Effect of electric field and gas mixture on RPC time resolution

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Advanced Detectors for Nuclear, High Energy and Astroparticle Physics
Bose Institute, February 17, 2017

Outline

Motivation

- The proposed ICAL detector at INO will be an assembly of large number of RPCs placed in stakes of about 150 layers with Iron plates sandwiched between them.
- The passage of muons through the setup will be found out using the position and timing information from each RPC layer.

$$\nu_\mu + \text{n} \rightarrow \mu^- + \text{p}$$

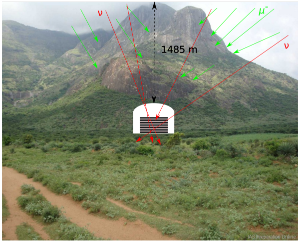


Figure: Proposed ICAL setup under rock cover, to shield atmospheric muons.

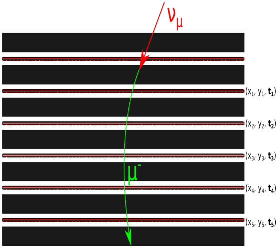


Figure: Neutrinos interact with iron plates and produce muons, which are tracked by RPC layers.

Motivation (cont.)

- The fast measurement of the muon hits depend on the signal generation time of the detector.
- The precision of the timing measurements depend on the time resolution of the detector. A lower value of time resolution can help in distinguishing between up-going and down-going muons.
- Understanding different factors influencing timing performance of the detector will help in understanding its behavior, interpreting the result and optimizing the detector parameters to improve its performance.
- The timing performance of the detector has been calculated considering the underlying processes behind the generation of RPC signal, under different conditions.

Physics of RPC operation

Step 1

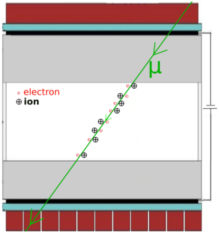


Figure: Primary ionization within RPC gas chamber by the incident particle.

Step 2

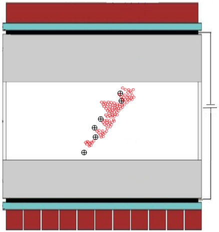


Figure: Secondary ionization by the fast moving electrons.

Step 3

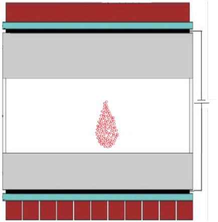


Figure: Movement of the electrons and ions induce current on the nearby conductors.

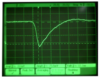


Figure: Typical RPC signal.

- Gas mixture: Ionizing gas + UV photon quencher + electron quencher.
- Electric field : Helps in drift of electrons and ions.

Physics of RPC operation (cont.)

- The current induced on a read-out strip due to movement of charge q with velocity $\overrightarrow{v}(t)$ is given by **Shockley-Ramo** theorem[1,2] :

$$i(t) = q\overrightarrow{v}(t).\overrightarrow{W}(\overrightarrow{x}(t))$$

- Value of q depends on the ionizing particle, gas mixture and the electric field.

$$N = N_0 e^{(\alpha-\eta)x}$$

$N_0 \rightarrow$ Primary number of electrons

N $\rightarrow$ Total number of electrons

$\alpha \rightarrow$ Townsend co-efficient

$\eta \rightarrow$ Attachment co-efficient

- Instantaneous velocity of the charge, $\overrightarrow{v}(t)$ depends on the gas mixture as well as on the electric field.

Ref: [1] *W. Shockley, Journal of Applied Physics, 9* **(10)** *p635, 1938.*

Ref: [2] *S. Ramo, Proceedings of the IRE. 27* **(9)** *p584, 1939.*

Physics of RPC operation (cont.)

- Proper working of the detector depends upon the applied field as well as on the used gas mixture.
- In the present work,
  - The timing properties of a RPC has been calculated numerically.
  - The effect of applied voltage (electric field) and gas mixture on it has been found out.
  - Experiments have been performed to find the same effect and to validate the numerical findings.

Numerical Calculations: Method

- **Garfield**[3] (interfaced with **neBEM**, **HEED**, **Magboltz**) framework is used for the calculation of induced signals.

