Low-loss strip-merging extensions for the iRPC chambers

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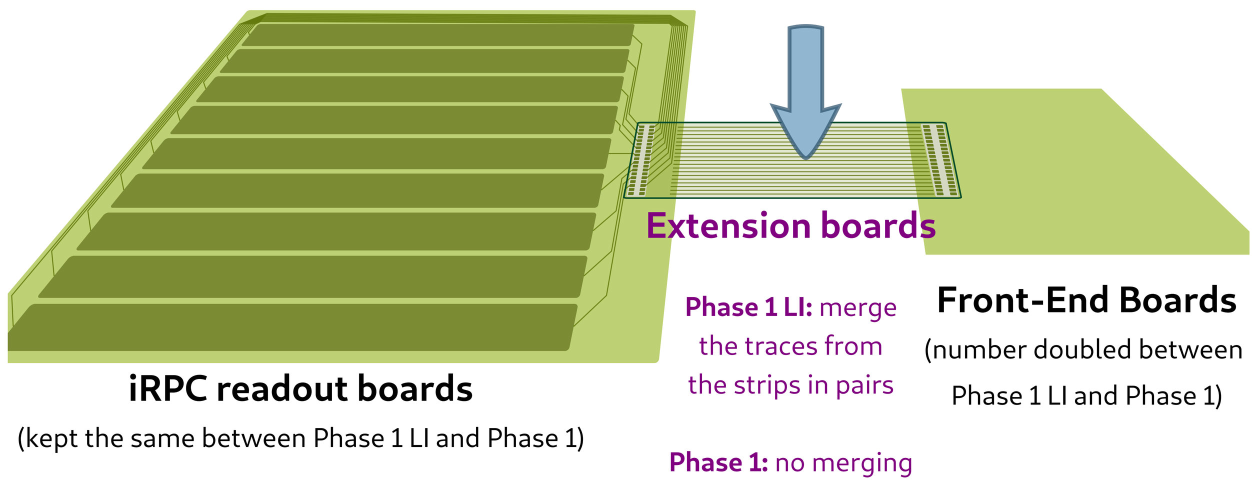
Introduction

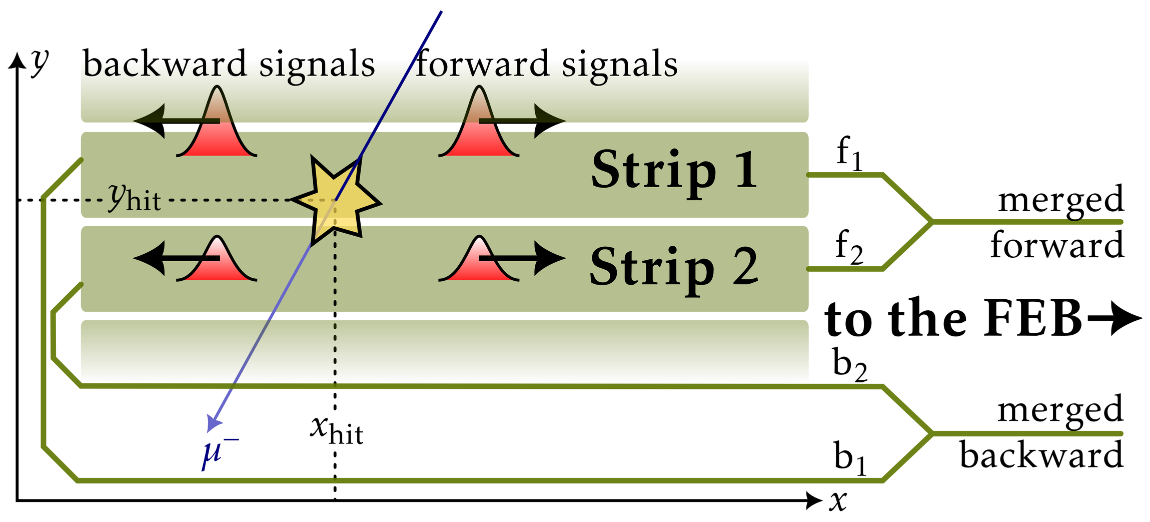
The COMET experiment at J-PARC aims to detect coherent muon-to-electron conversion with a sensitivity of $\mathcal{O}(10^{-15})$ in Phase I (starting 2028). The primary signal is a 105 MeV electron track in a Cylindrical Drift Chamber, while cosmic-ray muons are the dominant background. To reject them, COMET uses a Cosmic Ray Veto (CRV) system with RPC chambers. The CRV's front area faces high neutron and electromagnetic backgrounds (up to 2 kHz/cm^2), complicating cosmic muon identification. We propose using upgraded CMS RPC chambers, featuring pickup strips read out by FPGA-based Front-End Boards (FEBs) — the system's most costly component. To reduce costs, we designed modular extension boards to merge adjacent strips in pairs, enabling a phased FEB production. This poster presents a proof of concept for RPC signal merging, addressing challenges like low signal amplitudes, impulsive signals, noise, and impedance mismatches.

