Improvements in the NOvA Detector Simulation based on JINR stand measurements

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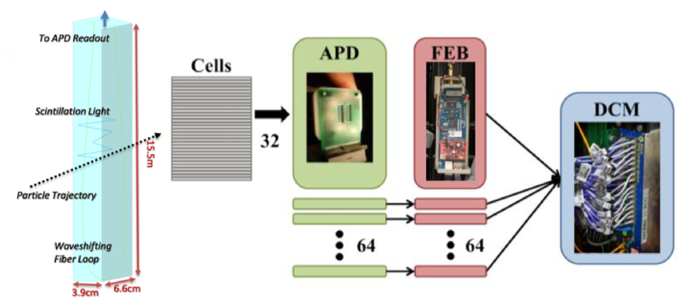
NOvA Detectors

NOvA is a long-baseline neutrino experiment aiming to study neutrino oscillation phenomenon in the muon neutrino beam from the NuMI complex at Fermilab (USA). Two identical detectors have been built to measure the initial neutrino flux spectra at the near site and the oscillated result at a 810 km distance, which significantly reduces many systematic uncertainties. To improve electron neutrino and neutral current interaction separation, the detector is constructed as a finely segmented structure filled with liquid scintillator.



- Light is generated by charged particles and collected by Wave-Length Shifting (WLS) fiber
- Each Avalanche PhotoDiode (APD) reads out 32 cells
- APD is connected to a Front-End Board (FEB)
- The FEB digitizes signal, sends it to a Data Concentrator Module (DCM)
- Each DCM can read 64 FEBs.

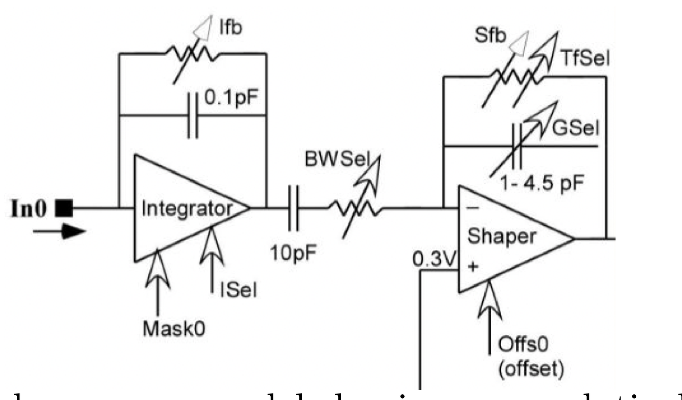
NOvA Simulation

All steps, described previously in the paper[a], to simulate neutrino events and background simulation include several well-known packages to make energy spectra of the neutrino flux (GEANT simulation, including MINERvA data driven corrections), to generate neutrino events (GENIE) and cosmic ray muons (CRY), to propagate particles through the detector and to produce energy deposits in the materials (GEANT). While GEANT4 is capable of simulating optical photon processes, generating scintillation light and propagating it through the cell, up the fiber, and to the APD is very time consuming. Instead, NOvA has its own routines for the processes in the detectors with a simulation chain as shown on the picture on top.

[a] A. Aurisano et al., The NOvA simulation chain, J. Phys.: Conf. Ser. 664, 072002 (2016).

Simulation tunes based on electronic test stand measurements

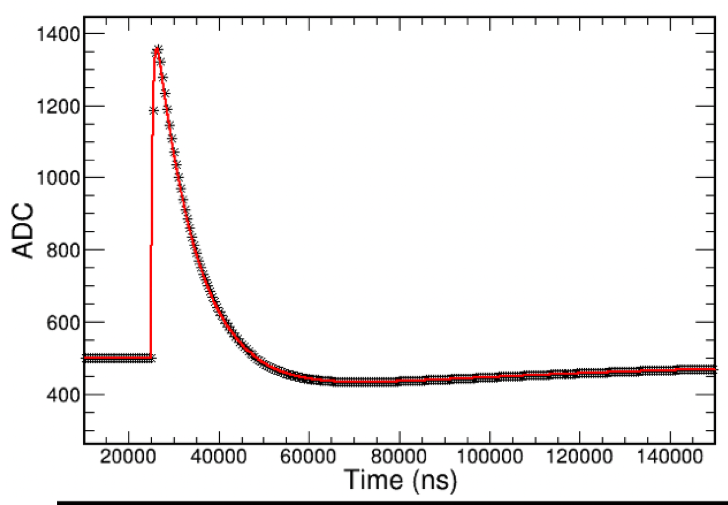
The electron pulse produced by the APD in response to incoming scintillation photons is next processed by an ASIC. The pulse-shaping circuit within the ASIC consists of a preamplifier, which integrates the charge produced by the APD, and a CR-RC circuit that produces a pulse with a fast rise time controlled by an integrator unit and a slow fall time controlled by a differentiator unit.

