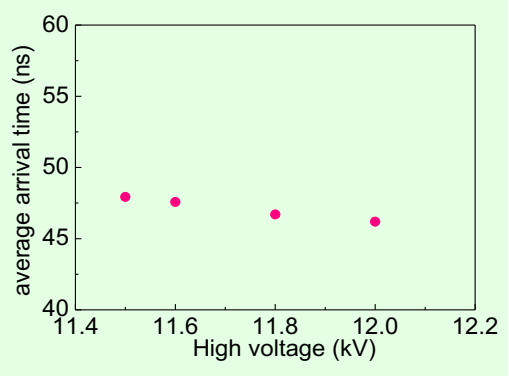
Results with high fraction (5%) of SF_6

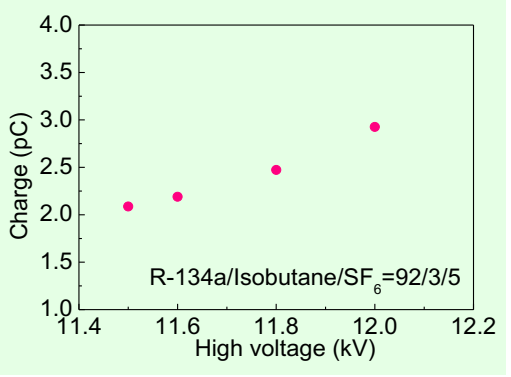




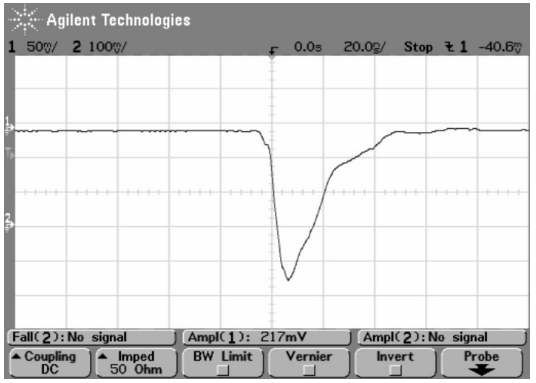
R-134a / Iso-butane/SF_6 : 92/3/5

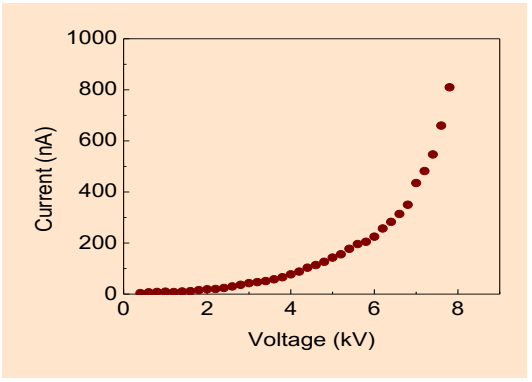


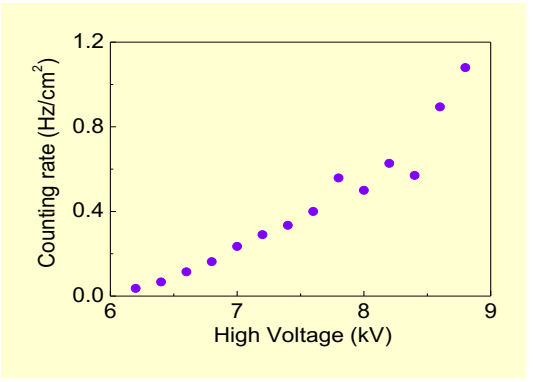


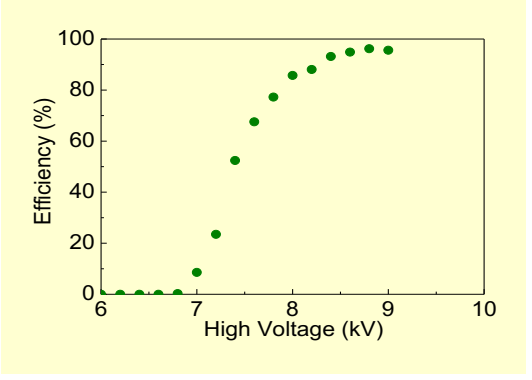


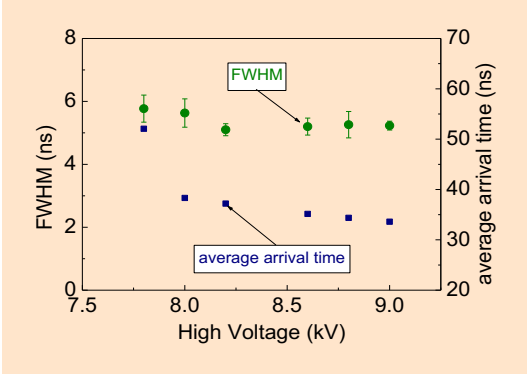
Results of 1m × 1m RPC







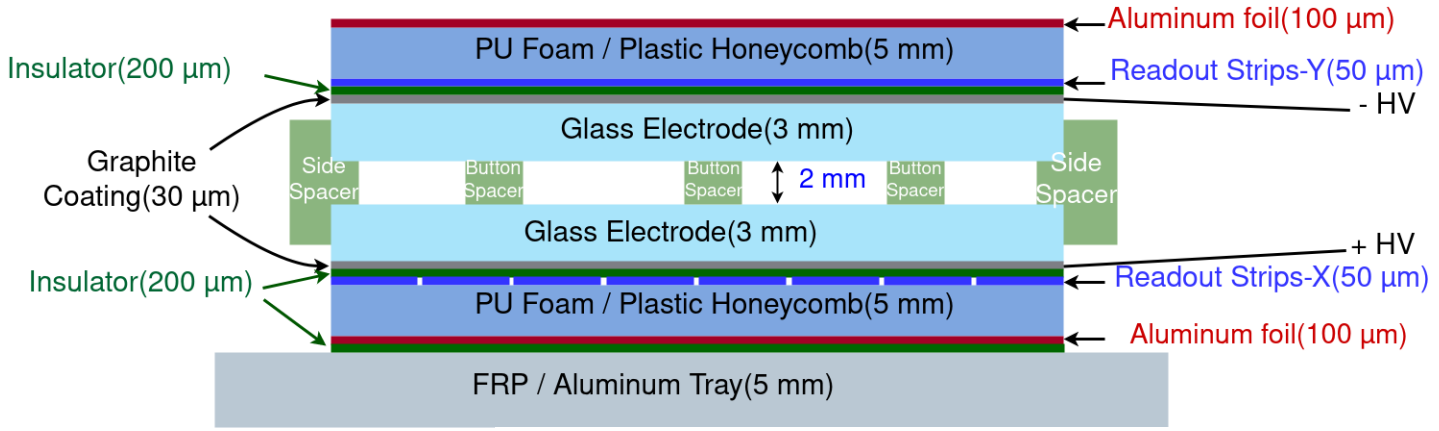