Context: statement of need and potential problems



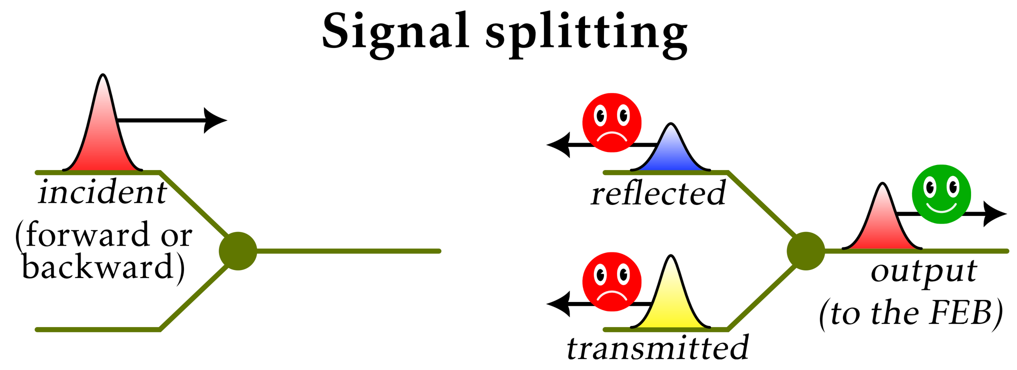
The instantaneous luminosity will triple from COMET Phase I-LI to COMET Phase I. We can start with a lower segmentation and then double the number of channels for COMET Phase I. This implies to:

1. build all RPC modules from the beginning;
2. use fine-segmented readout PCBs from the start;
3. use a **low-cost extension board** that can merge adjacent strips for COMET Phase I–LI, later replaced by a simple extender for Phase I.



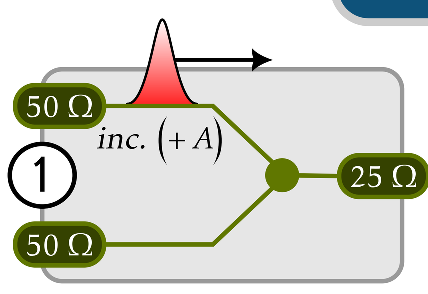
In the chosen iRPC [1], readout signals are collected at both ends of each strip (*forward* & *backward* signals). The T.o.F. difference provides the hit's longitudinal coordinate (x_{hit}), while the strip number directly gives the transverse coordinate (y_{hit}). During Phase I-LI, **extension boards will merge forward and backward signals** from adjacent strips in pairs.

Signal splitting



Merging two input traces into a single output inherently splits the incident signal: only a fraction of each input is forwarded to the FEB, while the remaining portion is reflected back to the input strip and transmitted to the paired strip.
This results in two direct consequences: **insertion loss** and **signal echoes**. This poster demonstrates how we **minimize the former** and **fully suppress the latter**.

Our solution: theory, simulation and board production

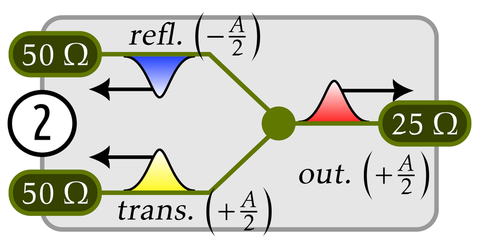


What happens to a signal arriving to the junction from one strip?
Impedance of lines:

$Z_1 = Z_2 = 50\Omega$, $Z_3 = 25\Omega$

Voltage reflection coefficient:

$$\Gamma = \frac{\frac{Z_2 Z_3}{Z_2+Z_3} - Z_1}{\frac{Z_2 Z_3}{Z_2+Z_3} + Z_1} = -\frac{1}{2}$$