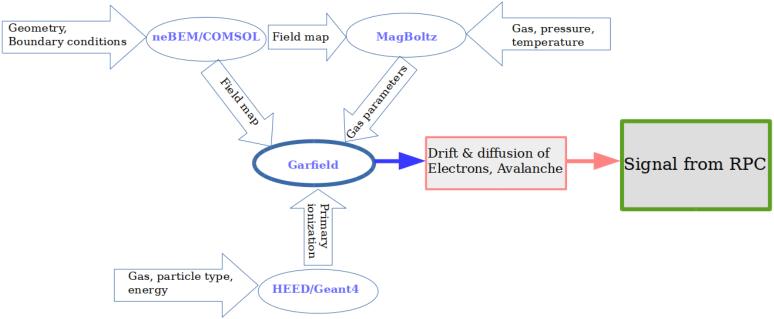


Figure: Garfield simulation framework to calculate RPC signal.

Ref: [3] *R. Veenhoff, NIM A* **419** *(1998) p.726-730*

Numerical Calculations: Method (cont.)

Component name	Material (ϵ_r)	Dimensions
gas chamber	air (1.013)	$x = y = 29$ cm, $d = 2$ mm
resistive plate	bakelite (5.4)	$x = y = 30$ cm, $d = 2$ mm
conductive coating	graphite (12.0)	$x = y = 29$ cm, $d = 20\,\mu$m
edge spacers	mica (5.4)	$d = 2$ mm, $w = 5$ mm
button spacer	mica (5.4)	$r1 = 5.1$ mm, $r2 = 5.5$ mm, $d1 = 1.4$ mm, $d2 = 0.3$ mm
insulating layer	mylar (3.2)	$x = y = 29$ cm, $d = 0.1$ mm
read-out strips	copper	$l = 30$ cm, $w = 2.5$ cm, $d = 0.2$ mm

Figure: RPC components used in calculation.

- A gas mixture of R-134A + Isobutane + SF_6 is used with varying SF_6%.
- Muons of energy 2 GeV are passed through RPC gas chamber in directions varying randomly in the range:
  $\theta = 0^\circ$ - 10°, $\phi = 0^\circ$ - 360°.

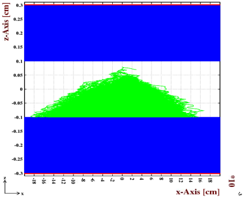


Figure: Avalanche created by a single electron in RPC gas chamber.

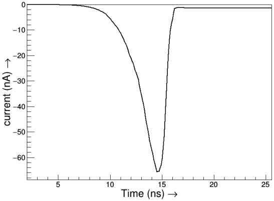


Figure: Typical RPC signal due to passage of muon through RPC.

Numerical Calculations: Method (cont.)

- The time corresponding to the crossing of a current threshold has been calculated (onset/arrival of a detectable signal).
- A distribution of signal onset/arrival time has been obtained from repeated calculations of 5000 events.
- The mean of the distribution is considered as the average signal arrival time.
- The RMS of the distribution gives an estimate of the time resolution.
- Data analysis using ROOT[4].

Ref: [4] *https://root.cern.ch*

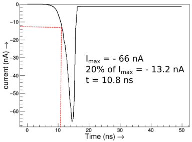


Figure: The time corresponding to the crossing of 20% of I_{max}.

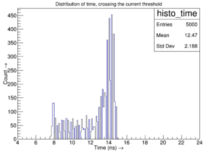


Figure: Time distribution.

Numerical Calculations: Result

Electrostatic field map[5] :

- Applied voltage = ± 6.0 kV.

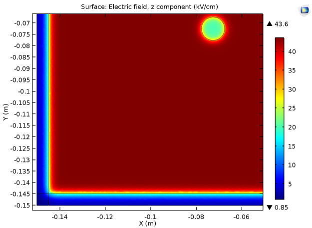


Figure: Surface map of E_z at z=0 plane.

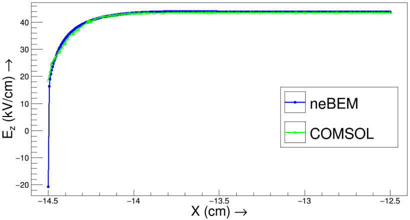


Figure: Effect of edge spacer on E_z.

