Development and Design of New Detector of Unusual Cosmic-ray casKades

By: Dmitriy Beznosko
For DUCK Collaboration

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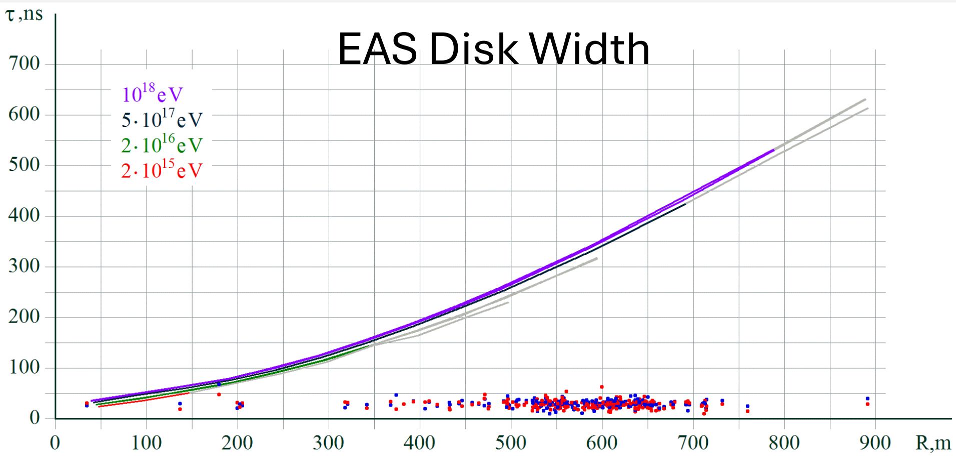
Introduction of DUCK system

- The project goals
  - development, design and construction and deployment of core modules of DUCK (Detector system of Unusual Cosmic-ray casKades) [1, 1.1, 2]
  - The project will involve computer simulation activities, design and construction, data acquisition system design, data collection and analysis, allowing participation of students pursuing not only Physics but also other STEM fields, such as Chemistry, Engineering and Computer Science. The project will extend the research potential and facilities at CSU and support efforts to develop physics major based on existing minor degree, support the newly proposed engineering technology major.
- DUCK system is aimed
  - To study the Extensive Air Shower (EAS) disk thickness as compared to CORSIKA [3] simulations
  - To join the efforts in the search for the Cosmic Ray Ensembles [4]
  - To further study the latest advances in the cosmic-rays by other detectors [5] in the field of unusual cosmic events [6].

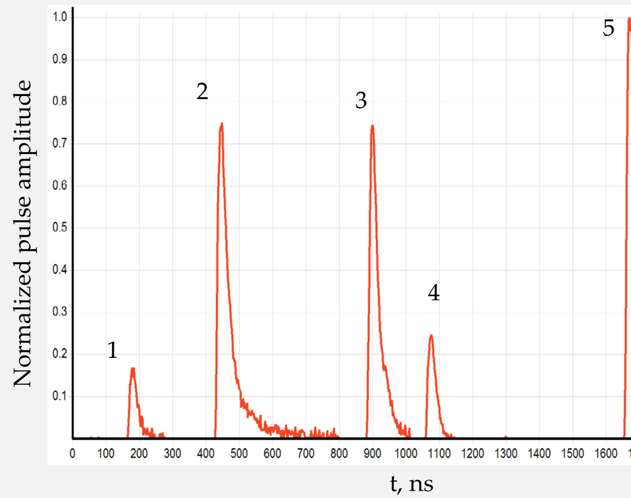
EAS structure reminder [1, 6]

- EAS Disk width (pulse width)