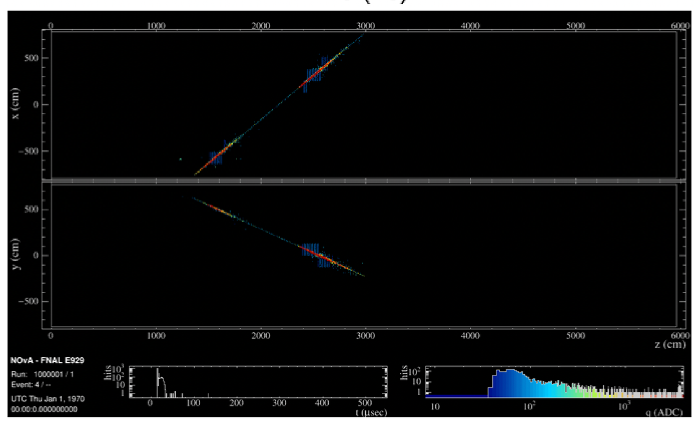


In the first analysis, the preamplifier was neglected and the shaper was modeled using an analytical solution of the response of the CR-RC circuit to a unit charge impulse. However, during the design of the ASIC it was noted that the fall time of the CR-RC circuit varied as a function of the magnitude of the input. Later, it was shown on the JINR test stand that the fall time scaled linearly with the number of incident photoelectrons. A new form includes pulse shaping with preamplifier effect.

$$f(t)=\frac{F}{F-R}\left(e^{-(t-t_0)/F}-e^{-(t-t_0)/R}\right) \Rightarrow f(t)=IF\left(\frac{e^{-(t-t_0)/F}}{(I-F)(F-R)}-\frac{e^{-(t-t_0)/I}}{(I-F)(I-R)}+\frac{e^{-(t-t_0)/R}}{(I-R)(R-F)}\right)$$

where R, F are rise and fall times, I is time scale over which photoelectrons should be integrated to determine how the fall time should vary, and F is varied over the time shift as an additional linear component F_m to the F_0.





A comparison of the output numerically integrating the preamplifier and shaper circuit equations with the analytical solution of the response of the circuit to a delta function impulse. Due to the modeling of the preamplifier, the circuit output undershoots the original baseline after many fall times.

The "Sag" effect was implemented into the simulation in 2016 in case the total amount of light captured by all pixels of an APD exceeds 5000 ADC in any given 15 ns window. Final traces are computed for pixels in all the 32 APD channels. This models the FEB flashing behavior seen in data when high energy cosmic rays traverse the detector.

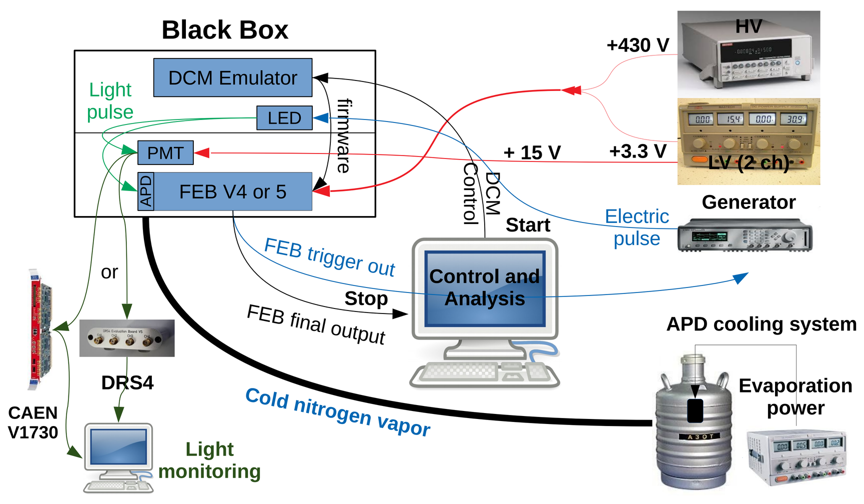
An event display showing a simulated 1 TeV muon traversing the Far Detector after allowing for FEB flashing behavior. The block-shaped regions along the track show points where enough light was captured by the APD to produce saged traces capable of generating triggered hits on every pixel of the APD.

