Proceedings of the 27th International Symposium Nuclear Electronics and Computing (NEC'2019)
Budva, Becici, Montenegro, September 30 – October 4, 2019

IMPROVEMENTS IN THE NOVA DETECTOR SIMULATION BASED ON JINR STAND MEASUREMENTS

O.B. Samoylov[a], N.V. Anfimov, A.I. Antoshkin, A.P. Sotnikov

Joint Institute for Nuclear Research, 6 Jolio-Curie st., Dubna, 141980, Russia

E-mail: [a]samoylov@jinr.ru

NOvA [1] is a long-baseline neutrino experiment aiming to study neutrino oscillation phenomenon in the muon neutrino beam from complex NuMI at Fermilab (USA). Two identical detectors have been built to measure the initial neutrino flux spectra at the near site and the oscillated one 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. Charged particles lose their energy in the detector materials, producing light signal in a cell which are recorded by readout electronics. The simulation models this using the following chain: a parameterized front-end simulation converts all energy deposits in active material into scintillation light, the scintillation light is transported through an optical fiber to an avalanche photodiode, and the readout electronics simulation models the shaping, digitization, and triggering on the response of the photodiode. 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-board. The parameters measured using these test stands have been implemented in the custom NOvA simulation chain.

Keywords: liquid scintillator, detector electronics

Oleg Samoylov, Nikolay Anfimov, Alexander Antoshkin, Albert Sotnikov

1. NOvA Experiment

By observing both the disappearance of the muon (anti)neutrinos and appearance of the electron (anti)neutrinos in the beam, NOvA can impose constraints on the yet undetermined parameters of the neutrino oscillation phenomenon, such as the neutrino mass ordering, CP violation and the octant of the large mixing angle. NOvA also studies the neutral-current neutrino interactions by extending its scope beyond the standard three-flavor paradigm. The latest NOvA measurement was published in the paper [2].

2. NOvA Detectors

NOvA detectors with an active volume of 65% collect as much light as possible using the long-wavelength shifting fibers. Then the light is read out by using avalanche photodiodes (APDs). The detectors are made of long strips of PVC cells with the cross-section of 4 cm x 6 cm filled with a liquid scintillator. These cells are located next to each other to build the readout planes. To provide three-dimensional reconstruction of physical interactions, each consecutive plane is located orthogonally relative to the previous one. The NOvA near detector is smaller than the far detector, since it is close to the NuMI beam with the volume of 4 x 4 x 15 m^3. The NOvA far detector is considerably larger, 14 kilotons, with the volume of 15.6 x 15.6 x 60 m^3. There are 896 individual planes containing 344,064 individual channels in the NOvA far detector.

3. NOvA Simulation

All steps to simulate the neutrino events and the background simulation, described previously in the paper [3], include several well-known packages. The energy spectra of the neutrino flux are performed by the GEANT simulation, including the MINERvA data driven corrections. The neutrino events are generated by GENIE and the cosmic ray muons are produced by CRY. Moreover, the latest results are based on the overlay sample with the collected cosmic muon data. Afterwards, GEANT propagates the particles through the detector where they produce their energy deposits in the detector materials.

Though GEANT4 is capable to simulate the optical photon processes, to generate the scintillation light and to propagate it through the cell, up the fiber, and to the APD, it is very time consuming. Instead, NOvA has its own routines for the above-mentioned processes in the detectors with a simulation chain.

4. Test Stands at JINR

The two test stands were built at JINR (Dubna, Russia) to measure the proton light response of the NOvA scintillator and the electronic signal shaping of the NOvA front-end electronics. The parameters measured by using these test stands were implemented in the custom NOvA simulation chain.

4.1. NOvA Scintillator Studies

To measure the proton response in the NOvA liquid scintillator [4], we used the neutron time-of-flight technique (TOF). A neutron is produced by an isotope PuBe-source and occurs simultaneously with a gamma-quantum, which triggers at the same time the start counter (NaI-crystal). The neutron produces a recoil proton in the liquid scintillator sample in the transparent cuvette, read out by a PMT, which generates the stop signal. This technique was previously used within the linear alkybenzene (LAB) scintillator studies [5].

By measuring the neutron's TOF (2 m distance from the source), one can obtain its real energy. We use the edge at the recoil proton spectrum as a maximum of the transferred energy from a neutron ($E_p = E_n$). The response from the protons was calibrated with respect to the following gamma-sources: ^{137}Cs, ^{60}Co, ^{228}Th; assuming the negligible quenching effect for the fast electrons (Compton spectrum edge).

The data were analyzed by using the NOvA simulation software based on the GEANT deposit energies and custom simulation for the light output. The Birks coefficient is $k_B = (1.155 \pm 0.065) \cdot 10^{-2}$ g/(MeV cm^2). The calculations were cross-checked by the numerical integration using the NIST tables accounting for the NOvA scintillator composition, $k_B = (1.13 \pm 0.07) \cdot 10^{-2}$ g/(MeV cm^2).

4.2. NOvA Electronics Tests

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

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

The signal pulse produced at the ASIC output is expected to be of the constant shape. It was shown that the electronics works as an integration circuit increasing fall time of the signal with respect to the initial amplitude. Our studies show the existence of the "cross-talk" between the APD channels. Another effect was observed when one APD channel breaks down. In this instance, it causes a voltage drop on the entire PCB, which passes through the capacitance of all other APDs. This effect was dubbed "Sag", and in NOvA's case has a contribution of about 2%. This effect has no impact on the beam neutrino events and might need special consideration only for the high energy dissipation (exotics, cosmics). For the high energy events it can trigger "Flash" effect in all 32 channels simultaneously. All the effects are included in the simulation.

5. Future Plans

The parameters measured by using these test stands were 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 the running NOvA test beam program providing tagged the beams of electrons, muons, pions, and protons, which will enable the detailed understanding of the detector's muon energy scale, electromagnetic and hadronic response, and, in addition, provide the real data for the detailed study of the particle identification techniques.

6. Acknowledgements

We gratefully thank A.Aurisano, N.Felt, D.M.Kaplan, M.D.Messier, A.G.Olshevskiy, R.D.Rechenmacher, P.Shanahan, R.J.Tesarek for the initiation of this work, arrangements, help and valuable discussions. We very appreciate the technical support during the liquid scintillator measurements by our JINR colleagues from the Radio-Chemical Laboratory: V.G. Egorov, S.V. Kazartcev and V.B. Brudanin.

The research is supported by the grant of the Russian Science Foundation (project № 18-12-00271).

References

[1] D. S. Ayres et al. [NOvA Coll], "NOvA: Proposal to Build a 30 Kiloton Off-Axis Detector to Study nu_mu to _nu_e Oscillations in the NuMI Beamline," hep-ex/0503053.

[2] M. A. Acero et al. [NOvA Coll], "First Measurement of Neutrino Oscillation Parameters using Neutrinos and Antineutrinos by NOvA," Phys. Rev. Lett. 123, no. 15, 151803 (2019) doi:10.1103/PhysRevLett.123.151803 arXiv:1906.04907 [hep-ex].

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

[4] S. Mufson et al., Liquid scintillator production for the NOvA experiment, Nucl.Instrum.Meth. A799 (2015) 1-9, doi: 10.1016/j.nima.2015.07.026, arXiv:1504.04035 [physics.ins-det].

[5] B. von Krosigk, L. Neumann, R. Nolte, S. Rottger, K. Zuber. Measurement of the proton light response of various LAB based scintillators and its implication for supernova neutrino detection via neutrino-proton scattering. Eur.Phys.J. C73 (2013) no.4, 2390.