Simulation of Signal Propagation in Thin-Gap RPCs

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Based on NIMA Paper:

Simulation of the signal propagation for thin-gap RPC in the ATLAS Phase-II upgrade

For DRD1 WG4

31 Jan 2024

Outline

- Introduction
- Transmission simulation
- Measurements & Validation
- Discussions

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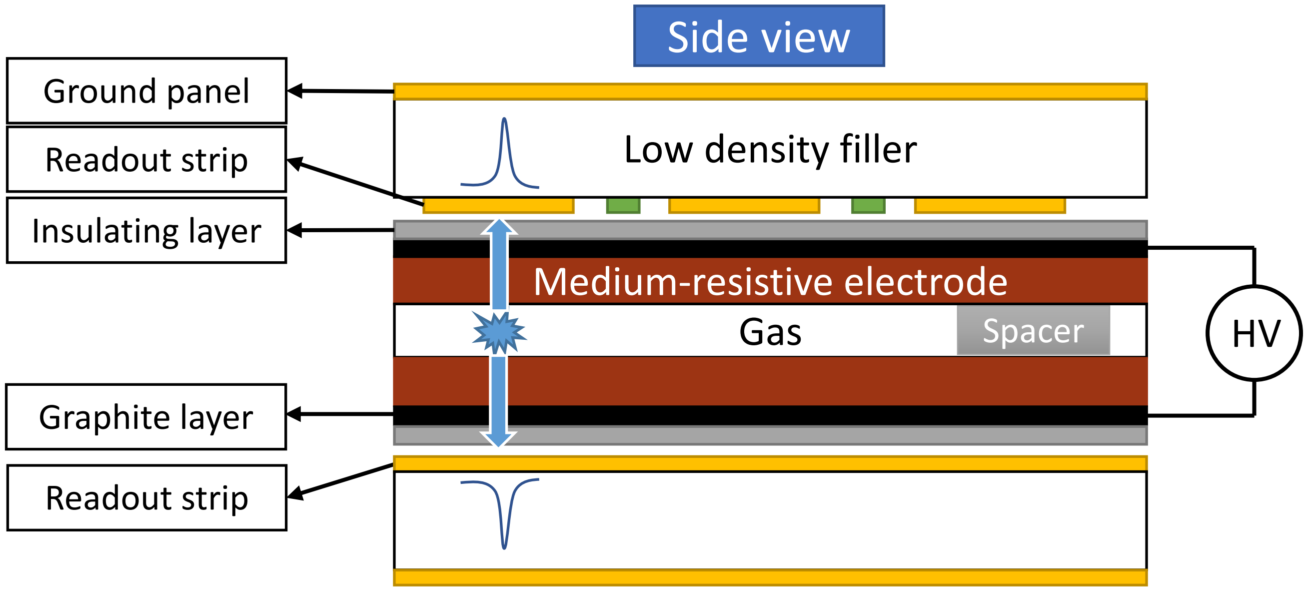
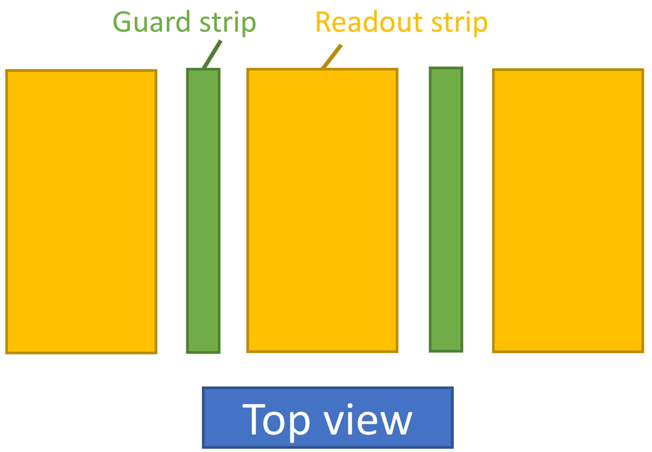
RPC prototype in this talk



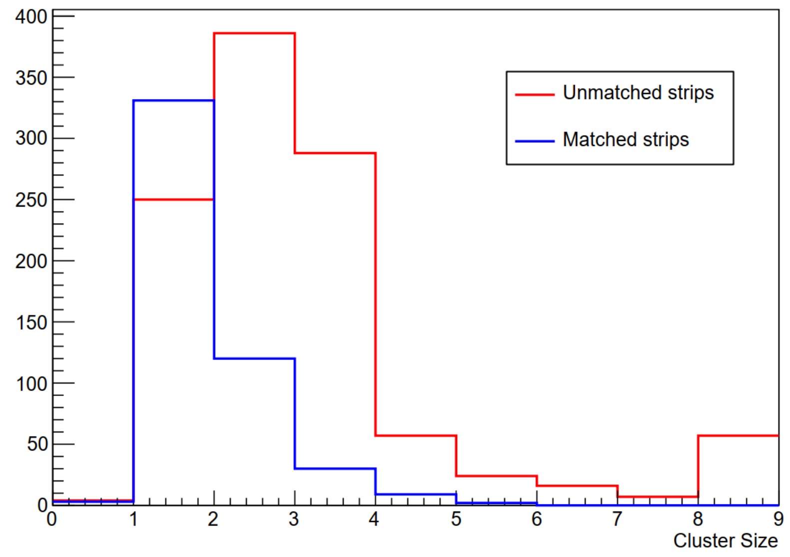


- Basic information
  - LHC-ATLAS muon-spectrometer component detector
  - To be installed at next upgrade
- Thin-gap RPC
  - 1 mm gas gap
- Panel layout
  - 25 mm strip width + 2 mm spacing
  - 0.8 mm guard strip