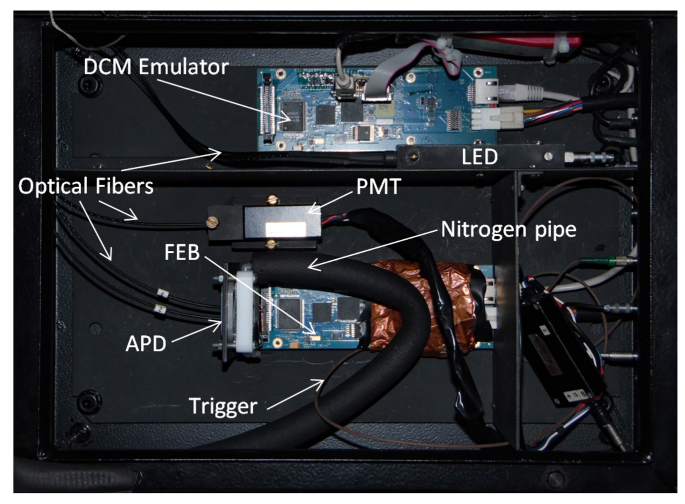
Summary

Two test stands have been built in JINR (Dubna, Russia) to measure the proton light response of NOvA scintillator and the electronic signal shaping of the NOvA front-end electronics. The parameters measured using these test stands have been implemented in the custom NOvA simulation chain. Further improvements are possible with detailed studies on Cherenkov light at a new test stand and more straightforward with running the NOvA test beam program providing tagged electron, muon, pion, and proton beams, which will enable a detailed understanding of the detector's muon energy scale, electromagnetic and hadronic response, in addition to providing real data for the detailed study of particle identification techniques.

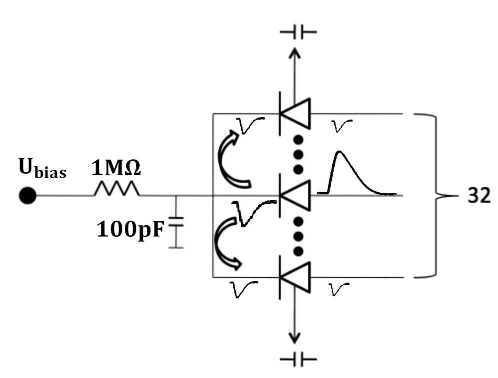
NOvA electronics test @ JINR

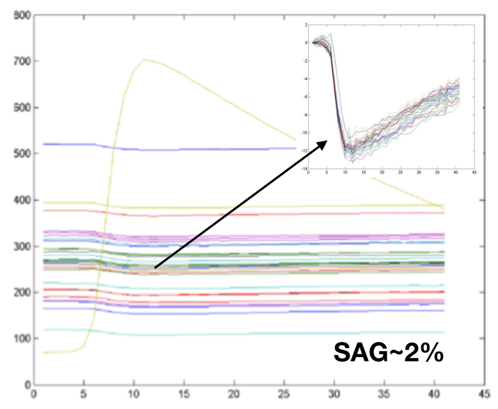
First test stand based on the native NOvA FEB reads out 32 APDs sitting on a single PCB. General readout of NOvA's FEB is carried out by a DCM emulator, which is another FEB with modified firmware and an additional interface board for remote control by a computer node. A green LED (λ = 505 nm) is supplied by the pulse generator (Agilent 81104A) produces light flashes with a broad range of amplitudes and widths. To deliver light to the APD sensor an optical fiber splitter is used with monitoring by a fast PMT (Hamamatsu R6780) at one end of the splitter. To provide a real APD environment with negative (-15 °C) temperatures we use cold nitrogen flow evaporated from a cryostat. The APD board is biased by a precise Keythley 6487/E power supply.