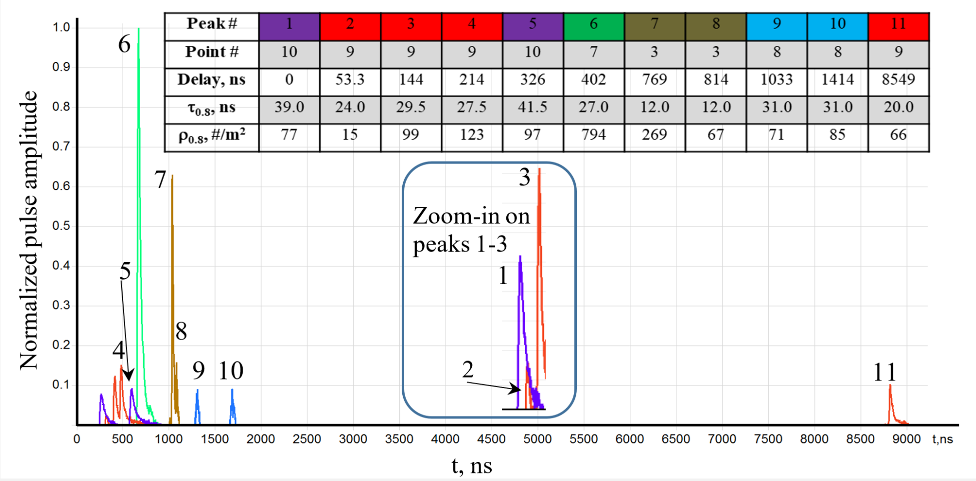


- The EAS Disk Width plot contains:
  - experimental data (blue dots – first pulse width, red – second pulse width) for unusual bimodal events (2 peaks)
  - the EAS disk width from the simulations for different E_0 (solid lines)
- Expect one pulse in detector response from EAS disk passage
  - Unusual events – more than one pulse in multiple detectors.

Unusual Events

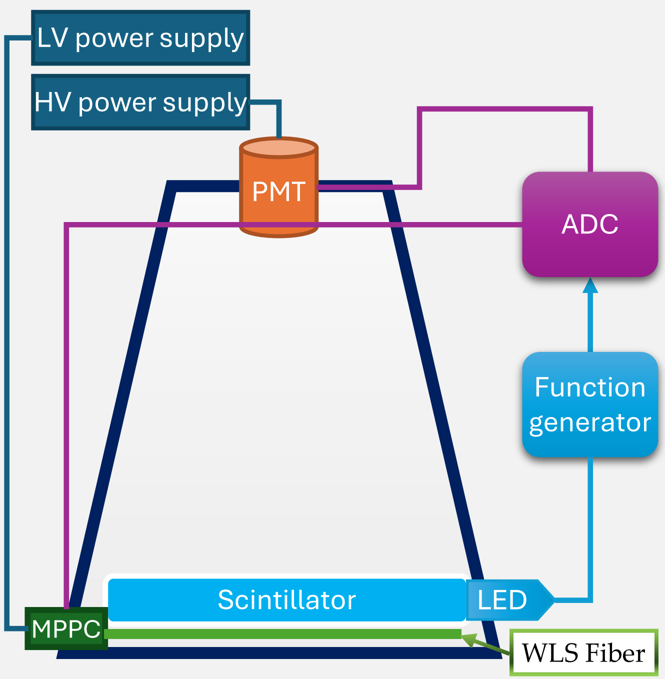


Peak #	Delay ns	$\tau_{0.8}$ ns	$\rho_{0.8}$ #/m²
1	0	28	32
2	265	34	256
3	720	31	187
4	894	31	52
5	1493	35	339



Peak #	1	2	3	4	5	6	7	8	9	10	11
Point #	10	9	9	9	10	7	3	3	8	8	9
Delay, ns	0	53.3	144	214	326	402	769	814	1033	1414	8549
$\tau_{0.8}$, ns	39.0	24.0	29.5	27.5	41.5	27.0	12.0	12.0	31.0	31.0	20.0
$\rho_{0.8}$, #/m²	77	15	99	123	97	794	269	67	71	85	66

Current Hardware Choice



- A total of 4 modules is planned initially, 1x1m.
- This allows to use the chronotron method
  - that is the time difference in EAS arrival at each module, to determine the arrival direction of the EAS.
- Each module would be calibrated to provide the particle density
- Fast response of each module makes possible to record waveform of the signal to look for the unusual events
- CAEN DT5730 FADC is used, with 14-bit resolution and 500 MHz digitization
- Hamamatsu H11284-30 (former R7723) PMT is chosen – large area and fast pulse combination
- MPPC + WLS fiber for MIP calibration of each module
- LED for PMT gain monitoring and single photon calibration