- The value of E_z is less near the edges and corners.
- This will affect the signal amplitude and the timing properties of RPC in those regions.

Ref: [5] *A. Jash et al., JINST* **10** *P11009*

Numerical Calculations: Result (cont.)

RPC signal :

- Average signal amplitude has been calculated by passing 100 muons, each of energy 2 GeV, through a regular region and regions near edge.
- Gas mixture ⇒ R-134A : Isobutane = 95 : 5.

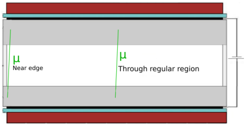


Figure: Muons passed through different regions.

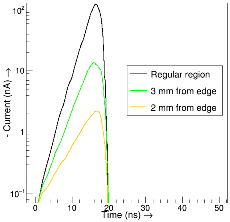


Figure: Signal amplitude from different regions for applied voltage = 12.1 kV.

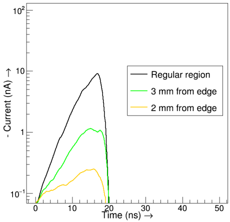


Figure: Signal amplitude from different regions for applied voltage = 11.7 kV.

Numerical Calculations: Result (cont.)

RPC timing response :

Effect of edge spacer

- Applied voltage = ± 7.05 kV (to generate proper signal shapes near edge).
- Gas mixture ⇒ R-134A : Isobutane : SF_6 = 95.0 : 4.8 : 0.2.

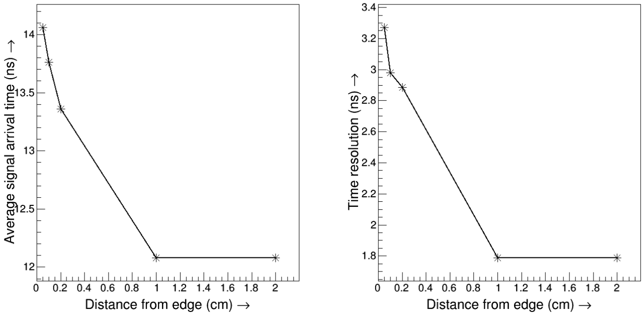
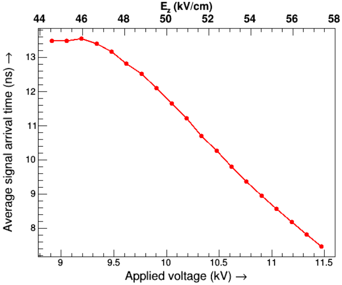


Figure: Variation of timing parameters with distance from edge spacer of RPC.

Numerical Calculations: Result (cont.)

Effect of applied voltage[6]



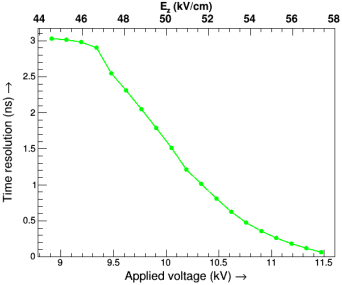


Figure: Variation of average signal arrival time and time resolution with voltage.

- Higher voltages ⇒ Fast generation of detectable signal ⇒ Reduction of average signal arrival time.
  ⇒ Less fluctuation of electron drift path ⇒ Better time resolution.

Ref: [6]*A. Jash et al., JINST* **11** *C09014*

Effect of SF_6 amount[6]

- Gas ⇒ R-134A : Isobutane : SF_6 = 95 : 4.5 (4.8, 4.9) : 0.5 (0.2, 0.1)

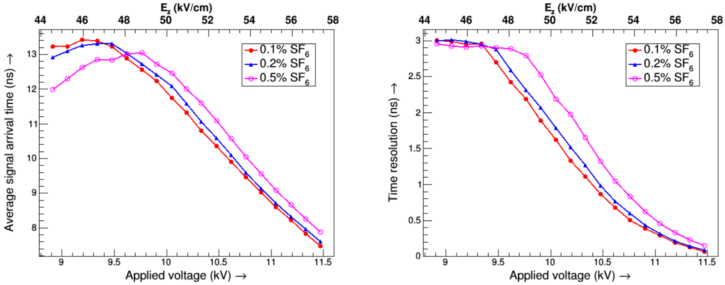


Figure: Variation of average signal arrival time and time resolution with the applied voltage for different SF_6 percentages.