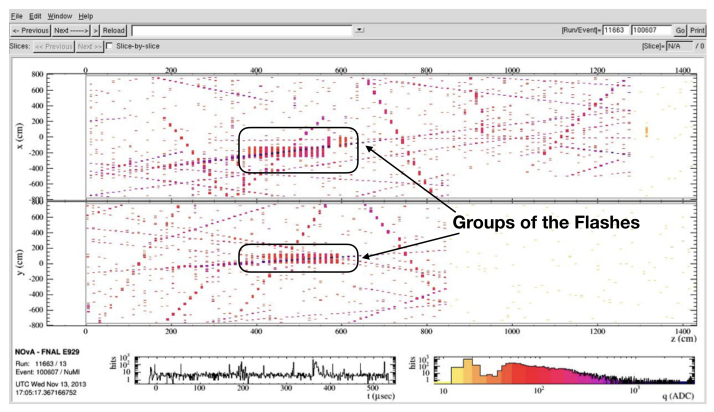




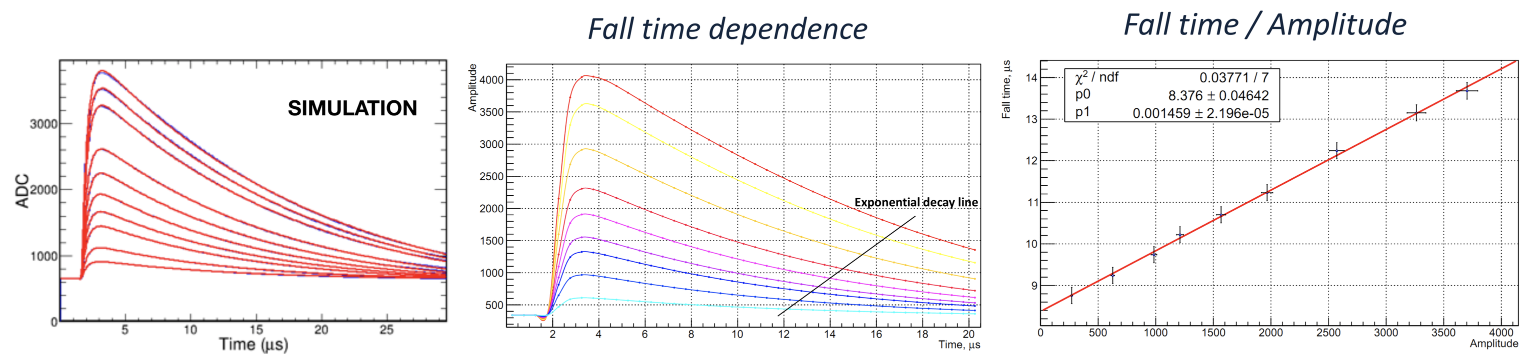
Our studies show the existence of "cross-talk" between APD channels. When one APD breaks down it produces a voltage drop on the entire PCB, which passes trough the capacitance of all other APDs. This effect was dubbed "Sag", and in NOvA's case has a contribution of $\sim 2\%$. This effect has no impact on beam neutrino events and might need special consideration only for high energy dissipation (exotics, cosmics). For high energy events it can trigger all 32 channels simultaneously - "Flash" effect.