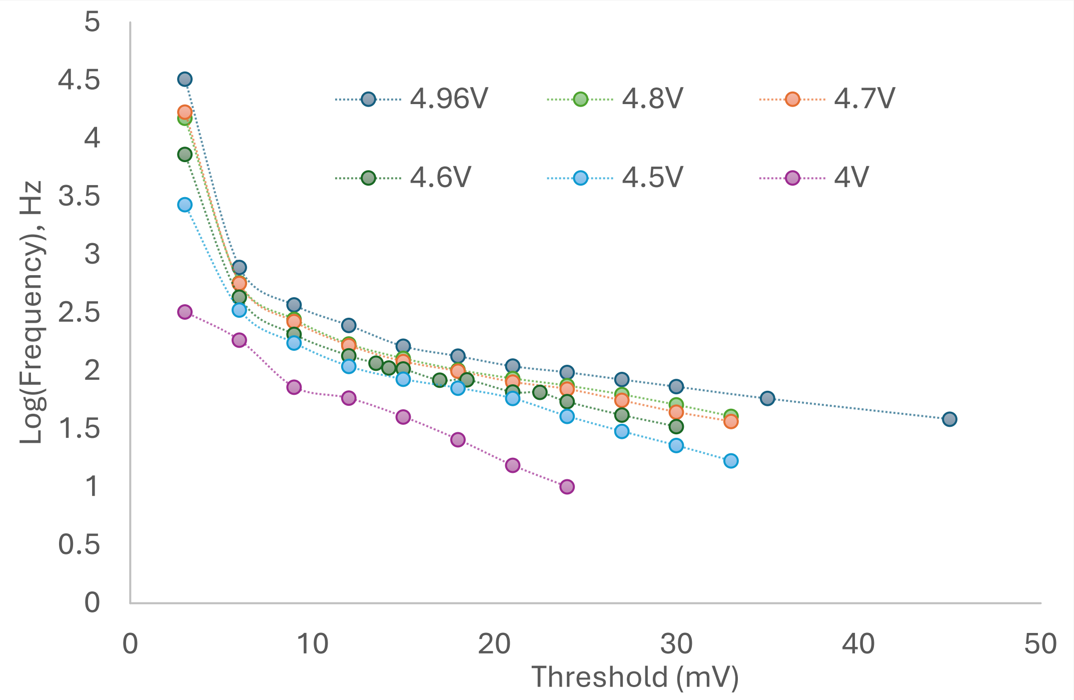
Paddles and Prototype Module

- For double-coincidence scheme
- Two simple detectors are needed
- Placed above and under the module under testing.
- Simple detectors – paddles
- flat piece of the scintillator 2.4mm thick + PMT. The square part of the paddle being about 25 x 35 cm.
- Form the hodoscope for the cosmic muon calibration coincidence scheme. Same model PMTs are used for the detector modules.

Shown are the completed paddle and the layers exposed. The PMT connector part is 3D-printed. The scintillator is covered by Tyvek for higher light yield. Additionally, aluminum foil, insulation tape, and duct tape were added for both light insulation and structural support.

PMT Initial Calibration

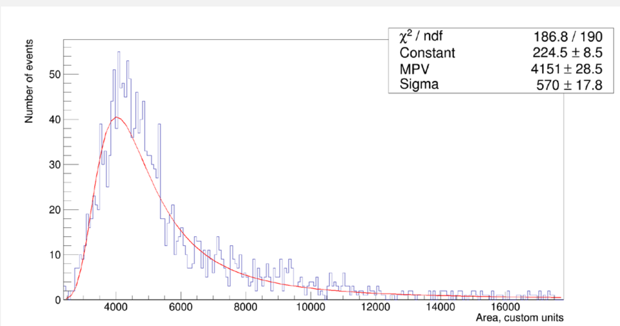
- Characterization of the PMTs
  - optimal voltage and threshold combination for efficient cosmic ray detection for each individual detector.
  - This calibration is done by connecting each detector (prototype and each of the paddles) to the event counter (oscilloscope) and measuring the event rate at different voltages and thresholds.



