Study on RPC signal attenuation

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Motivation

- Thin-gap RPC for ATLAS Phase II upgrade has smaller avalanches
- Simulation indicates the existence of ‘attenuation’ [backup 0]
  - ‘Attenuation’ means the reduction or loss of charge, amplitude and frequency of the signal readout from one strip
- Positive correlation between attenuation and signal propagation distance along readout strips
- Negative correlation between attenuation and graphite surface resistivity $\rho_S$
  - Higher $\rho_S$ also brings larger voltage drop on graphite
  - To limit the voltage drop, lower limit of $\rho_S$ is needed

Simulation results: attenuation of signal amplitude during propagating in BI RPC in HL-LHC:
- Surface resistivity: $\rho_S = 600 \, k\Omega/\square$
- Hit rate: $r = 1200 \, Hz/cm^2$
- Total charge per hit: $c = 6 \, pC$
- Length: $L = 2.4 \, m$

Simplified ATLAS BI RPC graphite model
- Maximum $\Delta V = \frac{1}{2} r c \rho_S L^2 = 62 \, V$
Experiment setup: hardware

❖ **Gas gap**
- 1.2 m in length
- Similar design to ATLAS BIS8 RPC except $\rho_s$
- Graphite $\rho_s = 10 \, k\Omega/\square, 100 \, k\Omega/\square, 1 \, M\Omega/\square, 10 \, M\Omega/\square$
- Ordered from GT (General Technica)

❖ **Readout panel**
- 1.0 m in length
- Readout strips: 25 mm width separated by 2 mm
- Similar design to ATLAS BOE RPC (foam filling)
- Ordered from GT (General Technica)

❖ **Oscilloscope**
- Sampling rate: 20 GS/s
- Bandwidth: 4 GHz
- External cosmic-ray trigger from coincidence of scintillators
Experiment setup: readout scheme

❖ Readout scheme

1. Consider signal 0 & signal 1 induced identically by muon hit at distance \( l \)
2. Signal 0 gets absorbed at right end by the matching resistor
3. Signal 1 gets reflected at left end, absorbed at right end after signal 0, with longer propagation distance
4. At right end waveforms recorded by oscilloscope without amplifiers

❖ Leading edge difference locates the hit

- Leading edge difference = \( \frac{2}{\text{velocity}} \times l \)
- Propagation distance difference = \( 2 \times l \)
- Positioning accuracy < 10 mm [backup 1]
Offline analysis: LPF & calibration

❖ Low-pass filter (LPF)
  - FWHM of signal of thin gap RPC $\approx 2\ ns$
  - 1 GHz bandwidth filter to eliminate high frequency noise

❖ Noise calibration
  - After signal 0 is induced on channel 1, ‘noise’ occurs on all channels
  - Signal 1 gets distorted
  - Calibrated by subtracting the waveform of nonadjacent channel (channel 3) [backup 3]
  - After calibration, waveforms of signal 1 are undistorted
  - RMS increases
Offline analysis: selection of events

- **Selection of events**
  1. RMS (noise) < 400 $\mu V$
  2. Number of peaks = 2, to cut muon bundles events
  3. Overlapped signal 0 and signal 1
  4. Signal amplitude > 5 $mV$ & & < 29 $mV$ (full scale of oscilloscope = 30 $mV$)
  5. Abnormal signal width due to noise [backup 2]
  6. Outliers: charge of signal 1 > 1.05 \times charge of signal 0
Charge attenuation: definition

- **Definition of charge**
  - Integration between leading edge and trailing edge at 10% of peak
  - Charge ratio: \( \frac{\text{charge of signal 1}}{\text{charge of signal 0}} \)

- **The charge ratio indicates the strength of charge attenuation**

- **The charge ratio is shown as a function of the propagation distance difference in 2D hist.**
  - In the left end, signal 0 and signal 1 are partially overlapped, events are cut (signal width = 3.4 ns, propagation velocity = 230 mm/ns)

Illustration of charge
Charge attenuation: exponential fit

❖ Profile X:
  • Project the 2-D histogram into a profile histogram along X
  • Stat error: standard error of the mean of $y$ of events in each $x$ bin
  • Systematical error: because of the nonideal calibration [backup 3]

❖ The charge ratio ($y$) VS. distance difference ($x$) could be represented by a fit function: $y = e^{-A_{\text{Charge}} \cdot x}$ (chi2 fit)
  • Fit range: 0.78 – 1.84 m (Scintillator coverage)
  • $A_{\text{Charge}} = 0.106 \pm 0.001$ [m$^{-1}$]
  • Chi2 and R2 indicate good fit quality which means negligible charge loss in signal reflection ($y(0) = 100\%$)
Charge attenuation: combined results

- $A_{\text{charge}}$ strongly depends on graphite $\rho_s$
- When $\rho_s > 1 \text{ M}\Omega/\square$, $A_{\text{charge}}$ approaches 0
- For ATLAS BI RPC, maximum charge loss would $\approx 10\%$ ($\rho_s = 600 \text{ k}\Omega/\square$, propagation distance = 2.4 m)
Definition of amplitude