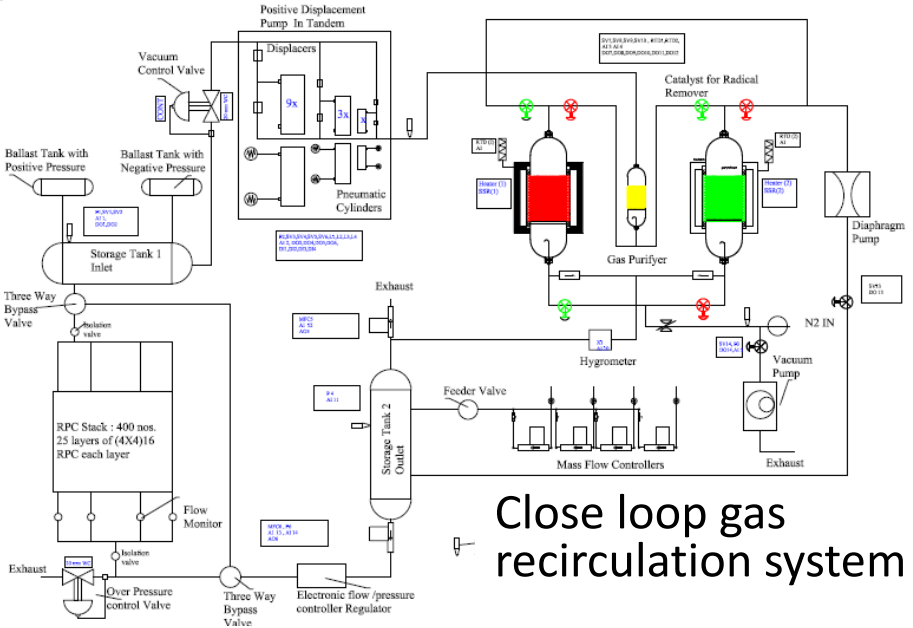
Efficiency > 90%

Time resolution ~ 3 ns

RPC R&D : The main detector component

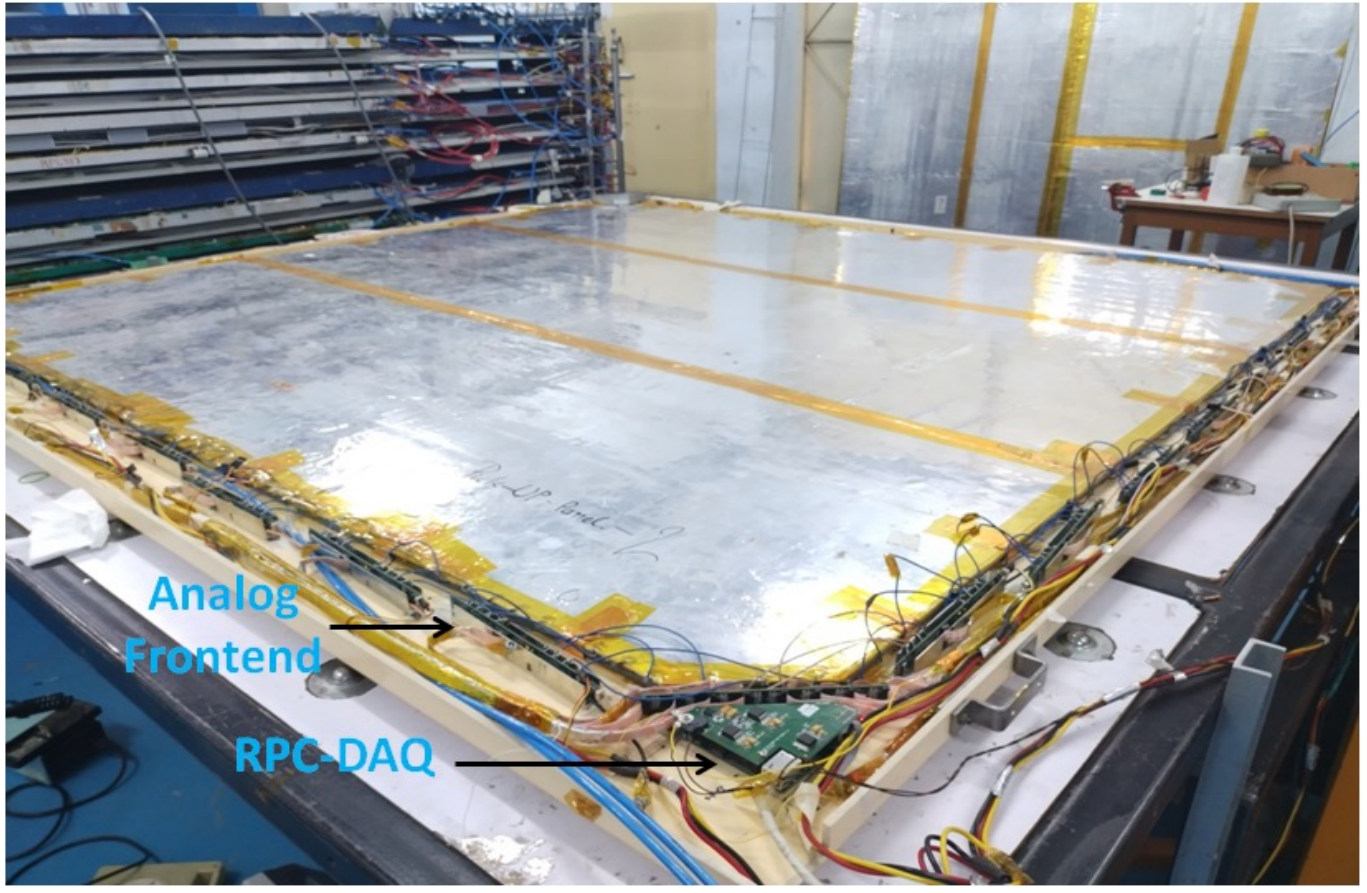


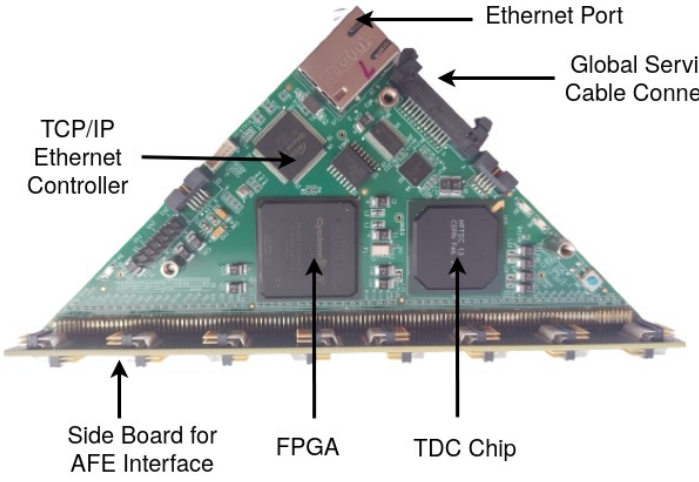
HV supply. Output voltage range is 0 to ±6KV and upto 2µA current. Developed by BARC

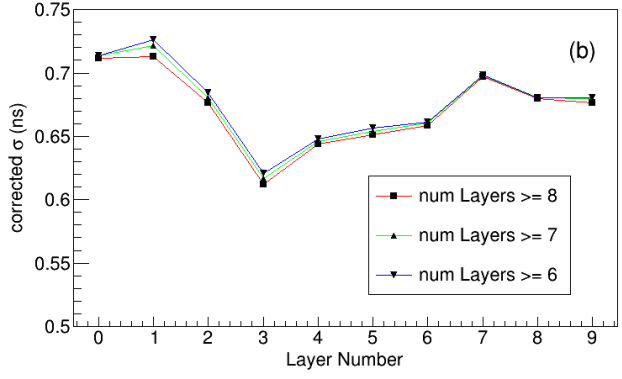


Close loop gas recirculation system

Fully assembled glass-RPC module (2m x 2m) (TIFR)