Multiplicity in RPC readout

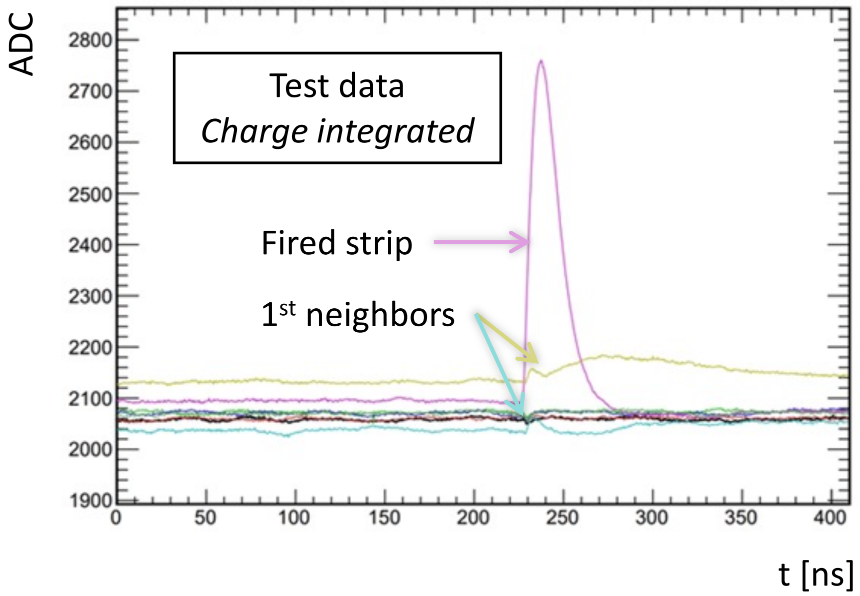
- Current configuration to limit multiplicity:
  - ✓ Higher graphite layer resistivity
  - ✓ Guard strip
  - ✓ Optimized termination

- Potential improvements:
  - ○ More delicate impedance matching
  - ○ Crosstalk mitigation
  - ➢ Transmission simulation provides guidance



Termination optimization

From ATLAS MS Phase-II Upgrade TDR



Crosstalk signal observed on neighboring strips

X.Y. Xie, et.al, *A new approach in simulating RPC and searching for the causes of large cluster size of RPC*, 2019 JINST 14 C09012

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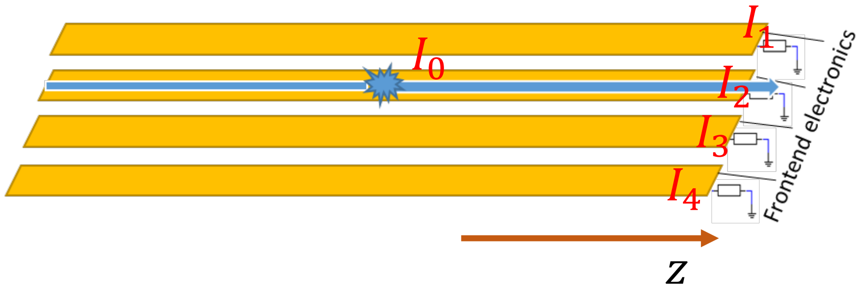
Lossless Multi-conductor transmission line (MTL) for RPC

- Transmission model
  - Induced charge treated as a point-like current source I_0 on the fired strip:

$$\vec{I}(t, z_0) = \begin{pmatrix} 0 \\ I_0(t) \\ 0 \\ 0 \end{pmatrix}$$

  - Collected signal at frontend distorted:

$$\vec{I}(t, L) = \begin{pmatrix} I_1(t) \\ I_2(t) \\ I_3(t) \\ I_4(t) \end{pmatrix}$$



Signal transmission

- Issues of interest
  - Calculate signal distortions using PRC modelling
    - Reflection and crosstalk
  - Find distortion mitigation methods

Theory assumptions:
✓ *'Transparent' graphite layer*
✓ *Resistance of copper ignored*

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MTL simulation tools

- Fundamental formulae:

$$\frac{d^2}{dz^2}\vec{V}(z,t) = \hat{L}\hat{C}\frac{d^2}{dt^2}\vec{V}(z,t)$$
$$\frac{d^2}{dz^2}\vec{I}(z,t) = \hat{C}\hat{L}\frac{d^2}{dt^2}\vec{I}(z,t)$$

  - $\hat{C}, \hat{L}$: capacitance and inductance matrices of parallel readout strips
    - $\hat{C} = \begin{pmatrix} C_{gnd} & -C_m \\ -C_m & C_{gnd} \end{pmatrix}$; $\hat{L} = \begin{pmatrix} L_{gnd} & L_m \\ L_m & L_{gnd} \end{pmatrix}$
    - Given by **Maxwell**
  - $\vec{V}(z,t), \vec{I}(z,t)$: vectors of signal
    - $\vec{V} = \hat{Z}\vec{I}$, $\hat{Z}$ impedance matrix
    - Solved using **Mathematica**