- The peak of the signal
- Amplitude ratio \( = \frac{\text{amplitude of signal} \ 1}{\text{amplitude of signal} \ 0} \) as an indicator of the amplitude attenuation

The amplitude ratio VS. distance difference could be represented by a fit function:
\( y = e^{-A_{\text{amplitude}} \cdot x} \)
- \( y \) stands for amplitude ratio
- \( x \) stands for propagation distance difference
- \( A_{\text{amplitude}} = 0.210 \pm 0.002 \ [m^{-1}] \)
- Chi2 and R2 indicate good fit quality
Amplitude attenuation: combined results

- Amplitude strongly depends on graphite $\rho_s$
- When $\rho_s > 1 \text{ M} \Omega/\square$, $A_{\text{amplitude}}$ approaches a constant value
- $A_{\text{amplitude}}$ has an upwards shift comparing to $A_{\text{charge}}$
Definition of frequency

- Fourier transform hard to give frequency
- ‘Equivalent frequency’ = \( \frac{1}{\text{FWHM}} \)
- Frequency ratio = \( \frac{\text{frequency of signal 1}}{\text{frequency of signal 0}} \), as an indicator of frequency attenuation
- Wider distribution in \( y \) axis due to fast RPC signals and limited sampling rate

The frequency ratio VS. distance difference could be represented by a fit function:
\[
y = e^{-A_{\text{frequency}} \cdot x}
\]
- \( y \) stands for frequency ratio
- \( x \) stands for propagation distance difference
- \( A_{\text{frequency}} = 0.107 \pm 0.002 \ [m^{-1}] \)
Frequency attenuation: combined results

- $A_{\text{frequency}}$ is observed not to depend on $\rho_s$
- $A_{\text{amplitude}} - A_{\text{frequency}} \approx A_{\text{charge}}$, (i.e. all signals have similar shape) explains the shift between $A_{\text{amplitude}}$ and $A_{\text{charge}}$
- Signal would be 23% wider after 2.4 m propagation
Potential countermeasure

- Highly simplified model of readout strips and graphite
  - $C$: equivalent capacitance between one strip and graphite per unit length
  - $R$: equivalent orthogonal resistance between two equivalent capacitance per unit length, $\propto \rho_s$
  - Orthogonal diffusion on graphite [ref 1]

- Potential countermeasure
  - Split the graphite layer like readout strips with narrower spacings
  - $R \to \infty$, not depends on $\rho_s$
  - Effective in simulation [backup 4]
Summary and conclusions

1. Charge, amplitude and frequency of the signal readout from one strip are attenuated while signal propagating along strips, the measurements on attenuation are given

2. Attenuation of charge could be suppressed by high $\rho_s$, while voltage drop on graphite should be considered

3. For ATLAS BI RPC, maximum charge attenuation $\approx 10\%$, may need to be considered in electronics configuration (e.g. by specifying the threshold of the discriminator at far end)

4. Splitting the graphite may suppress the attenuation of charge and limit the maximum voltage drop as well
3D PEEC method: (Partial element equivalent circuit)
- Calculate the $R, C, L, G$ network like finite-elementary-method
- Surface resistivity could be simulated for the first time

Could explain the large cross-talk problem
- Caused by low graphite surface resistivity

Published proceeding: [link](#)
With amplifiers
Use orthogonal strips to give the reference position
5 GS/s sampling ADC and offline analysis

<table>
<thead>
<tr>
<th>Velocity [mm/ns]</th>
<th>(\sigma_x) [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ch0</td>
<td>241.2</td>
</tr>
<tr>
<td>Ch1</td>
<td>233.9</td>
</tr>
<tr>
<td>Ch2</td>
<td>230.4</td>
</tr>
<tr>
<td>Ch3</td>
<td>227.9</td>
</tr>
</tbody>
</table>
❖ Signal width between leading-edge trailing-edge at 10% of peak has obvious ‘background’
❖ Caused by the noise
❖ Cut range: ±0.3 ns from MPV (most probably value)
Strip 1 accidently disconnected, strip 3 not calibrated, and has periodic fluctuation

‘Noise’ may come from the induction of charge induced on graphite with opposite polarity

Lower $\rho_s$ would lead to larger difference in frequency ratio between calibrated and uncalibrated data

$$\rho_s = 10 \, k\Omega/\square$$
Uncalibrated

Calibrated

\[ \rho_s = 100 \, \text{k}\Omega/\square \]
Horizontal axis: the frequency ratio difference between calibrated data and uncalibrated data

\( \frac{1}{2} \sigma \) of the difference distribution is used to estimate the systematic error due to non-ideal calibration
Ref 1: G. BATI'ISTONI, NIM 202, 459-464

Graphite splits:
- Splits could be narrower than 1 mm to not influence the electricity field
- Graphite could be partially unsplitted in favor of HV connection

For simulation
- For study of attenuation, the RC model should be 2D network
- Lumped model no longer fits
- 3D PEEC method is suitable (Partial element equivalent circuit)
- In simulation, after split the $A_{amplitude}$ of $\rho_s = 1k\Omega/\square$ is suppressed from 0.5 to almost 0 $m^{-1}$