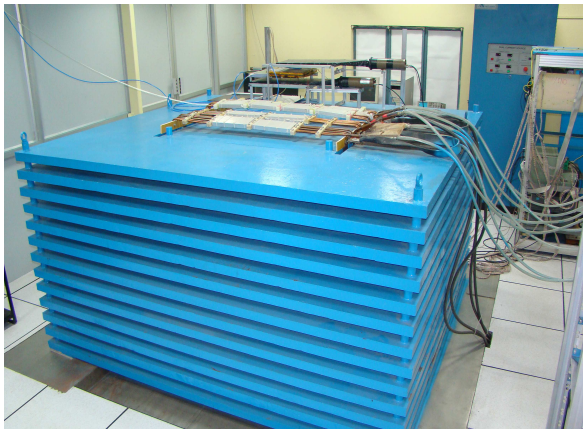


ICAL prototype at VECC, Kolkata

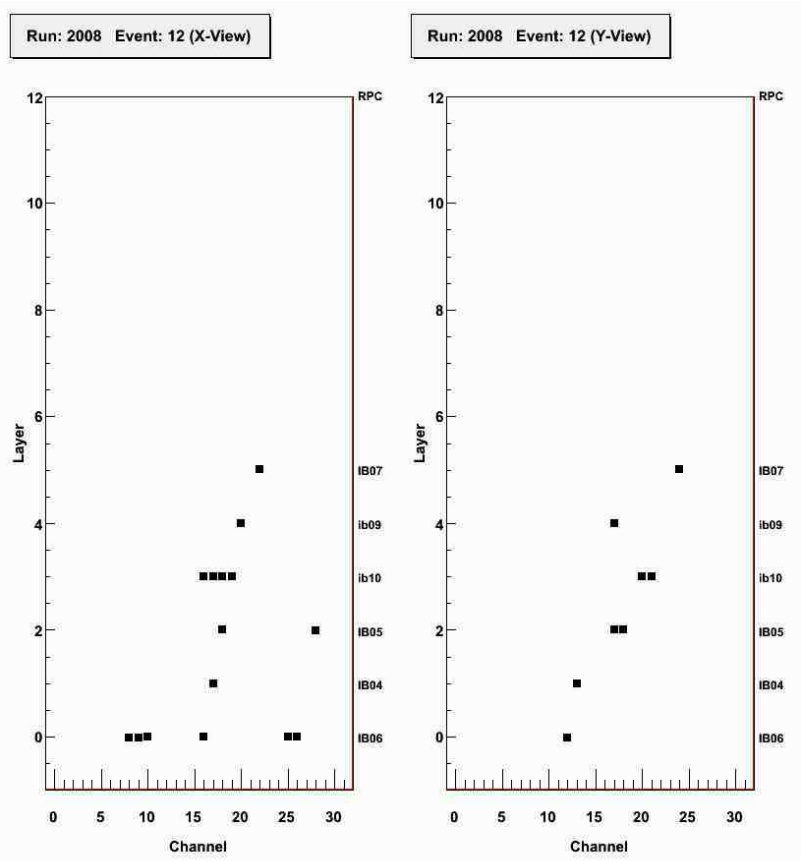
- 13 layers of iron
- Dimension: 2.5m × 2.5m × 1.3m
- 5 cm thick iron plates separated by 5 cm, with Resistive Plate Chambers (RPCs) as active elements
- Total mass ~ 30 Ton
- Magnetic field ~1.25 Tesla
- 12 RPCs (both glass and bakelite) of dimension 1m × 1m (active area) will be used