Amplitude:

$$\frac{A_{refl.}}{A} = \Gamma = -\frac{1}{2}$$

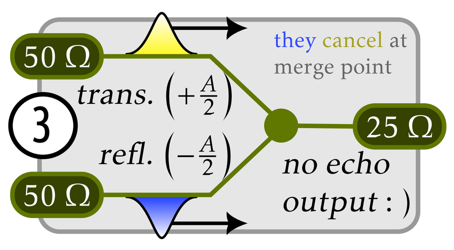
$$\frac{A_{trans.}}{A} = \frac{A_{out}}{A} = 1 + \Gamma = +\frac{1}{2}$$

Power: $P \propto \frac{A^2}{Z}$

$$\frac{P_{refl.}}{P} = \frac{P_{trans.}}{P} = \frac{1}{4}$$

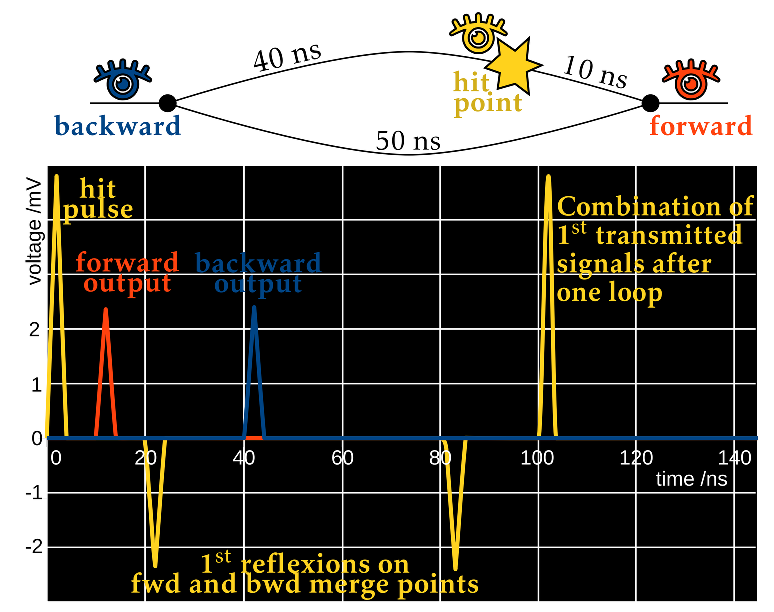
$$\frac{P_{out}}{P} = \frac{1}{2}$$

50% of the power is extracted to the FEB.



What about echoes?

When the reflected signal and the transmitted signal meet again after one loop, they cancel each other exactly because their amplitudes are opposite and they have traveled the same distance.
The echoes are fully suppressed.

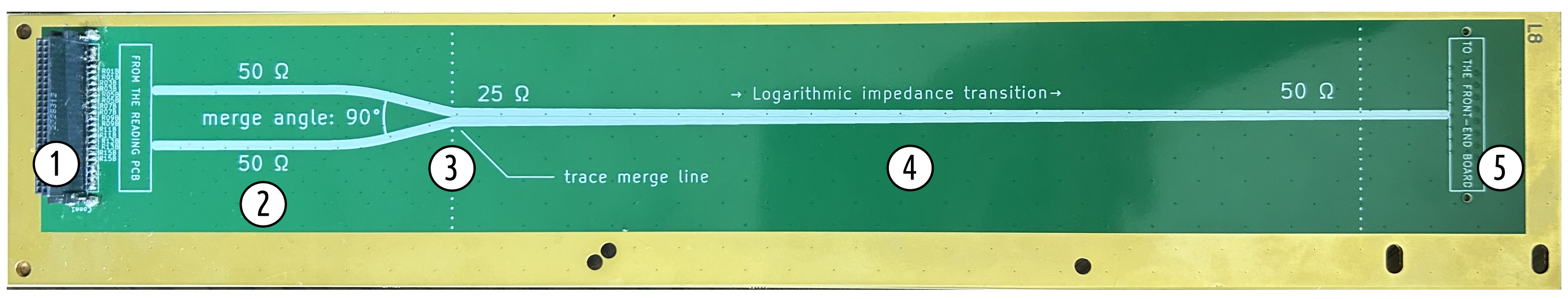


A simulation of the system using `ngspice` shows that a hit produces only one output signal on each side of the strip (blue and red), while echoes of opposite polarities continue to travel along the transmission lines (yellow). When a hit is distributed across two strips, the graph is more complex, but the outcome remains consistent.