Ansys MAXWELL

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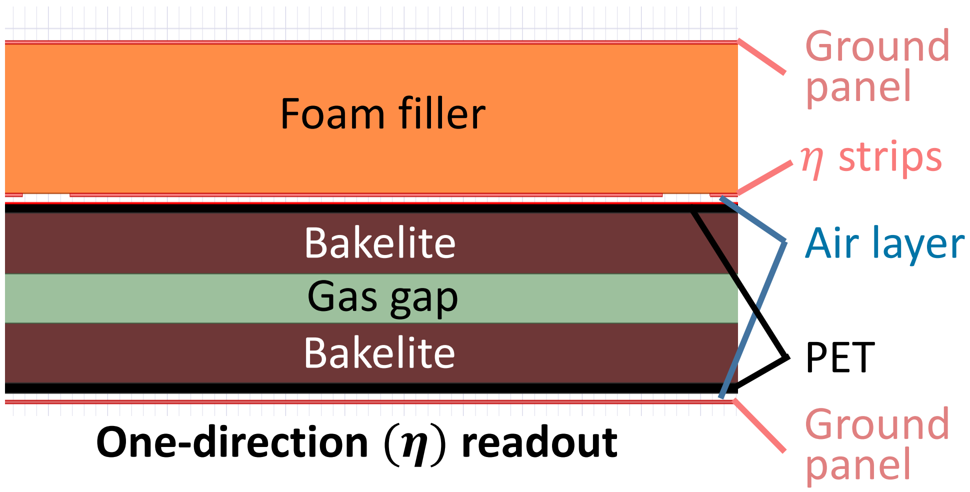
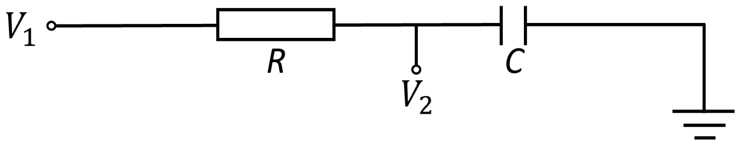
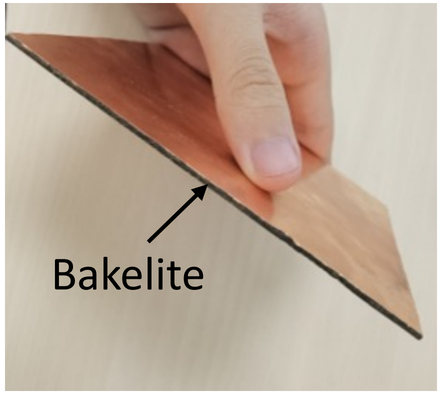
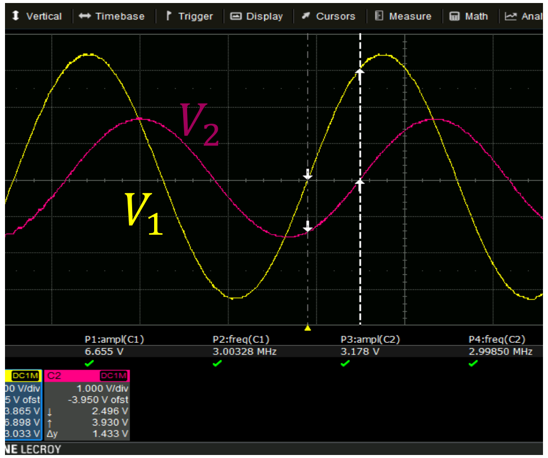
Maxwell-2D setup



	Layer	Material	Thickness [mm]	Relative permittivity
Gas chamber	Gas gap	Gas mixture	1.0	1
	Electrode	Bakelite	1.2	5.2
	Insulator	PET	0.2	3.7
	Extra air layer	Air	0.15	1
Readout panel	Filler	Foam	3.1	1
	Ground panel/Strips	Copper	0.05	N/A

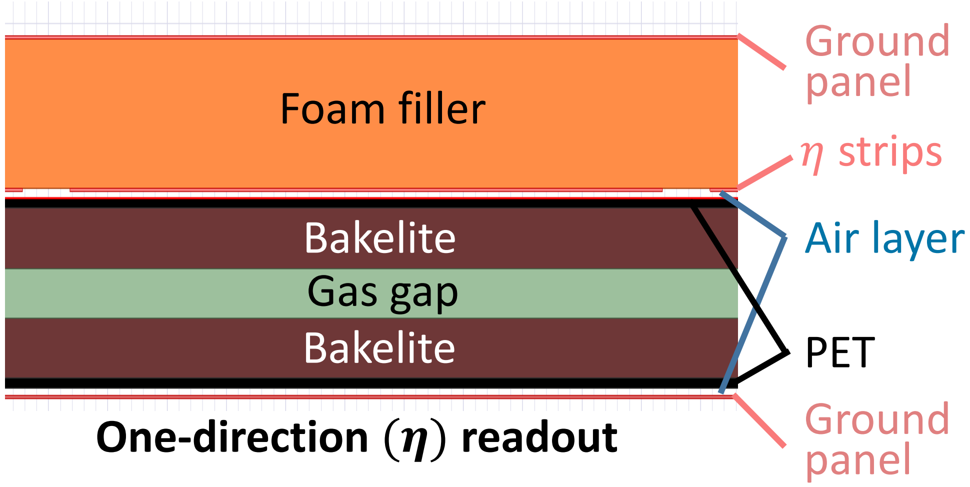






- **Permittivity measurement**
  - Conductor with bakelite medium
  - V_1, V_2 connected to oscilloscope
  - $\Rightarrow \varepsilon_r(bakelite) = 5.2$

Maxwell-2D setup



One-direction (η) readout

	Layer	Material	Thickness [mm]	Relative permittivity
Gas chamber	Gas gap	Gas mixture	1.0	1
	Electrode	Bakelite	1.2	5.2
	Insulator	PET	0.2	3.7
	Extra air layer	Air	0.15	1
Readout panel	Filler	Foam	3.1	1
	Ground panel/Strips	Copper	0.05	N/A

- **Spacer indicator**
  - Thickness: 0.15 mm
  - Air layer between readout strips and gas chamber

Maxwell results: $\hat{C}$; $\hat{L}$; $\hat{Z}$ matrices

- **Simplest case: One-direction $(\boldsymbol{\eta})$ parallel readout**
  - $\hat{C} = \begin{pmatrix} 229.5 & -12.4 & 0 \\ -12.4 & 229.5 & -12.4 \\ 0 & -12.4 & 229.5 \end{pmatrix}$ [pF/m]
  - $\hat{L} = \begin{pmatrix} 153.9 & 5.4 & 0 \\ 5.4 & 153.9 & 5.4 \\ 0 & 5.4 & 153.9 \end{pmatrix}$ [nH/m]
    - Note: $C_{13}, C_{31}, L_{13}, L_{31}$ negligible