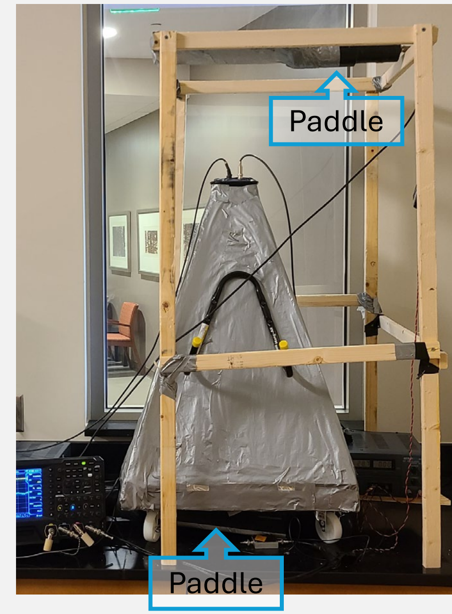
- The number of hits recorded over time is converted to frequency (rate) as $\frac{\#\ of\ hits}{time} = Freq$. These data points are plotted on a log scale vs. threshold in figure.
- The purpose of this graph is to identify where the plateau lies. The starting point of the plateau indicates the most optimal threshold and voltage, as it provides the highest detection efficiency of cosmic rays with minimal noise.

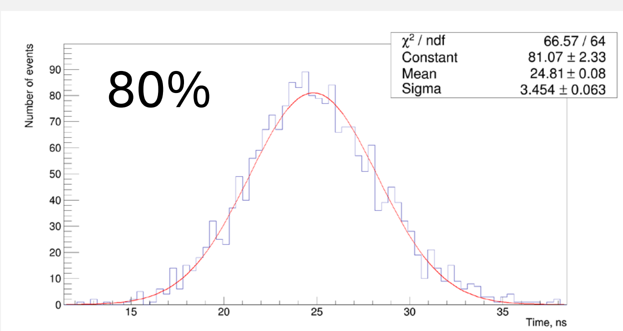
Tyvek lining and pulse width 1

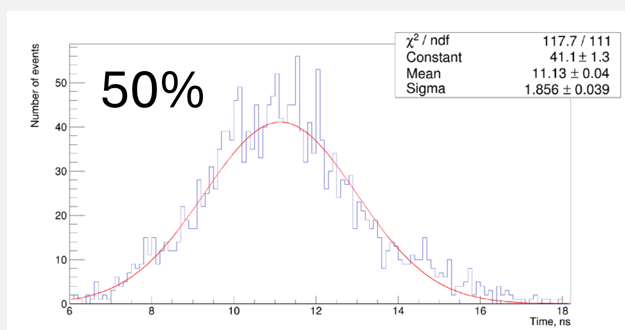
- Initial module prototype (0.5x0.5 m) had all inner walls lined with Tyvek
- 2.4mm of plastic scintillator was used (POP and POPOP)



- Test was done with external trigger (paddles above and below the module).
- Area is measured as integral under the pulse
- Fitted with Landau.
- Pulse width measured – very large, multiple reflections within the detector [8]

