Fusion-Inspired Analog Filtering for Prompt Cherenkov Signal Identification in Particle Detectors

1. Motivation

Long-baseline neutrino experiments today aim to determine whether neutrinos violate the charge–parity (CP) symmetry. The sensitivity of these measurements depends on accurately separating electron and muon like events, which requires differentiating the Cherenkov light from the slower scintillation light. The standard process currently is to digitize full waveforms and apply software separation; this creates large data volumes and often requires slow post-processing. We are proposing an analog front-end that enhances the initial signal before digitization. If successful, it could reduce data volume, improve real-time triggering and help future experiments.

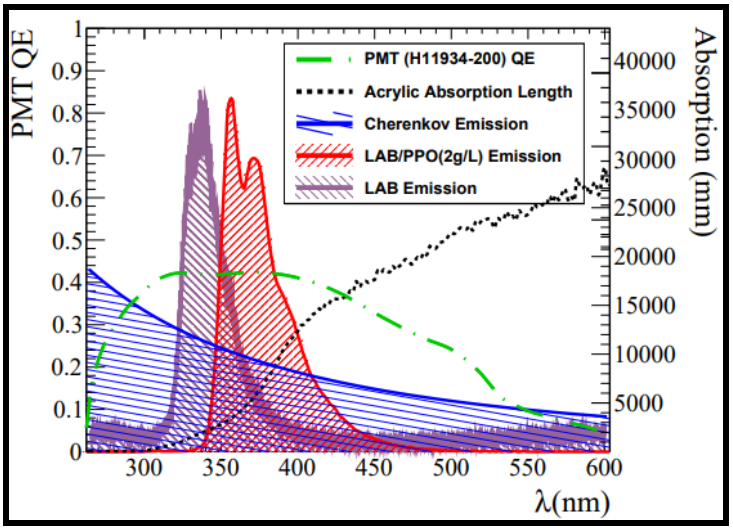

Figure 1. Cherenkov and scintillation emission spectra in LAB-based liquid scintillators with photomultiplier quantum efficiency. Adapted from Caravaca et al., *Phys. Rev. C* 95 (2017).

2. Background

Charged particles travelling faster than light in a medium ($\beta > 1/n$) emit Cherenkov radiation at the angle given by **$\cos \theta_c = 1/(n\beta)$**, where n is the refractive index. In water and water-based liquid scintillators (WbLS), relativistic charged particles emit Cherenkov light in a cone. Scintillation light, produced when molecules de-excite, is isotropic and decays in several nanoseconds. Hybrid detectors attempt to capture light from both sources. Recent technologies demonstrate that photomultipliers and processing can reconstruct Cherenkov rings and achieve time resolutions of ~10–100 ps (Adams et al., 2015). In timing electronics, plasma physicists use RC networks to emphasise the leading edge of a signal and suppress tails. Recent reports show that a RC filter improved the timing resolution of multiplexed SiPMs by ~38% (Bieniosek et al., 2016). For a first-order RC high-pass filter the time constant is **$\tau = RC$**, and the cutoff frequency is **$f_c = 1/(2\pi RC)$**. A notch filter may be used to suppress electrical interference. These circuits are simple, inexpensive, and don't require digitization.

3. Experimental Design

3.1 Detector and Optical Interface

Light from a 10 cm WbLS target will be detected using a fast photodetector capable of sub-nanosecond timing resolution. To reduce the contribution of scintillation, a BG40 optical band-pass filter will be placed between the target and the photodetector. BG40 transmits blue wavelengths where Cherenkov emission is strong while attenuating longer wavelengths to reduce background light.

3.2 Analog Circuit

The central part of the design is a passive RC high-pass filter network that emphasises high-frequency components associated with Cherenkov light. A RC differentiator consists of a coupling capacitor and series resistor. Its transfer function has the form **$V_{out}/V_{in} = (sR_1C_1) / (1 + sR_1C_1)$**, and it attenuates frequencies below **$f_c = 1/(2\pi R_1C_1)$**. For a scintillation decay time of about 5 ns, a time constant of about 1 ns is appropriate. Choosing $R_1 = 50\ \Omega$ and $C_1 = 20$ pF makes τ about 1 ns and f_c about 160 MHz. Cascading two RC stages steepens the slope of the frequency response, providing further suppression of slow components. In practice we will prototype a two-stage network.