- Higher SF_6 ⇒ Long time to generate detectable signal ⇒ Increase of average signal arrival time.

Analytic values

- The variation of RPC time resolution with the applied voltage can be explained from the analytic formula[7] for time resolution:

$$\sigma = \frac{1.28255}{(\alpha - \eta)v}$$

$$\Rightarrow \sigma \propto \frac{1}{\alpha_{eff}},$$

$$\sigma \propto \frac{1}{V_z}$$

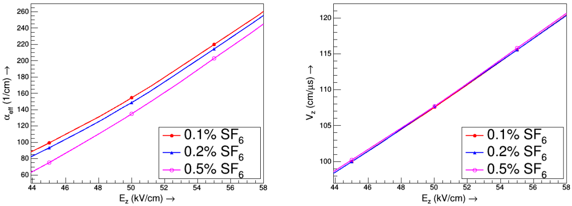


Figure: Variation of α_{eff} and V_z with E_z for R-134A based different gas mixtures.

- The value of time resolutions from the numerical calculations is slightly higher than that from the simplified analytic formula.

Ref: [7] *W. Riegler, C. Lippmann, NIM A 508 (2003) 14*

Experimental Setup

- One Bakelite RPC of dimension 30 cm $\times$ 30 cm has been operated with a pre-mixed gas mixture R-134A (95%), Isobutane and very small amount of SF_6 (maximum 1%). The exact amount can not be quoted (technical limitation).
- One finger scintillator along with two paddle scintillators formed a telescope to select muon events passing through one RPC strip.
- CAMAC based data acquisition system.
- Room temperature = (22 ± 1) °C. Relative humidity = (49 ± 4) %.

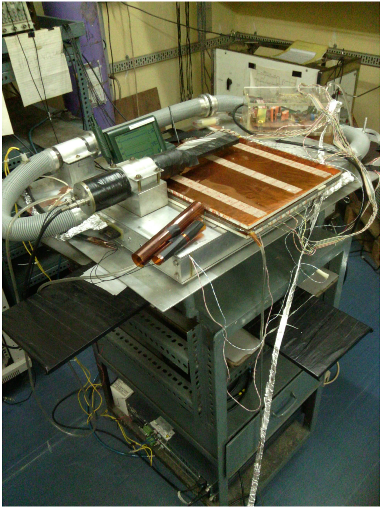


Figure: Experimental setup

Experimental Setup (cont.)

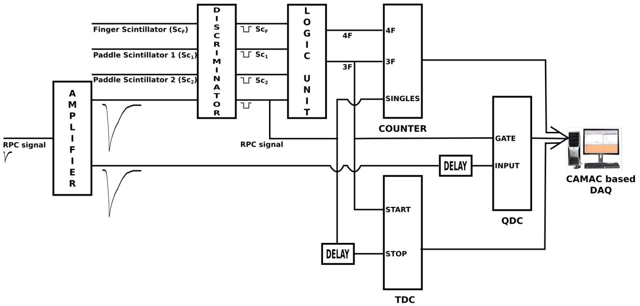


Figure: Schematic diagram of the electronics for TDC and QDC measurements

TDC

- START : 3F signal.
- STOP : RPC strip signal after wire delay.

QDC

- GATE: 3F signal, width = 100 ns.
- Q in: RPC strip signal after 10X amplification.

Experimental Result

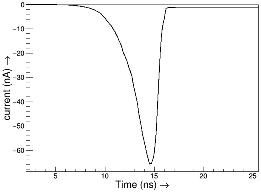


Figure: Typical RPC signal from simulation (averaged over 50 events).

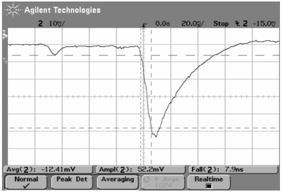


Figure: RPC signal as seen on oscilloscope.

- Falling edge should not be compared as no effect of the external electronic circuit has been considered in the present calculations.