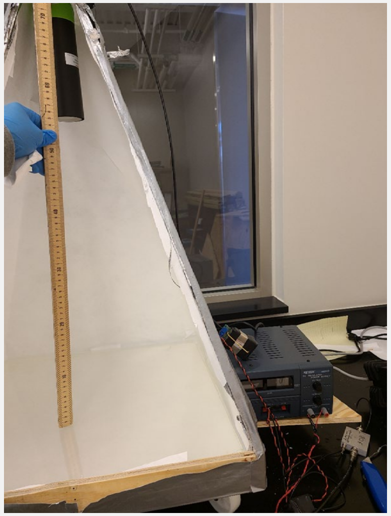


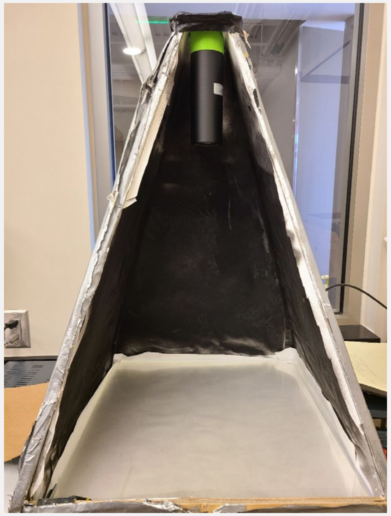




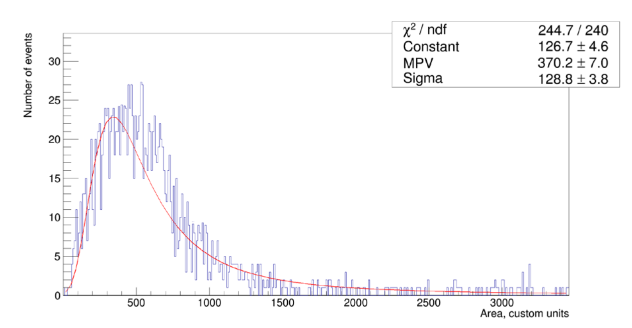
- Total pulse is measured as time between 10% and 80% of area. ‘Rise’ time – between 10% and 50%. Reduces noise and pulse tail effects (tail can be long due to RC effect in long cables)

Tyvek lining and pulse width 2

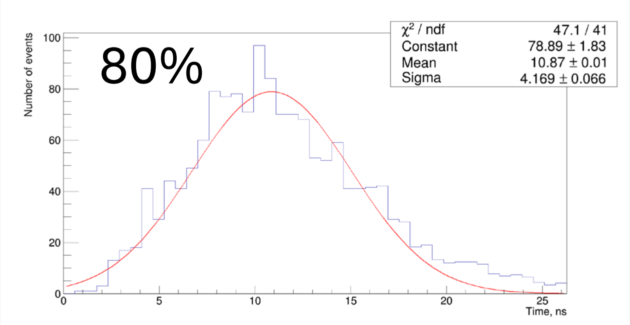


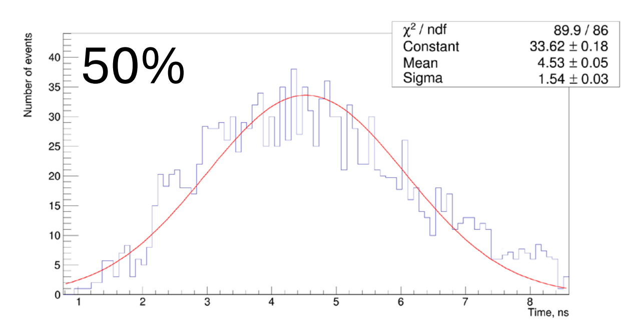


- Initial module prototype had all inner walls lined with Tyvek
- 2.4mm of plastic scintillator was used (POP and POPOP)
- Inner walls were painted black to reduce reflections



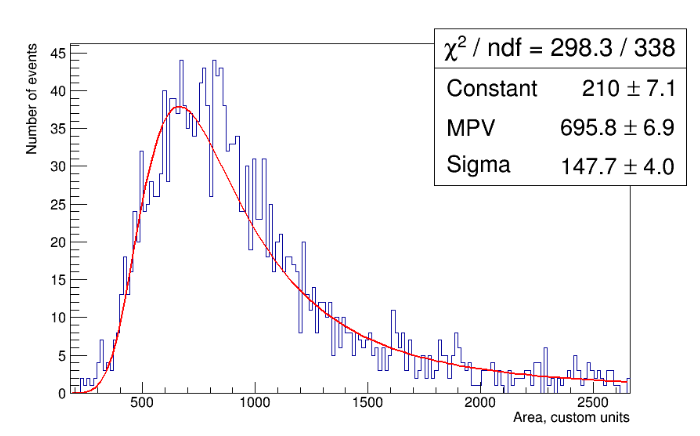
- The signal loss is very dramatic, however, its still possible to do the MIP calibration and the dynamic range is increased.





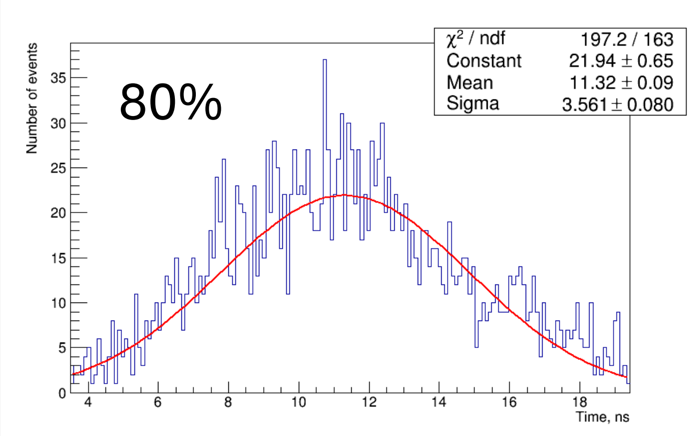
- Pulse width in decreased to the expected values
- For reliable calibration, somewhat larger pulse area (and amplitude) are desired, can try increase the scintillator thickness.