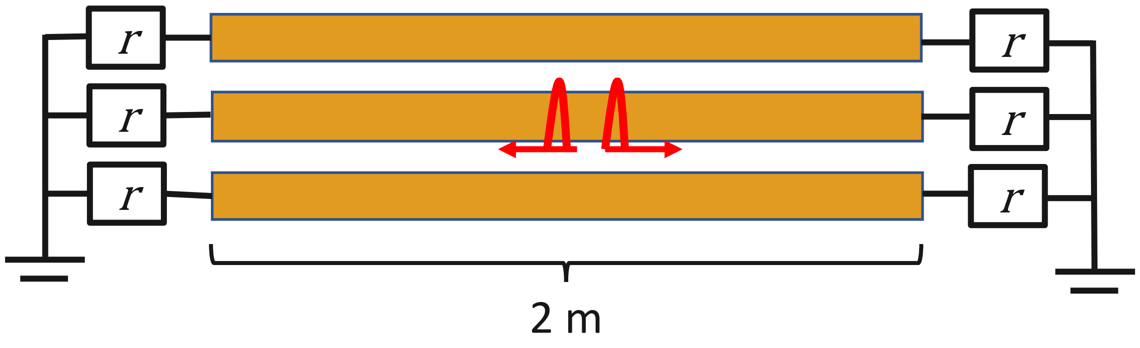
$$\hat{v}^{-2} = \widehat{M}^{-1}\hat{C}\hat{L}\widehat{M} \; ; \; \hat{Z} = \hat{L}\widehat{M}\hat{v}\widehat{M}^{-1}$$

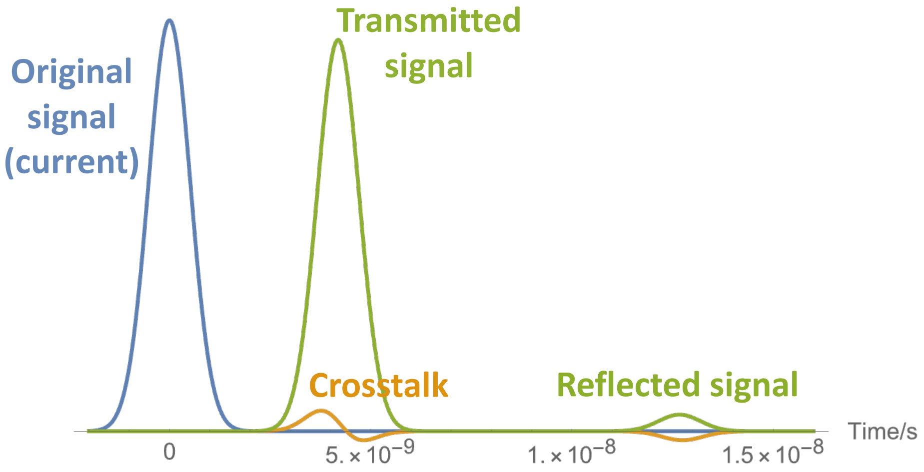
  - $\hat{v} = \begin{pmatrix} 237 & 0 & 0 \\ 0 & 240 & 0 \\ 0 & 0 & 243 \end{pmatrix}$ [mm/ns]
    - $\bar{v} = 240 \text{ mm/ns} \; ; \; \Delta v = 3 \text{ mm/ns}$
  - $\hat{Z} = \begin{pmatrix} 18.3 & 0.8 & 0.04 \\ 0.8 & 18.3 & 0.8 \\ 0.04 & 0.8 & 18.3 \end{pmatrix}$ [Ω]

Counterparts in experiment

- Leading order elements:
  - C_{11} ; $L_{11} \Rightarrow Z_{11}$, impedance
  - Impedance decides matching resistors
    - $\hat{Y} = \hat{Z}^{-1}, \hat{R} = \begin{pmatrix} (\sum_i Y_{1i})^{-1} & \cdots & -(Y_{1N})^{-1} \\ \vdots & \ddots & \vdots \\ -(Y_{N1})^{-1} & \cdots & (\sum_i Y_{Ni})^{-1} \end{pmatrix}$
    - $\hat{R} = \begin{pmatrix} 20 & 400 & 400{,}000 \\ 400 & 20 & 400 \\ 400{,}000 & 400 & 20 \end{pmatrix}$ [Ω]
- Sub-leading order elements:
  - C_{12} ; $L_{12} \Longrightarrow \Delta v$, dispersion
  - Dispersion decides the level of crosstalk

Mathematica results in time-domain





- Example setup:
  - 3 strips, middle strip fired
  - Input 1.22 ns FWHM gaussian pulse
  - Matching resistor $r = 20\ \Omega$ on both ends
  - No guard strips equipped

	Normalized Charge	Normalized Amplitude
Original	1	1
Transmitted	95.6%	95.3%
Crosstalk	0	6.0%
Reflected	4.4%	3.9%

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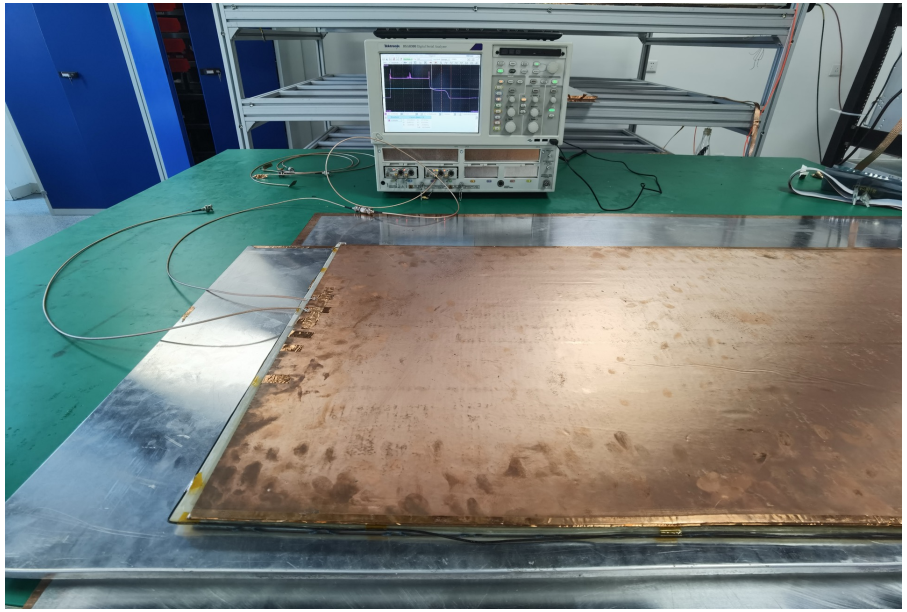
Leading order: impedance measurement