A. Behere et al., Nucl. Instr. and Meth. A 602 (2009) 784

Cosmic muon track in ICAL prototype at VECC, Kolkata



ICAL prototype



Track for Run No:2008 Event No:12

A. Behere et al., Nucl. Instr. and Meth. A 602 (2009) 784

Present RPC development at Bose Institute

Conventional technique of linseed oil coating

- Usually, linseed oil treatment the inner surfaces of the RPC is done after making the gas gap.
- Gap is filled with low viscous linseed oil and thinner solution and the liquid is drained out slowly.
- Dry air is flown through the gas gap to cure the thin linseed oil layer left on all the inner surfaces of the plates as well as those of the spacers.

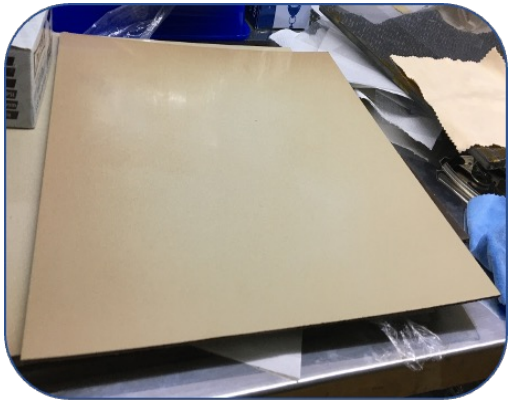
New technique of linseed oil coating

- In the present work the linseed oil coating is done on bakelite plate before making the gas gap.
- We take about 2g of linseed oil is applied over the 27 cm × 27 cm area of each plate.
- The linseed oil is distributed over the surfaces and both the plates are left for 15 days in a sealed box for curing.
- The advantage of this procedure is that after linseed oil coating it can be checked visually whether the curing is properly done or any uncured droplet of linseed oil is present.

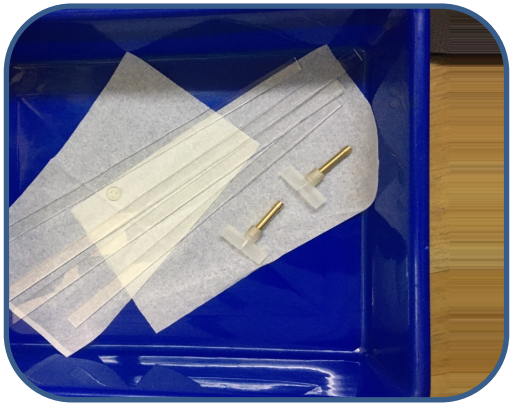
Fabrication steps

Resistivity= 3×10^{10} Ω cm

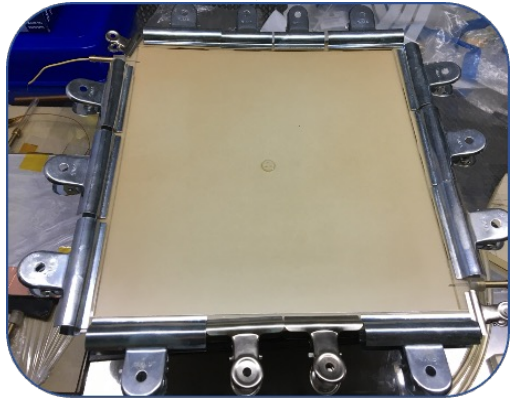
Application of linseed oil on the bakelite surface



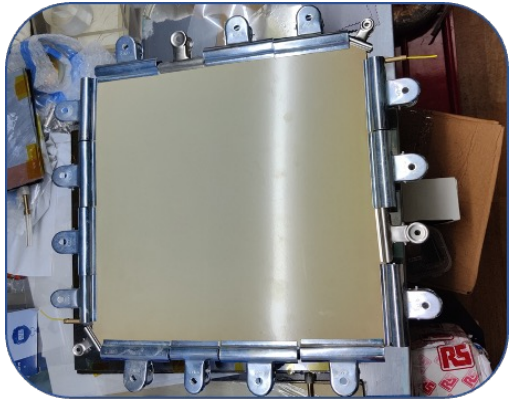
Cured linseed oil coated bakelite surface