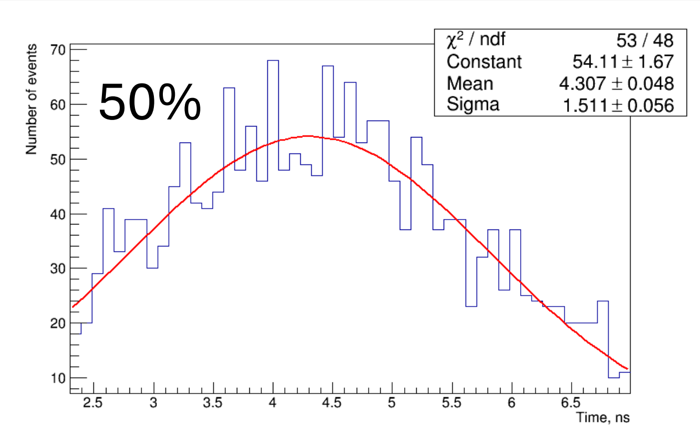
Tyvek lining and pulse width 3



- Initial module prototype had all inner walls lined with Tyvek
- 2.4*2=4.8mm of plastic scintillator was used (POP and POPOP)
- Inner walls were painted black to reduce reflections

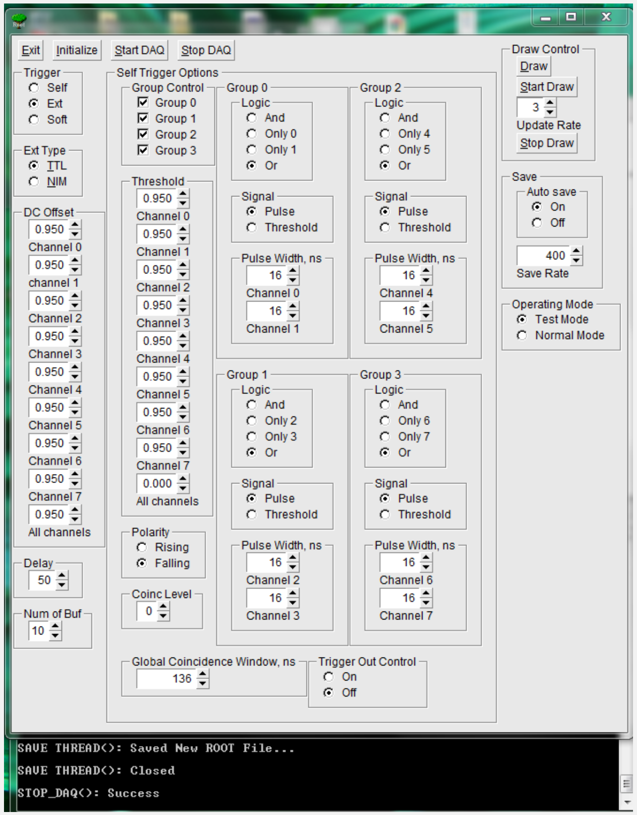
- The signal is partially recovered, can do the reliable MIP calibration and keep the large dynamic range

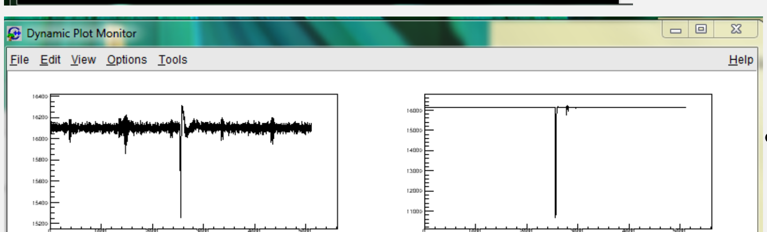




- Pulse width stays within the expected values
- Difference between thin and thick scintillator are within measurement precision

Software Controls





- CAEN DT5730 FADC needs custom software and controls
- The considerations that went into the software
  - provide the high-speed readout and ability to control all ADC functions
  - provide real-time even display that can show the data being recorded yet keep the priority to the data retrieval and saving over the display
- The software utilizes the TBB (tread building blocks) library to create the asynchronous queue that holds the data before its saved.
  - A single thread is tasked with checking the ADC if new data is available and retrieving this data
- Another thread takes events at adjustable times interval from the queue, makes a copy and draws it
  - This way, only select sampling of data is displayed
  - Allows the software can be run on computers with lower CPU and graphics capabilities
- ROOT file format is used to save data
  - Zip compression, events capability, easy event retrieval.