- Device: Tektronix DSA8300
  - As TDR (Time Domain Reflectometry)
- Experiment setup:
  - Thin-gap RPC size: 1 m × 0.5 m
  - Far-end grounded



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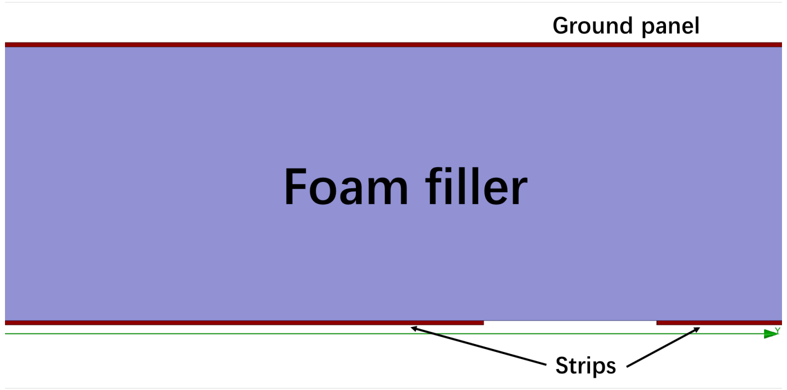
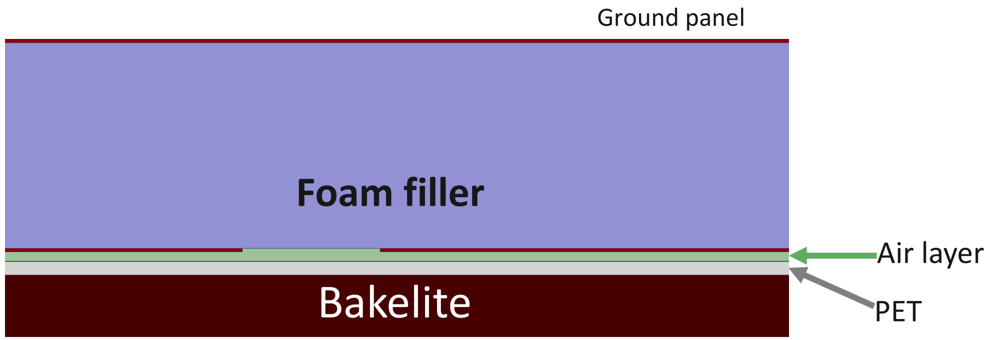
Leading order validation results

- Case 1: bare strip



- Case 2: assembled RPC
  - Only η panel
  - $110\ \mathrm{kg/m^2}$ pressure



Impedance [Ω]	Bare strip	Assembled
Measurement	32.2	18.5
Simulation	32.3	18.3 ± 0.4

✓ Good agreement between simulation & measurement

Sub-leading order: crosstalk & S-parameter

- Crosstalk sensitive to off-diagonal elements

$$\hat{C} = \begin{pmatrix} C_{11} & -C_{12} \\ -C_{21} & C_{22} \end{pmatrix} ; \hat{L} = \begin{pmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{pmatrix}$$

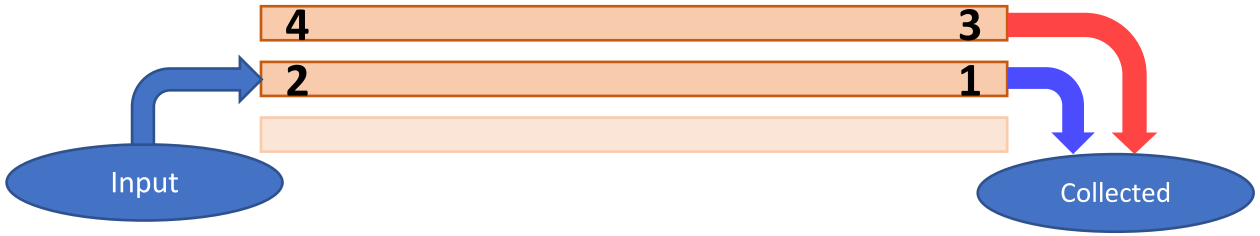
$$C_{12} \ll C_{11} ; L_{12} \ll L_{11} \Rightarrow Z \approx \sqrt{L_{11}/C_{11}}$$

- S-parameter definition:

$$S_{13}(f) = \frac{Amp_3(f)}{Amp_1(f)}$$

  - $Amp_3 \rightarrow$ neibouring strip collected signal
  - $Amp_1 \rightarrow$ fired strip collected signal
  - Note: phase information ignored

- $S_{13}(f)$ represents crosstalk level



- S-parameter property
  - Equals 0 when f << the characteristic frequency f_c of the system
  - Not dependent on signal shape or amplitude
  - Reflection on the fired strip also included in calculation