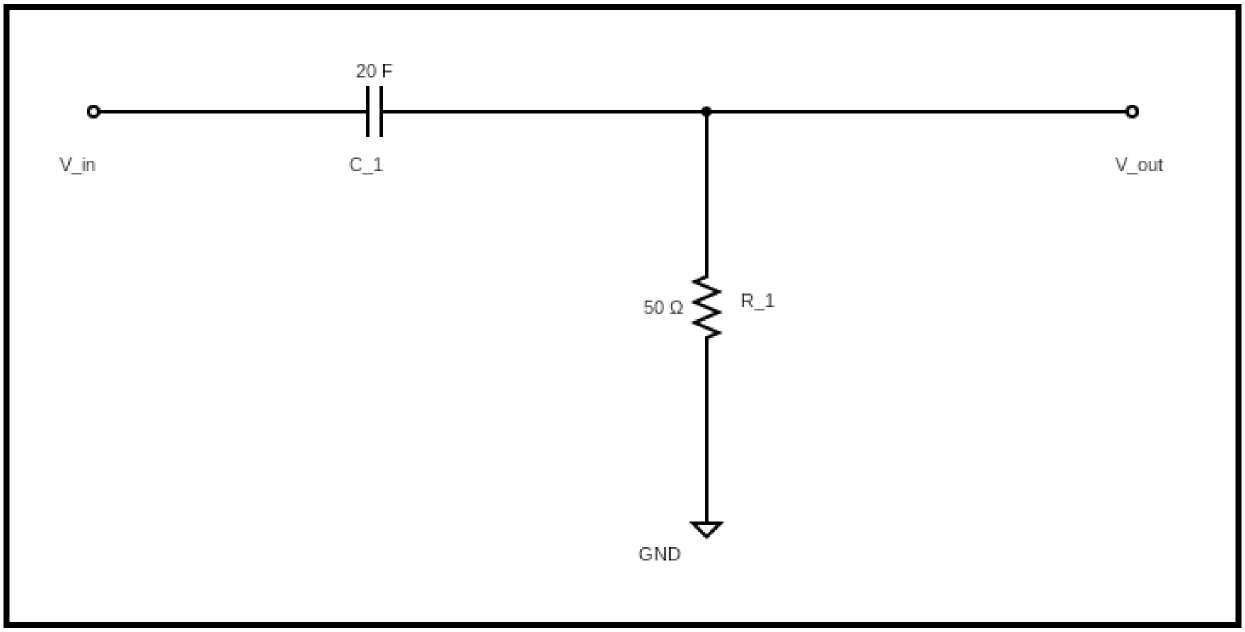

Figure 2. RC high-pass circuit used to emphasize fast signal components. The input signal V_{in} passes through capacitor C_1 and resistor R_1, suppressing scintillation components while preserving the Cherenkov pulse at V_{out}.

3.3 Noise Rejection

To suppress narrowband electrical interference, a twin-T notch filter will be incorporated. A twin-T network places a low-pass section and a high-pass section in parallel; the frequency at which both networks cancel is the notch frequency. For tests we will adjust the notch to reject power-line hum.

Photodetectors have inherent capacitance and dark-current decay times that distort the pulse. By adding a resistor in parallel with the coupling capacitor, we cancel part of the detector's pole; this flattens the baseline after the initial pulse. The parallel resistor will be tuned to match the photodetector's decay constant.

3.4 Data Acquisition and Simulation

The filtered and unfiltered signals will be digitized simultaneously using a fast waveform digitizer (≥1 GS/s). For each event we will measure the rise time, FWHM and the fraction of charge deposited in the first 2 ns. The improvement in initial fraction between the filtered and unfiltered channels will demonstrate the effectiveness of the analog filter in enhancing the Cherenkov-like signal components relative to the slower scintillation components.

We simulated the circuit using LTspice to verify the effectiveness of the RC high-pass network. The photodetector output was represented as a voltage pulse source, and the filter stage was implemented using R = 50 Ω and C = 20 pF, corresponding to our prior calculations where τ = 1ns and the cutoff frequency is around 160 MHz. We found that the filter produces narrow output pulses at the rising and falling edges of the input signal, demonstrating preferential transmission of fast signal components over slower waveform structure.