kicad–pycbnew

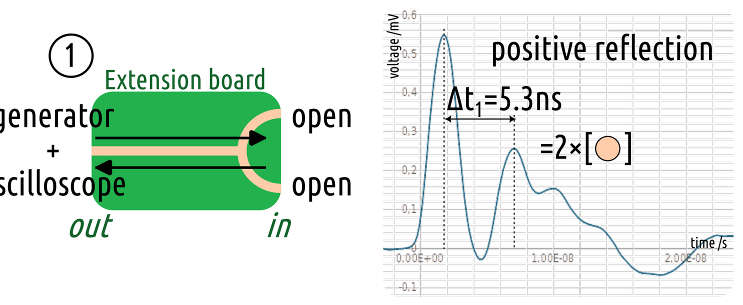
The extension board was designed and generated using `kicad-pycbnew` [2], an open-source Python library enabling fully script-based PCB production. This tool automates the creation of KiCad-compatible `.kicad_pcb` files. For this board, `kicad-pycbnew` allowed precise placement of signal traces, logarithmic impedance transitions,and structured ground via grids, all while ensuring reproducibility and design This approach reduces design time from days to hours, eliminates manual errors, and enables integration into CI/CD workflows, making it ideal for detector electronics and other high-precision applications.

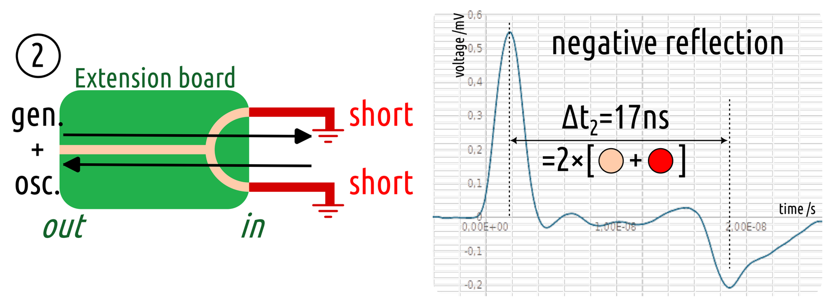
Results

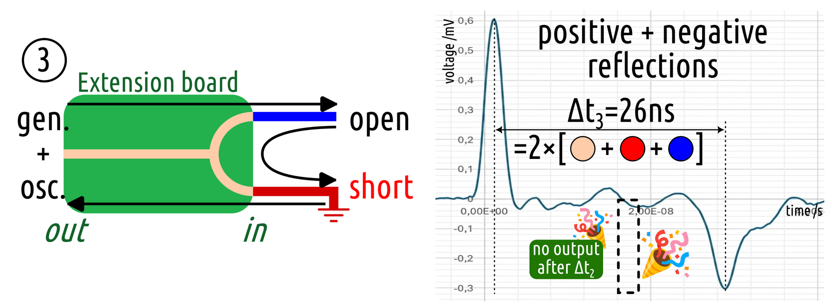


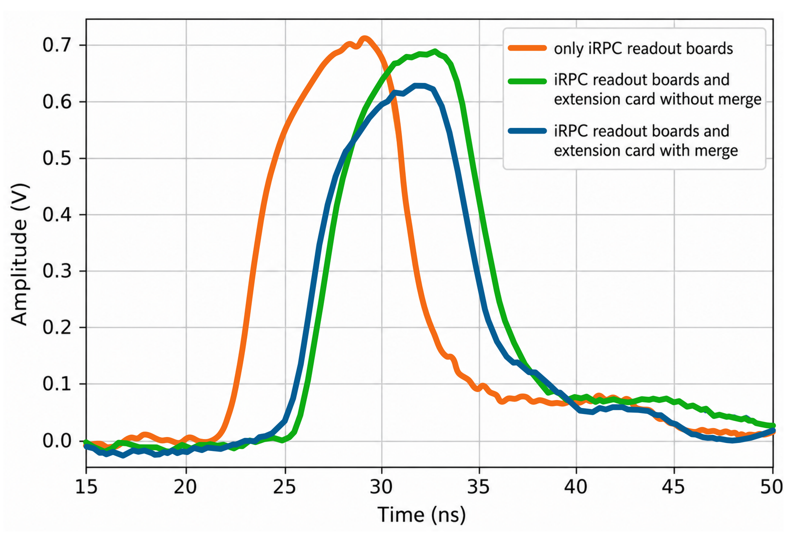
Photograph of the extension board. The Erny connector (1) connects the board to the iRPC: both ends of each iRPC strip are linked to a pin of this connector. (2) the 50 Ω traces run from the connector to the merge points (3), where they are combined in pairs into 25 Ω traces. (4) the impedance of the traces is logarithmically transitioned back to 50 Ω to match the FEB input impedance. The connector (5) (on the back) is intended for connection to the FEB. All traces are stripline-type on internal copper layers, sandwiched between ground planes, enabling precise impedance control and immunity to noise and radiation. A ground via grid minimizes inductive effects and crosstalk.