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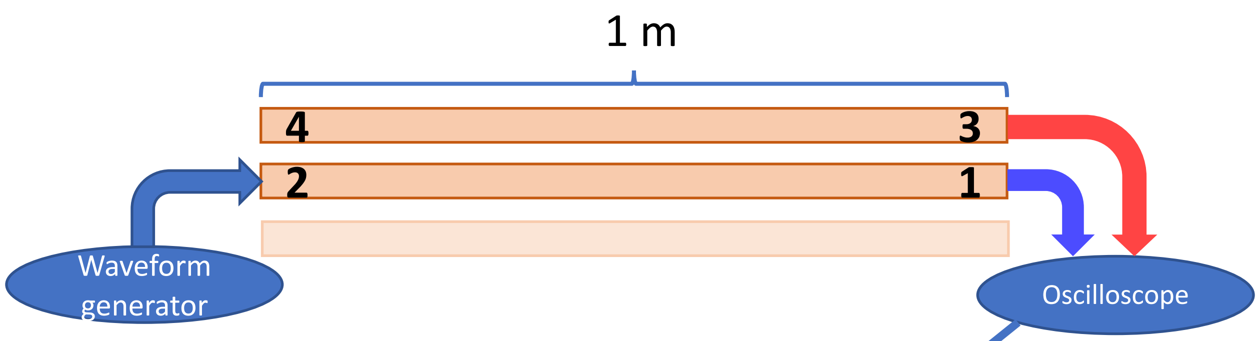
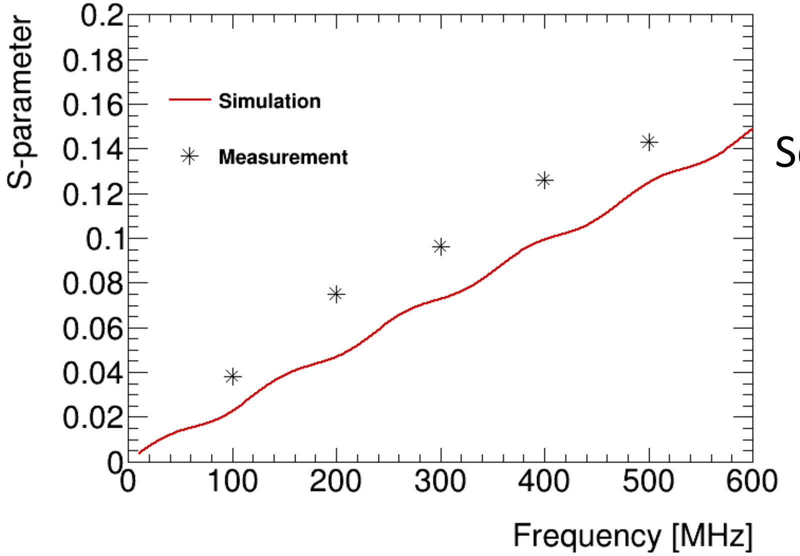
Sub-leading order validation results

- Experiment setup
  - Device:
    - Waveform generator: Tabor WX2182C
    - Oscilloscope: Lecroy 3104z, 1 GHz bandwidth
  - RPC:
    - 1 m × 0.5 m size, only η panel
    - 20 Ω matching resistor
    - 110 $\mathrm{kg/m^2}$ pressure

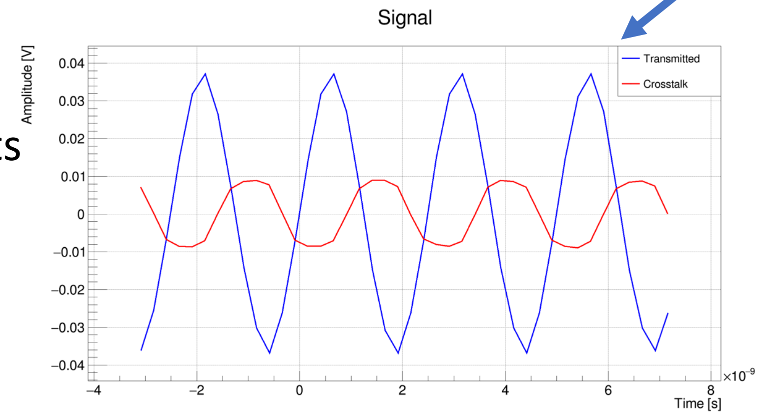


- Results



Measurement and simulation roughly consistent

Scan 5 points



Sinewave fit for Amp_1 and Amp_3

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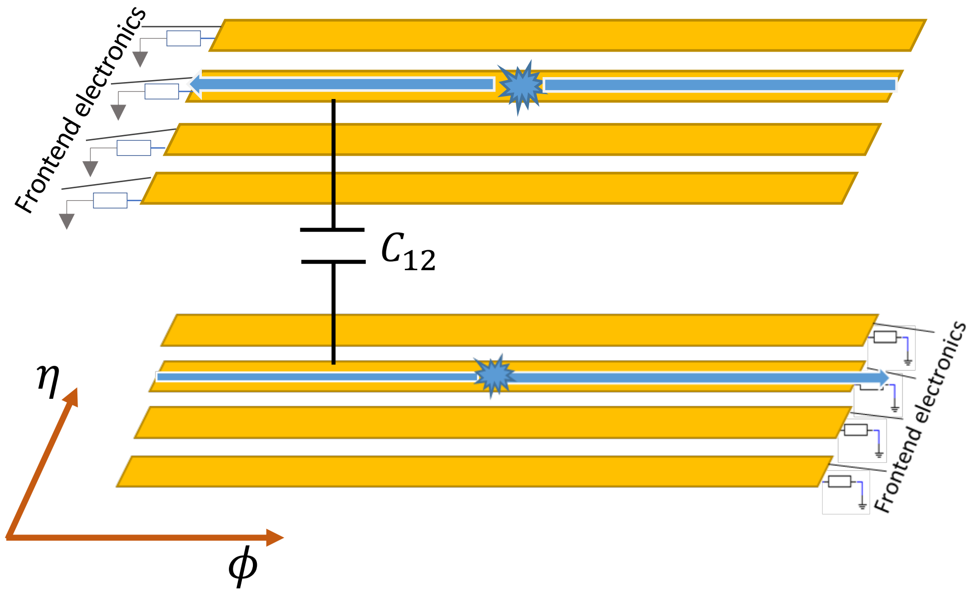
Discussion: $\eta - \eta$ readout