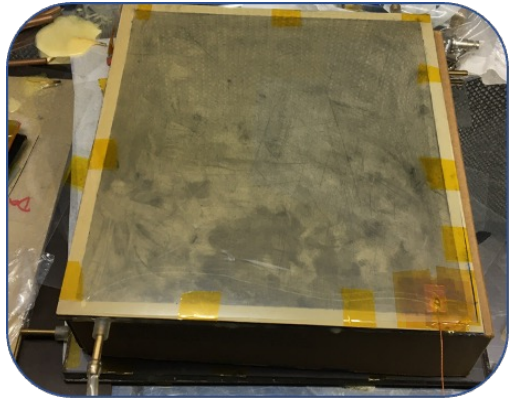
Gas nozzles and spacers



Gluing of spacers and nozzles

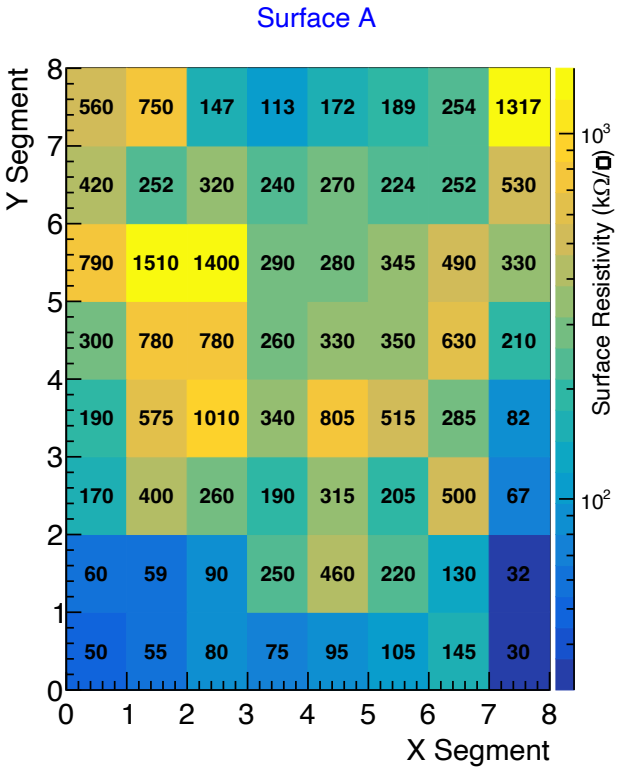


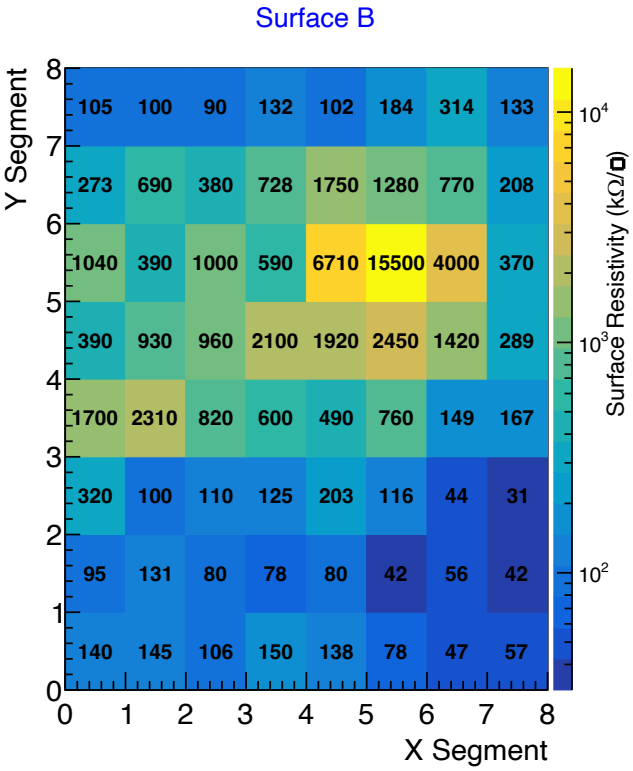
Making of gas gap



Complete RPC module after graphite coating

Measurement of surface resistivity

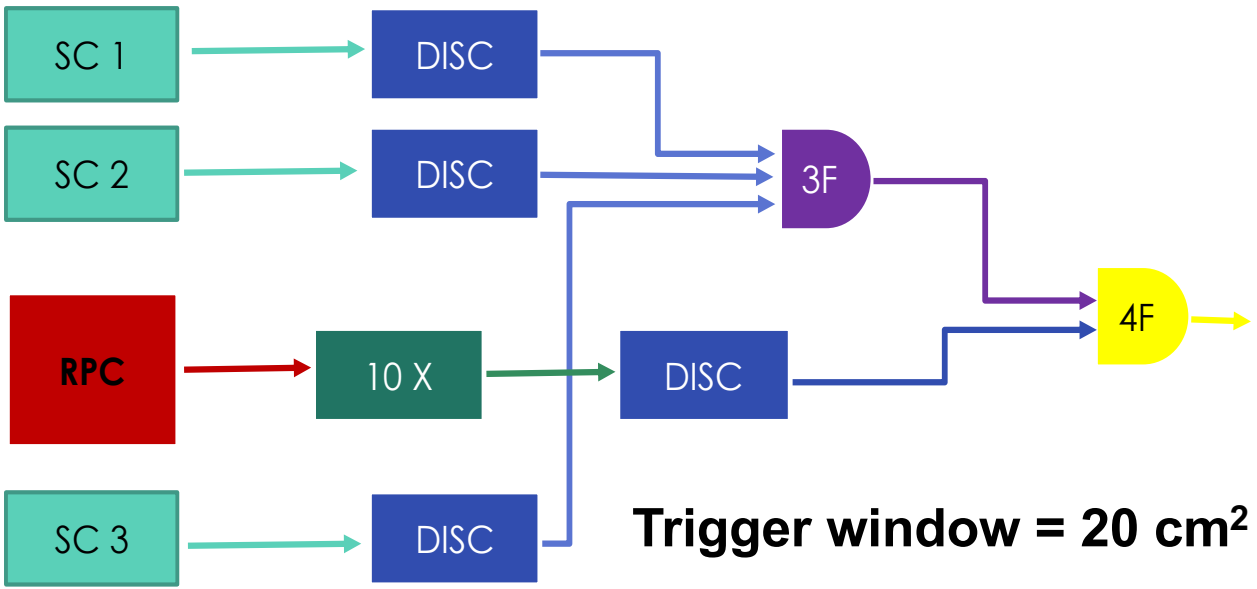




Average surface resistivity of **Surface A = 358 kΩ/□** and **Surface B = 409 kΩ/□**