- Signal rise time:
  - From oscilloscope $\sim$ 8 ns.
  - From numerical calculation $\sim$ 7 ns.

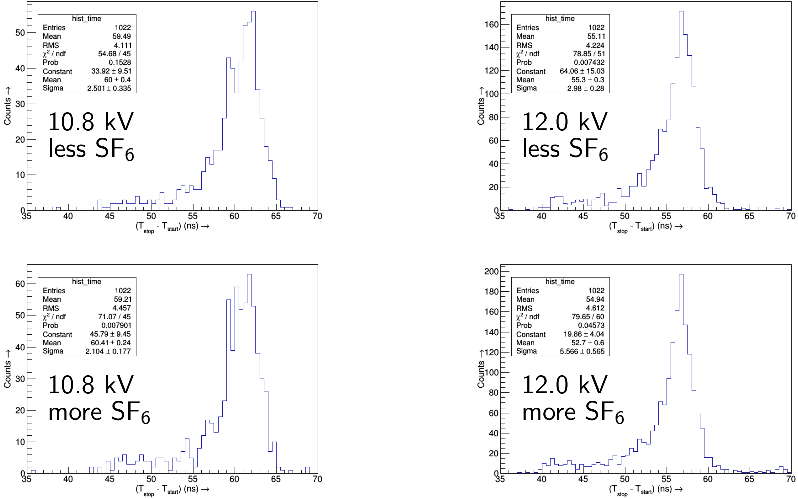


Figure: TDC spectra at different voltages for different gases.

Experimental Result (cont.)

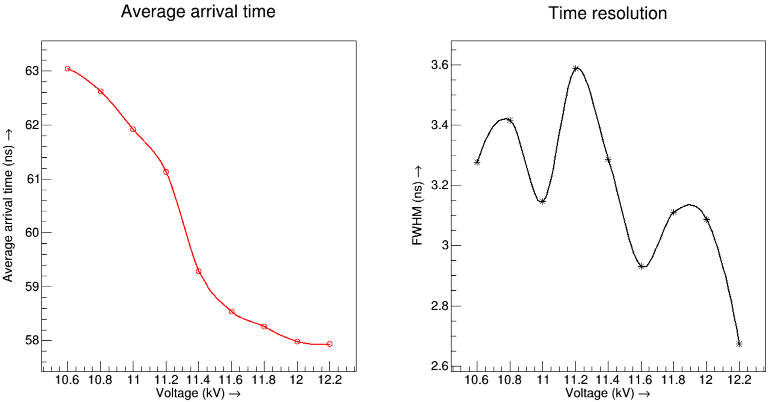


Figure: Variation of average arrival time and time resolution with applied voltage.

- RPC becomes faster with applied voltage.
- Overall improvement of time resolution, except some points.

Experimental Result (cont.)

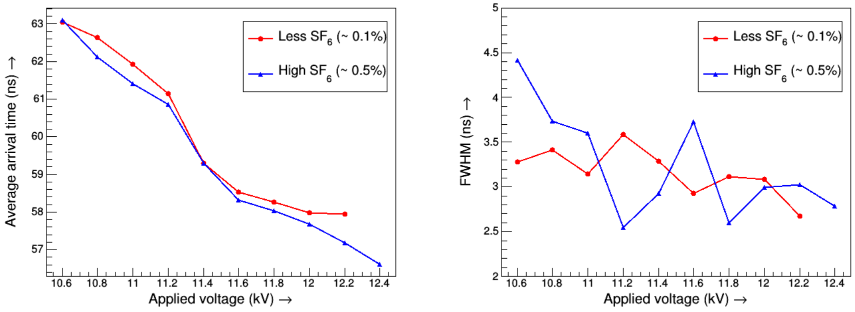


Figure: Variation of average arrival time and time resolution with applied voltage for different amount of SF_6.

- RPC becomes faster for higher amount of SF_6.
- The data for time resolution is not enough to draw any conclusion.

Experimental Result (cont.)