- Potential readout for ATLAS Phase II upgrade
  - From time difference to position
- Capacitance matrix:

$$\hat{C}_{\eta-\eta} = \begin{pmatrix} 228.9 & -115.1 \\ -115.1 & 228.9 \end{pmatrix}$$

  - C_{12}, C_{21}: face-to-face capacitance
- Impedance:

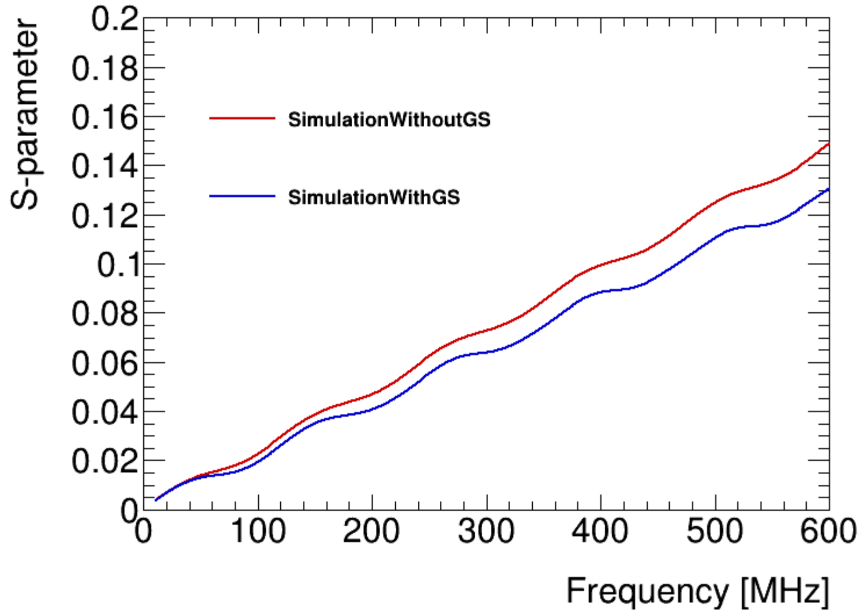


	$\eta - \phi$	$\eta - \eta$
Geometry	Adjacent	Face-to-face
Impedance	$\hat{Z} = \begin{pmatrix} 18.3 & 0.8 \\ 0.8 & 18.3 \end{pmatrix}$	$\hat{Z} = \begin{pmatrix} 22 & 10 \\ 10 & 22 \end{pmatrix}$
Termination network	$\hat{R} = \begin{pmatrix} 20 & 400 \\ 400 & 20 \end{pmatrix}$	$\hat{R} = \begin{pmatrix} 32 & 42 \\ 42 & 32 \end{pmatrix}$

- First order termination would be insufficient

Discussion: different geometry designs

- Guard strip
  - Strip impedance 18.3 Ω, guard strip impedance 100 Ω (simulated)
  - Crosstalk amplitude drops from 6% → 5.1%
    - 1.22 ns FWHM gaussian pulse
    - 1 m transmission distance



✓ *Guard strip slightly reduces crosstalk*

- Pitches and electrode thickness
  - Different pitch (2 mm spacing kept)

Width [mm]	Crosstalk amplitude (no guard strip)	Impedance [Ω]
35	3.8%	14.4
31	4.2%	16.0
27	6.0%	18.3
23	6.8%	21.2
20	7.5%	23.4

  - Bakelite thickness

Thickness [mm]	Crosstalk amplitude (no guard strip)	Impedance [Ω]
1.2	6.0%	18.3
1.4	6.8%	18.7

Summary and outlook

- MTL simulation method and its validation is presented
  - Leading order: simulated impedance agrees with measurement
  - Sub-leading order: S-parameter simulation roughly agrees with measurement
- Suitable for matching resistors selection
- Different readout schemes could be investigated via this method

Backup

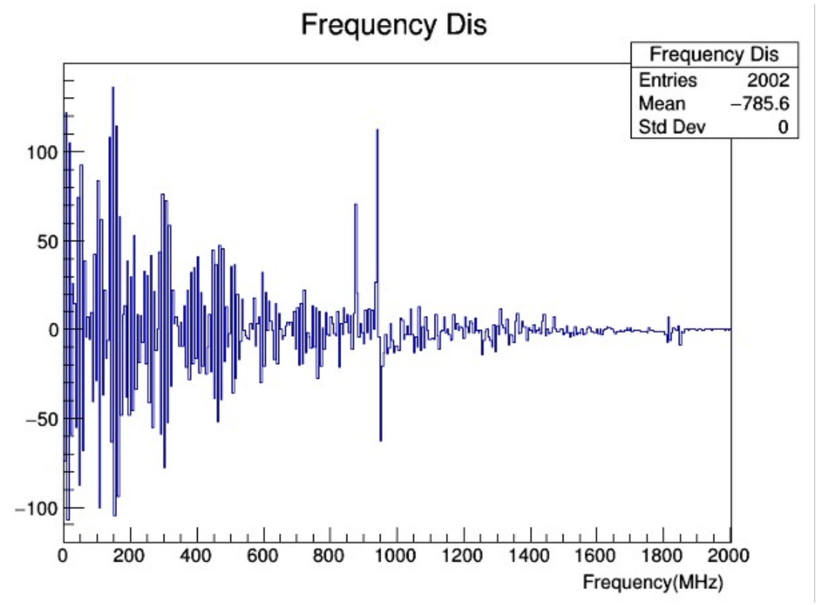
Key reference:

$$\vec{V}_T(t) = \frac{1+\hat{\Gamma}_0}{2}\sum_{j=0}^{\infty}(\hat{\Gamma}_D\hat{\Gamma}_0)^j \left\{ \hat{Z}_c\hat{M}\begin{pmatrix} \hat{M}_{1n}^{-1}I\left(t-\frac{y_0+2jD}{v_1}\right)\\ \vdots \\ \hat{M}_{Nn}^{-1}I\left(t-\frac{y_0+2jD}{v_N}\right)\end{pmatrix} + \hat{\Gamma}_D\hat{Z}_c\hat{M}\begin{pmatrix} \hat{M}_{1n}^{-1}I\left(t-\frac{2(j+1)D-y_0}{v_1}\right)\\ \vdots \\ \hat{M}_{Nn}^{-1}I\left(t-\frac{2(j+1)D-y_0}{v_N}\right)\end{pmatrix}\right\} \qquad (10)$$