Efficiency measurement

A. Sen et al., 2020 JINST 15 C06055

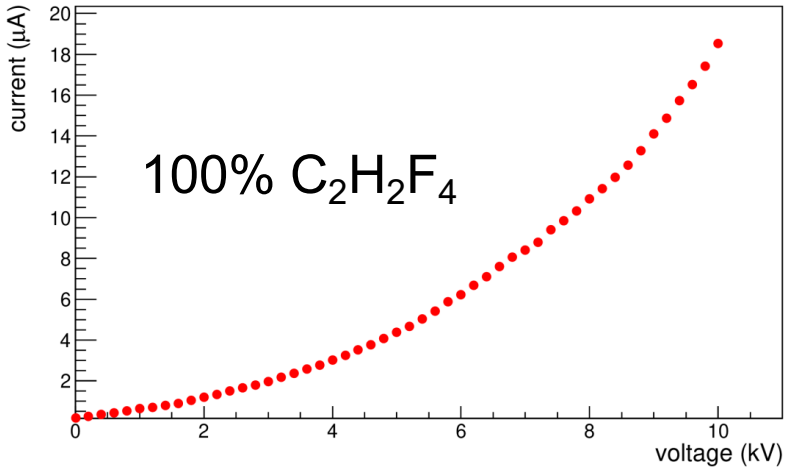


- Threshold to the Sc: - 15 mV
- Threshold to RPC: - 15 mV

Trigger = SC1 .AND. SC2 .AND. SC3

$$\text{Efficiency} = \frac{\text{RPC signal in coincidence with trigger (4F)}}{\text{Trigger (3F)}}$$

Results

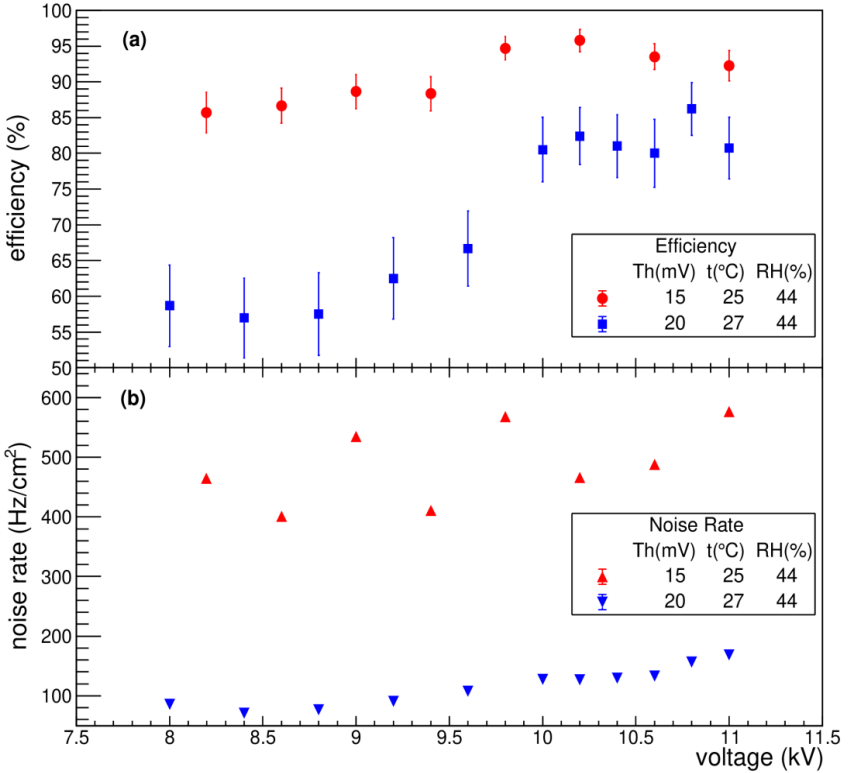


Leakage current as a function of the applied voltage

@ -15 mV threshold
- **Efficiency: ~ 95±1% from 9.4 kV onwards**
- **Noise rate ~ 500 Hz/cm²**

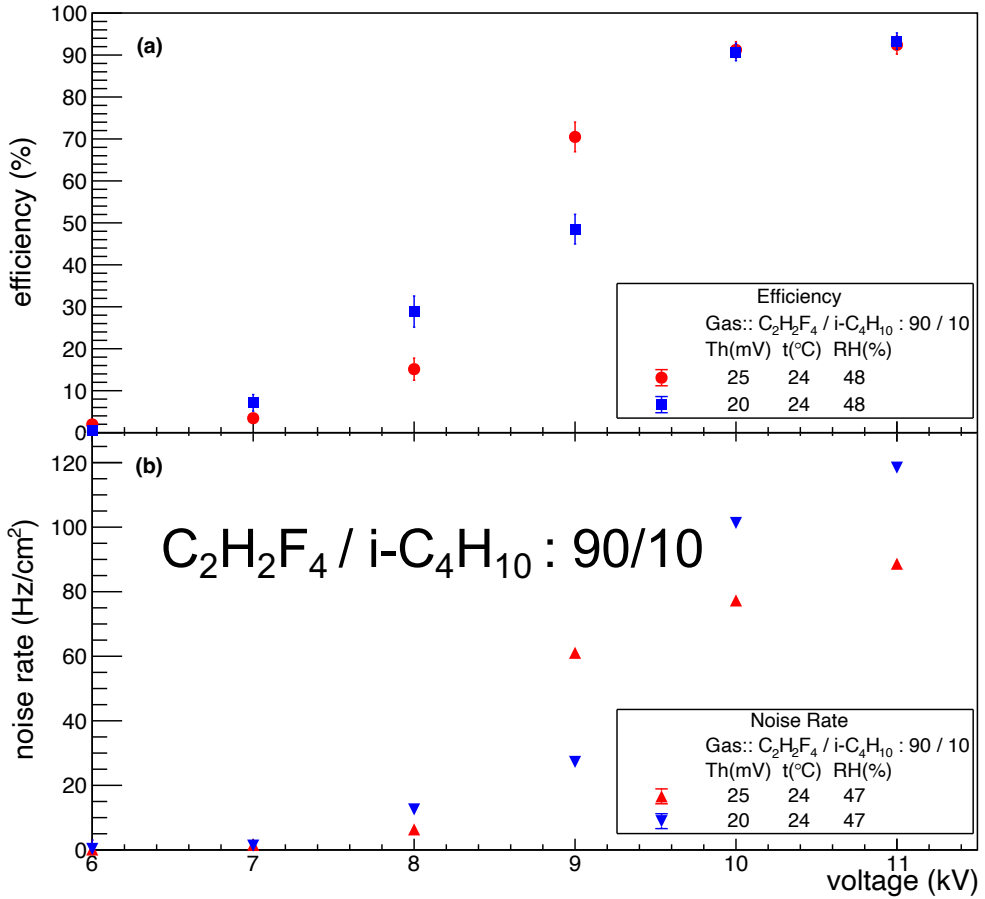
@-20 mV threshold
- **Efficiency: ~ 85±5% from 10.1 kV onwards**
- **Noise rate ~ 200 Hz/cm²**