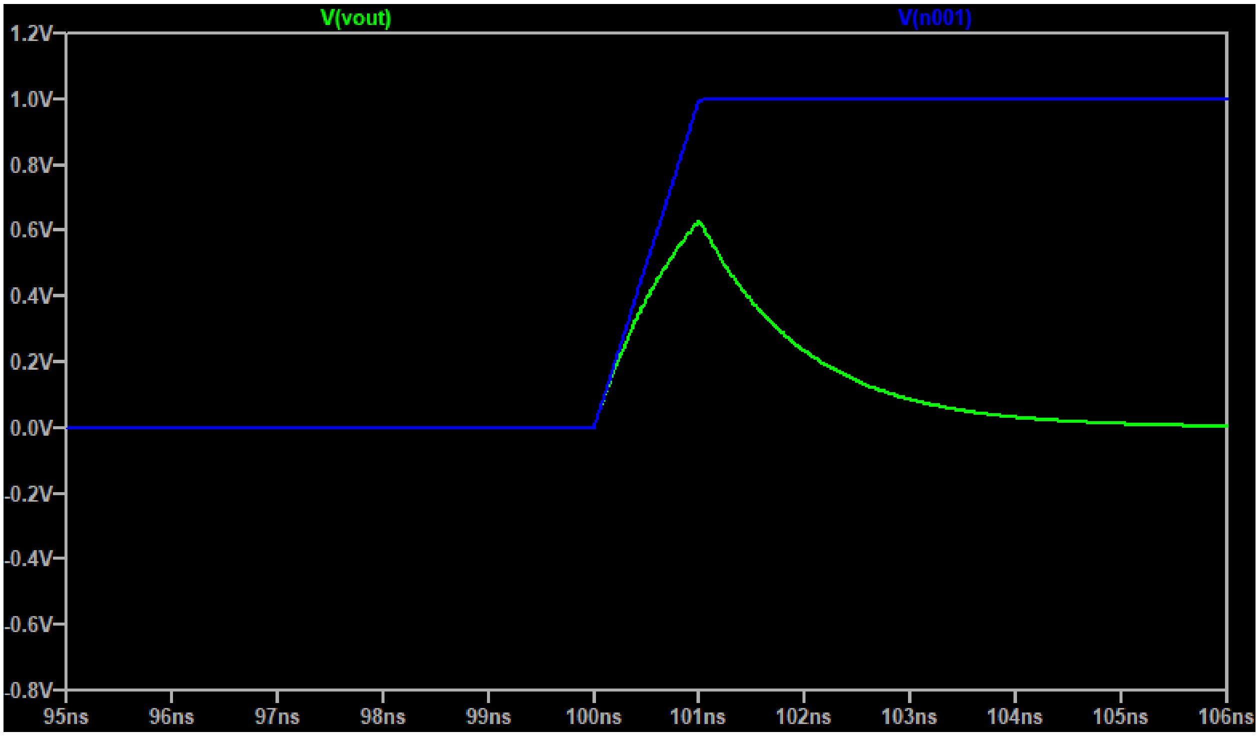

Figure 3. LTspice transient simulation of a 50 Ω–20 pF RC high-pass stage showing the output pulse produced by a fast input transition.

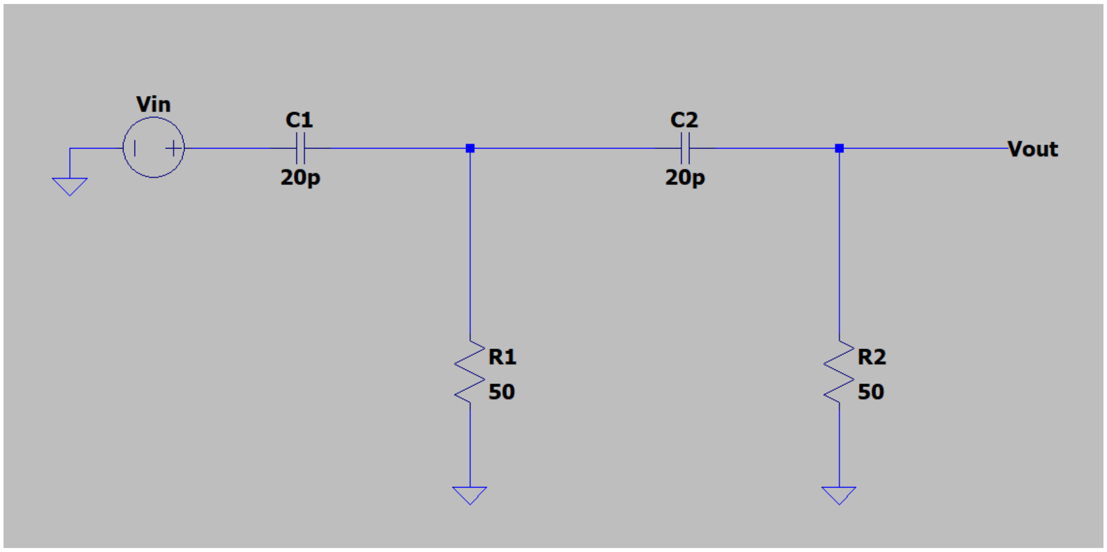

Figure 4. Schematic of the proposed two-stage passive RC high-pass network. Each stage provides a shaping time constant of approximately 1 ns. Cascading the stages increases suppression of slower waveform components while preserving prompt signal structure.