Conclusion

- The lab capabilities for the research have been established and students are involved in all steps of the process
- The prototype module has been constructed and in the process some corrections were added to the initial design
- The completion of the testing with the prototype will overlap with main module construction start
- Software has been completed for the ADC control. Data analysis will follow. Simulation activities are starting.
- Data is placed in the repository at https://sos.clayton.edu/DUCK/

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Conclusions and References

- References

  - [1] Dmitriy Beznosko, Valeriy Aseykin, Alexander Dyshkant, Alexander Iakovlev, Oleg Krivosheev, Tatiana Krivosheev, Vladimir Shiltsev and Valeriy Zhukov. “Prototype Setup Hardware Choice for the DUCK System”, Quantum Beam Sci. 07/10/2024, 8(3), 17; https://doi.org/10.3390/qubs8030017
  - [1.1] Dmitriy Beznosko, Valeriy Aseykin, Alexander Dyshkant, Alexander Iakovlev, Oleg Krivosheev, Tatiana Krivosheev, Valeriy Zhukov, ‘*Design Considerations of the DUCK Detector System*’, Quantum Beam Sci. 2023, 7(1), 6; https://doi.org/10.3390/qubs7010006
  - [2] Dmitriy Beznosko, Valeriy Aseykin, Alexander Dyshkant, Alexander Iakovlev, Oleg Krivosheev, Tatiana Krivosheev, Valeriy Zhukov, ‘DUCK Detector System Design’, 38th International Cosmic Ray Conference (ICRC2023), PoS(ICRC2023)187, DOI: https://doi.org/10.22323/1.444.0187
  - [3] D. Heck, J. Knapp, J.N. Capdevielle, G. Schatz, T. Thouw, ‘*CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers’*, Forschungszentrum Karlsruhe Report FZKA, vol. 6019, 1998.
  - [4] P. Homola et al., ‘*Invitation to the Cosmic Ray Extremely Distributed Observatory’*, PoS(ICRC2021)942, 2021, DOI:10.22323/1.395.0942
  - [5] RU Beisembaev, KA Baigarin, D Beznosko, EA Beisembaeva, MI Vildanova, VV Zhukov, MS Petlenko, VA Ryabov, T Kh Sadykov, SB Shaulov, ‘The Horizon-T cosmic ray experiment’, NIM A, Volume 1037, 166901, **06/2022**, ISSN 0168-9002, https://doi.org/10.1016/j.nima.2022.166901
  - [6] K. Baigarin et al., ‘Probing Fundamental Physics With Multi-Modal Cosmic Ray Events’, arXiv:2204.04045 [hep-ex], 04/2022, https://doi.org/10.48550/arXiv.2204.04045
  - [7] Dmitriy Beznosko, Valeriy Aseykin, Shriya Chakraborti, Alexander Dyshkant, Gerald Harris, Alexander Iakovlev, Oleg Krivosheev, Tatiana Krivosheev, Nicholas Muong, Alexander Ramirez, Vladimir Shiltsev, Valeriy Zhukov, ‘Prototype Setup for the DUCK’, 3rd Annual College of STEM Symposium, PROC(03ACSS2024)003 , https://sos.clayton.edu/proceedings/003/PROC(03ACSS2024)003.pdf
  - [8] D. Beznosko, R. U. Beisembaev, E. A. Beisembaeva, A. Duspayev, A. Iakovlev, T. X. Sadykov, T. Uakhitov, M. I. Vildanova, M. Yessenov, V. V. Zhukov. “Fast and simple glass-based charged particles detector with large linear detection range”, Journal of Instrumentation 12(07) T07008, DOI 10.1088/1748-0221/12/07/T07008 (2017/7/27)