A. Sen et al., NIM A 1024 (2022) 166095



(a) The efficiency vs the applied voltage
(b) Noise rate as a function of the applied voltage

Results



A. Sen et al., arXiv: 2206.04259

@ -20 mV threshold

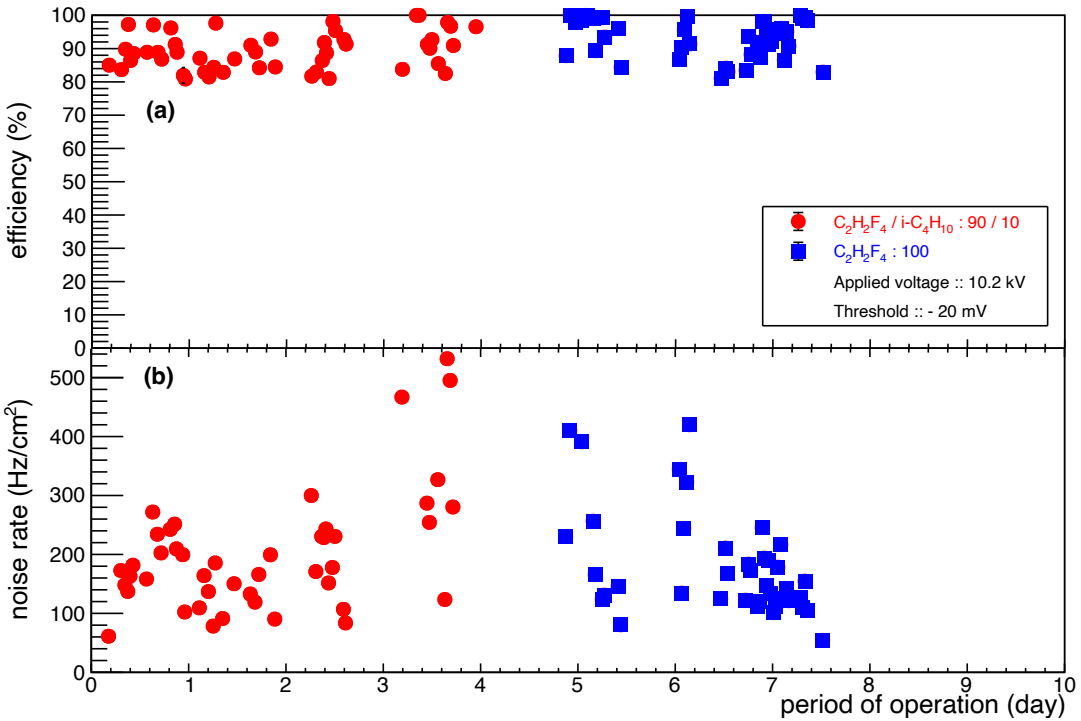
- **Efficiency: ~ 95±2% from 10 kV onwards**
- **Noise rate ~ 120 Hz/cm²**

@-25 mV threshold

- **Efficiency: ~ 95±2% from 10 kV onwards**
- **Noise rate ~ 80 Hz/cm²**

(a) The efficiency vs the applied voltage
(b) Noise rate as a function of the applied voltage

Stability test results (preliminary)