To validate the signal merging and echo cancellation, the extension board was used in reverse, with the generator connected to the FEB side (merged traces) and the input side (paired traces). Three termination configurations were tested: (1) open/open, (2) short/short, and (3) open/short. Open circuits reflect the signal with preserved polarity, while short circuits reflect it with reversed polarity. The open/short case demonstrates echo cancellation.





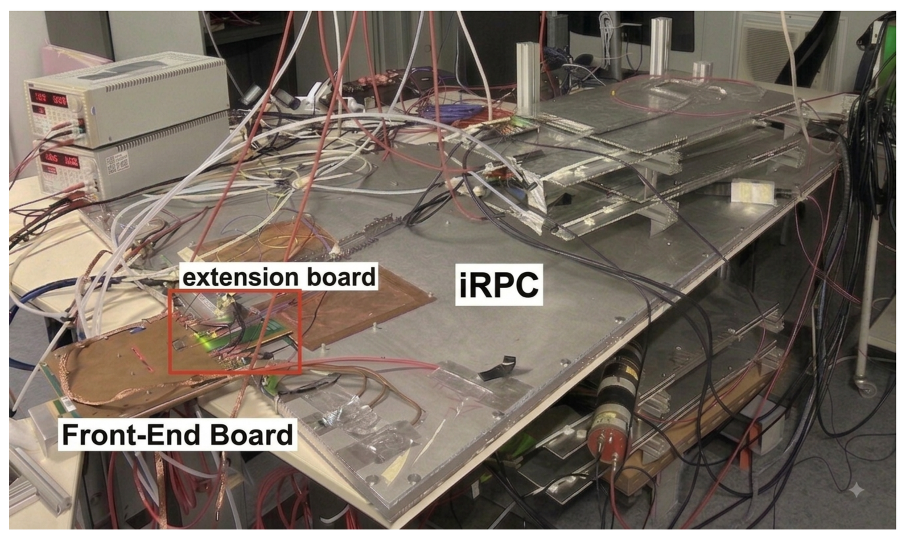




A 1 V pulse was injected into the iRPC readout board,

- without extension board,
- with extension board without merge,
- with extension board with merge.

The signals measured with the readout board alone and with the extension board (without merging) are nearly identical. With the extension board and merging, the maximum signal amplitude decreases by less than 10%, corresponding to an insertion loss of less than 1 dB.



The extension boards were validated using a cosmic telescope and an iRPC chamber. We verified that main parameters don't change if using or not the extension board: noise level and muon detection efficiency.

Conclusion

This work presents a **low-cost, modular solution** for merging RPC strip signals in the COMET experiment's CRV system. By leveraging **impedance-matched logarithmic transitions** and **echo-cancelling topology**, we achieved < 1 **dB insertion loss** and **full suppression of signal echoes**, as validated by both `ngspice` simulations and experimental tests.

The extension boards, designed using **script-based PCB automation** (`kicad-pycbnew`), enable **phased FEB production** while maintaining signal integrity and noise immunity. These results pave the way for **cost-effective, scalable readout electronics** in high-rate environments like COMET Phase I–LI, with potential applications in other detector systems.

[1] J. P. G. Pinheiro, M. A. Shah, M. Gouzevitch, "Improved Resistive Plate Chambers for Phase-II upgrade of the CMS detector in LHC," *Nuclear Instr. and Methods in Phys. Research Sect. A*, 2024. DOI: 10.1016/j.nima.2024.169923
[2] V. Raspal, vinraspa/kicad-pycbnew: kicad-pycbnew (Version v1.0.1) [Computer software], 2026. DOI: 10.5281/zenodo.18924130