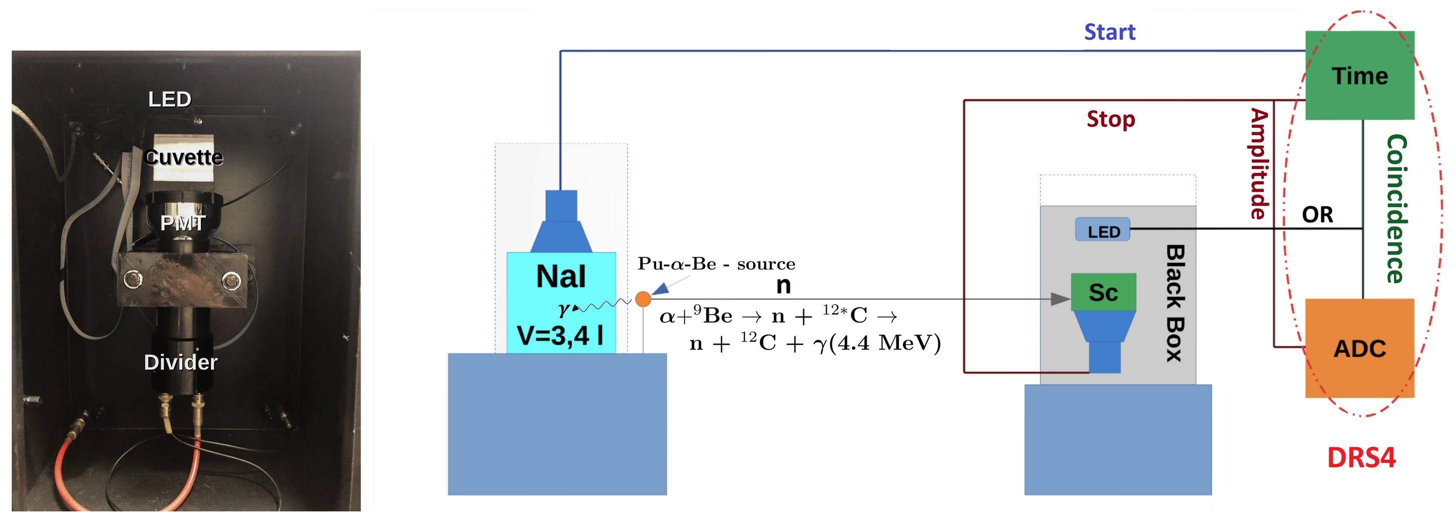


A signal pulse produced at ASIC output is expected to be of constant shape. It was shown that electronics work as integration circuit increasing fall time of the signal with respect to initial amplitude.

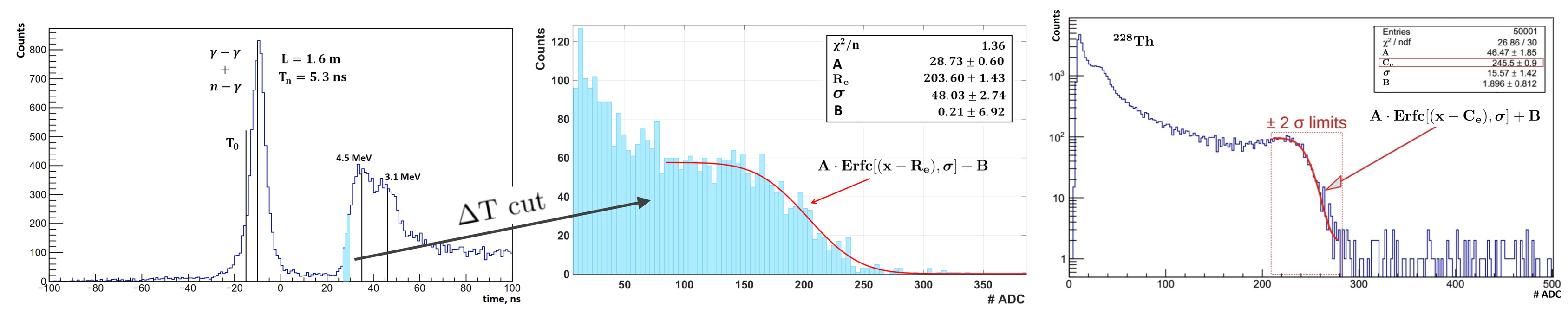


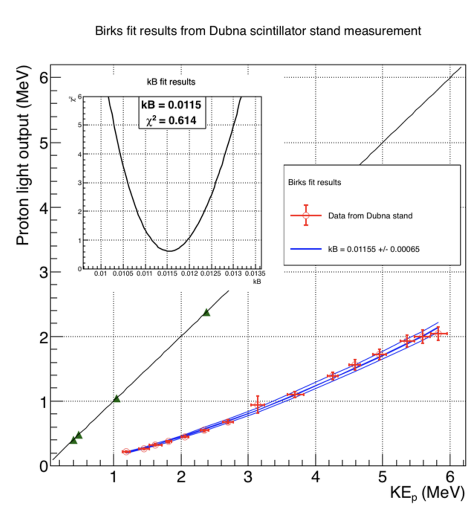
NOvA scintillator studies @ JINR

To measure proton response in the NOvA LS we used the Neutron time-of-flight (TOF) technique. A neutron is produced by an isotope PuBe-source simultaneously with γ-quantum, which triggers the start counter (NaI-crystal). The neutron produces a recoil proton in the LS sample in transparent cuvette read out by a PMT, which generates the stop signal.



By measuring the neutron's TOF (length) one can obtain its real energy. We use edge at recoil proton spectrum as a maximum transferred energy from the neutron ($E_p = E_n$). Response from protons was calibrated with respect to γ-sources (^{137}Cs, ^{60}Co, ^{228}Th) assuming negligible quenching effect for fast electrons (Compton spectrum edge).





Data were analysed by using NOvA simulation software based on GEANT deposit energies and custom simulation for light output. The Birks coefficient is

$$\mathbf{k_B = (1.155 \pm 0.065) \cdot 10^{-2} \left[\frac{g}{MeV \cdot cm^2}\right]}$$

Calculations were cross-checked by numerical integration using NIST tables accounting for NOvA LS composition

$$k_B = (1.13 \pm 0.07) \cdot 10^{-2} \left[\frac{g}{MeV \cdot cm^2}\right]$$

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