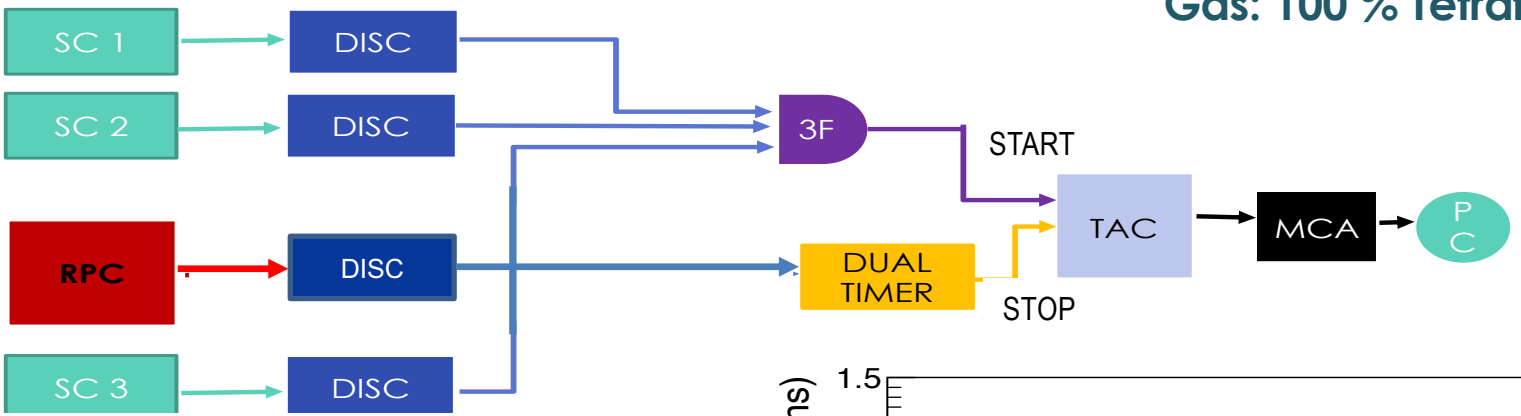


@ 10.2 kV applied voltage and -20 mV threshold

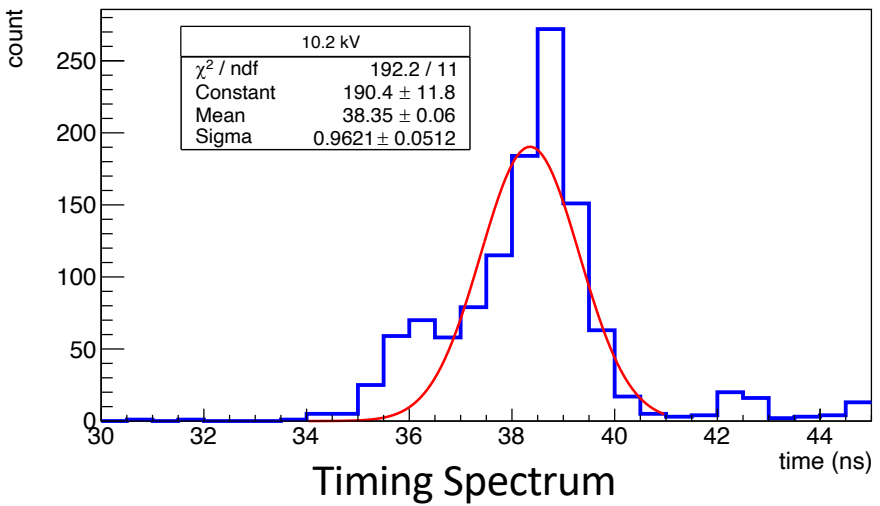
- **Efficiency: 89% from Noise rate ~ 181 Hz/cm^2 for $C_2H_2F_4$ / i-C_4H_{10} : 90/10**
- **Efficiency: 93% from Noise rate ~ 155 Hz/cm^2 for $C_2H_2F_4$: 100%**

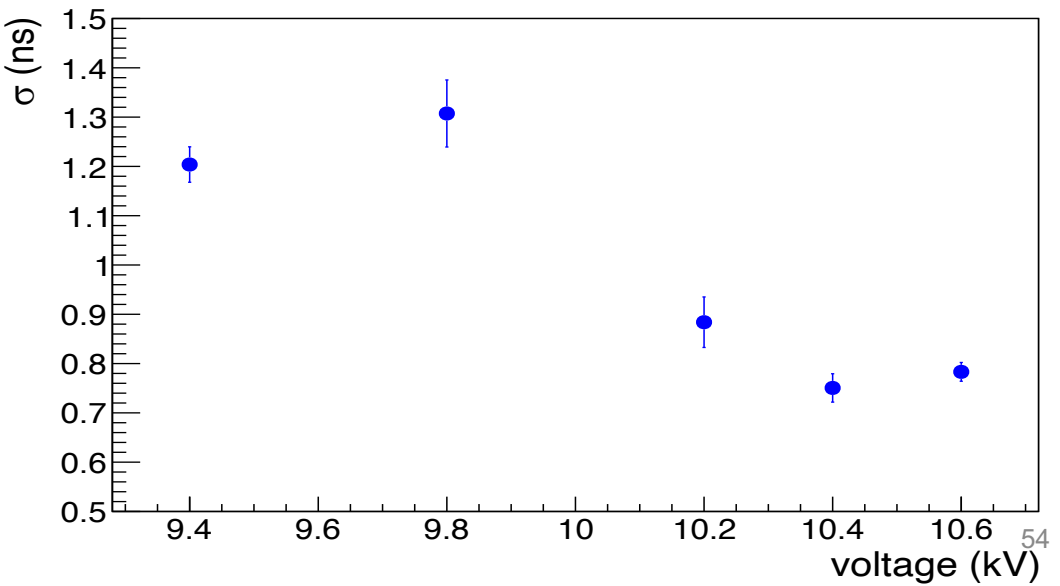
Time resolution measurement

Gas: 100 % Tetrafluroethane



Time resolution ~0.8±0.06 ns (σ)





Summary

- **Performance of Silicone coated bakelite RPC (Streamer mode):**
  - **Good I-V characteristics**
  - **High efficiency (~ 90-95 %)**
  - **Low counting rate (~ 0.1-0.2 Hz/cm^2)**
  - **Low cross-talk**
  - **Time resolution ~2 ns.**
  - **Tested for 130 days continuously and stable (Efficiency >90%, Leakage current (~500 nA) and Counting rate (~ 0.1 Hz/cm^2)**
- **Large (1 m × 1 m) RPC has been fabricated and tested satisfactorily**
- **Large prototypes are tested with magnet at VECC**
- **Silicone coated bakelite RPC is a viable alternative to semiconductive glass-based RPC for use in the ICAL detector of the INO.**

- *Several RPC modules are build with locally available bakelite material*
- ***A new technique is introduced for linseed oil coating in bakelite RPC***
- *With linseed oil coated electrode an efficiency ~ 95±1% for -15 mV threshold efficiency ~ 85±5% for -20 mV threshold for 100% $C_2H_2F_4$ gas*
- *The time resolution of the chamber is found to be ~ 0.8±0.06 ns (σ)*
- *For $C_2H_2F_4$ / i-C_4H_{10} : 90/10 gas composition an efficiency ~ 95% for both -20 mV and -25 mV threshold*

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VECC workshop
VECC PSI Lab

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