To further illustrate this effect, we simulated a waveform consisting of a fast Cherenkov component and a slower scintillation tail. After passing through the RC high-pass filter, the early part of the signal is enhanced while the slower tail is reduced. This demonstrates that the analog circuit can preferentially preserve early Cherenkov-like light before digitization.

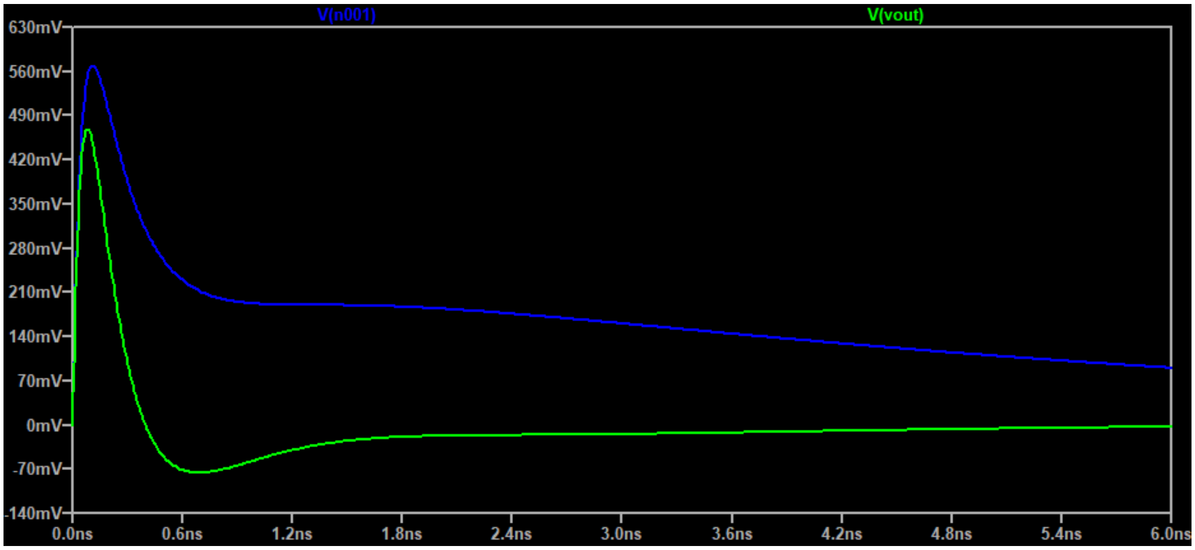

Figure 5. LTspice simulation of the proposed RC high-pass stage. A synthetic detector pulse composed of a prompt component and a slower exponential tail is used as input (blue). The filtered output (green) emphasizes the early prompt structure while suppressing the slower scintillation-like tail.

4. Expected Outcomes

By increasing the ratio of early to delayed light and improving timing resolution, our analog front-end could sharpen the separation of electron and muon events and reduce background. Improved separation leads to more precise oscillation measurements and tighter constraints. The reduced data volume and low latency also make the hardware attractive for high-rate near detectors.

5. Team Statement

We used AI to assist with drafting and organising this proposal; however, the idea itself, all scientific reasoning, design decisions, calculations, and data acquisition were made solely by us.

6. References

Abe, K., et al. "Constraint on the CP-violating phase in neutrino oscillations." *Nature* 580 (2020): 339–344.

Adams, B. W., et al**.** "Timing Characteristics of Large Area Picosecond Photodetectors." *Nuclear Instruments and Methods in Physics Research Section A* 795 (2015): 1–11.

Bieniosek, M. F., et al. "Analog filtering methods improve leading edge timing performance of multiplexed SiPMs." *Physics in Medicine & Biology* 61.16 (2016): N427–N440.

Caravaca, J., et al. "Experiment to demonstrate separation of Cherenkov and scintillation signals." *Physical Review C* 95 (2017): 055801.

Cates, J. W., Choong, W., and Brubaker, E. "Scintillation and Cherenkov photon counting detectors with analog SiPMs for TOF-PET." *Physics in Medicine & Biology* 69.4 (2024).

Easo, S. "Cherenkov detectors and particle identification." CERN HighRR lecture notes (2022).

Horowitz, P., and Hill, W. The Art of Electronics. 3rd ed., Cambridge University Press, 2015.

Kaptanoglu, T., et al. “Spectral photon sorting for large-scale Cherenkov and scintillation detectors." *Journal of Instrumentation* 15 (2020): P04009.

DUNE Collaboration. Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report. 2020.

Analog Devices. “LTspice® Simulator." Analog Devices, Inc., 2023.