QDC spectra at different voltages

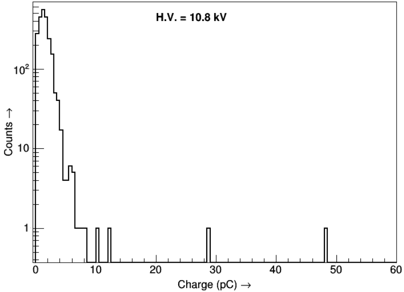


Figure: QDC spectra at 10.8 kV.

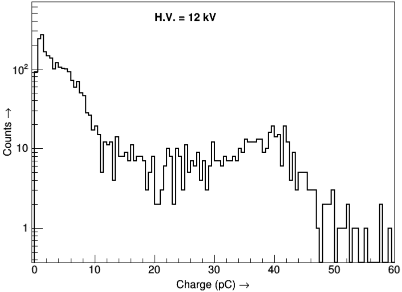


Figure: QDC spectra at 12.0 kV.

- Selection of avalanche mode of RPC operation from the QDC spectra.

Conclusion

- The numerical results show that the average signal arrival time and time resolution improve with the increase in applied voltage.
- Numerical calculations showed deterioration of time resolution with the increase in SF_6 amount.
- This trend is supported by the analytic formulation of time resolution reported in the reference [7].
- The presence of edge spacer affect the time resolution in comparison to the usual value as the electrostatic field map gets distorted in its surroundings.
- Numeric calculation of timing parameters near button spacers and corners are in progress.

Conclusion (cont.)

- The experimental result on the effect of SF_6 does not match with the numerical result. More careful study with controlled environmental conditions will be performed.
- A portable gas container has been designed and fabricated to analyse the used gas mixture using Residual Gas Analyzer (RGA).

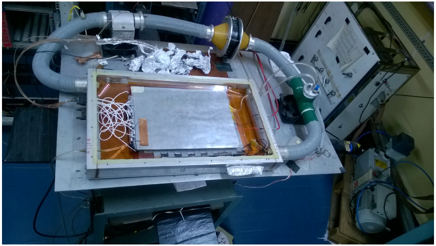


Figure: Experimental setup under controlled environment.

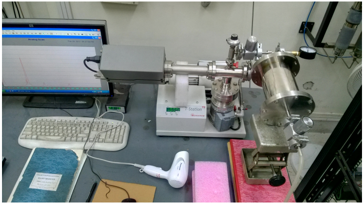


Figure: Portable gas container connected to RGA.

Acknowledgment

- We acknowledge the helpful suggestions of Prof. **Sudeb Bhattacharya** (SINP) and Prof. **Saikat Biswas** (Bose Institute) at different stages of the work.
- We thank **Ganesh Chandra Das** (VECC), **Chandranath Marick** (SINP), **Pradipta kr. Das** (SINP) and **SINP workshop** for their technical help and assistance in fabricating and setting up of the different parts of the experiment.
- Thanks to **Jaydeep Dutta** (SINP) and **Prasant Rout** (SINP) for many helpful discussions.
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Thank You

Additional Slides

Effect of shape of button spacer on E_z

Distortion of electric field around Button spacer :

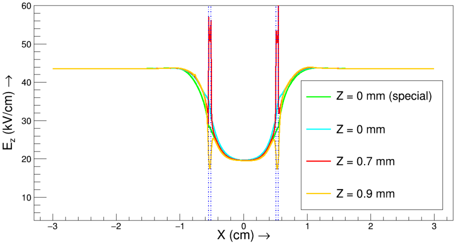

Figure: Variation of E_z along X-direction at different positions near a button spacer - COMSOL.

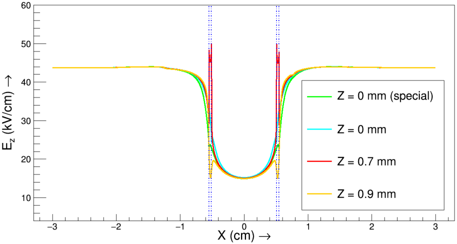

Figure: Variation of E_z along X-direction at different positions near a button spacer - neBEM.

RPC characteristics

- Breakdown occurs around 10.2 kV.
- $R_{plate} = 6.16\ G\Omega$.
- $R_{spacer} = 53.4\ G\Omega$.

Timing histograms at different voltages (numerical result)

Effect of applied voltage: (R-134A : Isobutane = 95 : 5)