Credit: *Signal coupling and signal integrity in multi-strip resistive plate chambers used for timing applications*
Diego Gonzalez-Diaz et al.

where $\vec{V}_T(t)$ is the N-dimensional array of voltages measured by a readout system placed at $y=0$ when the N-strip structure is excited along line n by a current $I(t)$ originated at position $y=y_0$. The sum extends over all j reflections. The reflection matrices at the near-end ($y=0$) and at the far-end ($y=D$) are defined as

$$\Gamma_0 = \frac{\hat{Z}_0-\hat{Z}_c}{\hat{Z}_0+\hat{Z}_c}, \quad \Gamma_D = \frac{\hat{Z}_D-\hat{Z}_c}{\hat{Z}_D+\hat{Z}_c}. \qquad (11)$$



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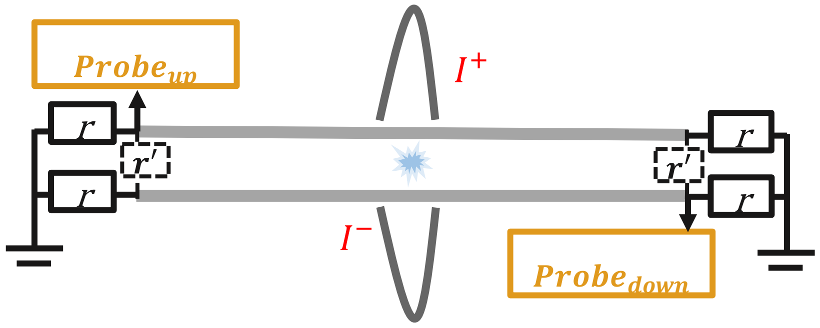
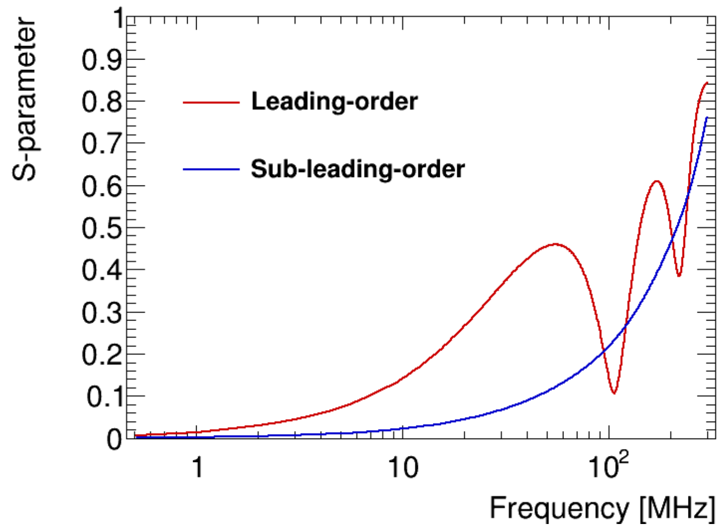
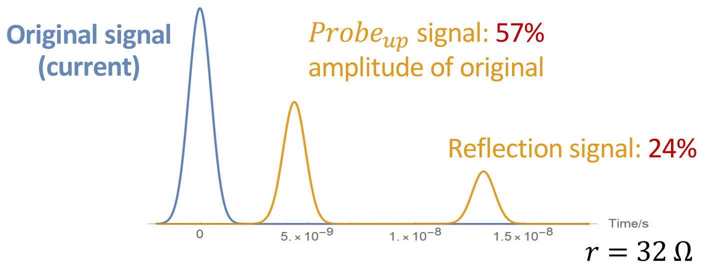
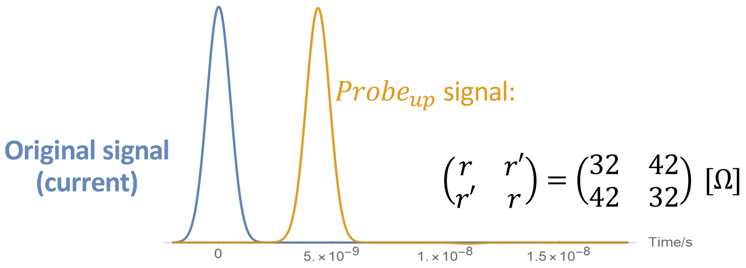
$\eta - \eta$ readout



- S-parameter
  - Characteristic frequency $f_c \cong 100$ MHz
    - Crosstalk is comparable with main signal
  - Ill matching at only leading-order termination
- Countermeasure
  - Include next-to-leading-order termination
    - Connect face-to-face strips with r'
      $r = 32\ \Omega\,; r' = 42\ \Omega$
  - Consider the minus current source on the other strip
    - I^+ and I^- together contribute to the total collected current







$\eta - \phi$ readout

- Pulse signal test
  - 2 ns width pulse from waveform generator
  - 1 m transmission distance
- Results
  - Crosstalk amplitude is about 6.6%
  - $\eta - \phi$ readout crosstalk amplitude is not significantly higher than single η readout
    - Note: the lower limit of the pulse width of this waveform generator is 2 ns
  - $\eta - \phi$ scheme introduces a more complex shape in crosstalk