Snowmass 2021 — Letter of Interest

DAQ System for a Large-Volume CRES Experiment

Topical Groups:

- **IF4** Trigger and DAQ
- **NF5** Neutrino Properties

Contact Information:
Noah S. Oblath: `noah.oblath@pnnl.gov`

Collaboration: Project 8

Authors:
A. Ashtari Esfahani, S. Böser, N. Buzinsky, C. Claessens, L. de Viveiros, P. J. Doe, S. Doeleman, M. Fertl, J. A. Formaggio, M. Gödel, M. Grando, J. Hartse, K. M. Heeger, X. Huyan, A. M. Jones, K. Kazkaz, B. H. LaRoque, A. Lindman, E. Machado, R. Mohiuddin, B. Monreal, J. A. Nikkel, E. Novitski, N. S. Oblath, W. Pettus, R. G. H. Robertson, L. J. Rosenberg, G. Rybka, L. Saldaña, M. Schram, P. L. Slocum, Y. H. Sun, P. T. Surukuchi, J. R. Tedeschi, A. B. Telles, F. Thomas, M. Thomas, T. Thümmler, L. Tvrznikova, B. A. VanDevender, J. Weintroub, T. E. Weiss, T. Wendler, E. Zayas, A. Ziegler

Abstract: The primary goal of the Project 8 experiment is to make a direct measurement of the absolute neutrino mass using Cyclotron Radiation Emission Spectroscopy (CRES) and the tritium beta-decay technique. The tritium-source volume will be surrounded by a cylindrical array of microwave antennas to detect the cyclotron radiation from the beta-decay electrons, and antenna signals will be combined using digital beamforming. The signals from individual electron events will be detected and reconstructed in real time by the data-acquisition (DAQ) system. We are currently developing the scalable architecture of the DAQ system, and the advanced algorithms that will be used to identify and reconstruct electron signals. This LOI presents the unique requirements for the Project 8 DAQ system, and the architecture and algorithms we are studying to address this challenge.

Large-Volume CRES The Project 8 collaboration is pursuing a measurement of the absolute neutrino mass using tritium beta-decay [1, 2]. The experiment is based on the Cyclotron Radiation Emission Spectroscopy (CRES) technique that was invented for this purpose [3]. The physics goals of the experiment are achieved in part by having a large source volume, so that the endpoint of the beta-decay spectrum can be measured as precisely as possible. For a CRES-based experiment, this means having a tritium source volume surrounded by antennas detecting the cyclotron radiation emitted from magnetically-trapped beta-decay electrons within that volume. The upcoming Phase III of Project 8 will start with a ring-array of approximately 75 antennas; later stages of Phase III and the final Phase IV apparatus will likely involve larger and/or more rings.

Digital Beamforming Similar to the way in which a radiotelescope uses digital beamforming [4] to steer a beam of high sensitivity across the sky, in Project 8 we will use digital beamforming to specify a sensitive region within the source volume. The signals from all of the antennas are summed in linear combination with a particular set of phase shifts relative to one another. Each location within the volume of the experiment corresponds to a particular set of phase shifts. The result of a particular combination of signals is a small sensitive volume shaped like a narrow cylinder within the larger cylindrical source volume. We can therefore spatially locate electrons in the experiment and even observe multiple electrons simultaneously based on their spatial separation. During the lifetime of a given electron in the trap (eventually it will scatter on a gas molecule in such a way that it is no longer trapped) the location of the electron in the volume will slowly change due to ∇B forces [5], so we have to track that motion and change the beamforming parameters accordingly.

DAQ Stages Data processing through the data acquisition (DAQ) system will comprise five stages:

1. Digitizer: analog signals from the antennas (one per antenna) are digitized.
2. Front end: each channel is independently filtered, Fourier transformed, and packed into UDP packets for transmission on a dedicated high-speed ethernet network.
3. Trigger: beamforming is performed in parallel for a fixed set of locations in the source volume, and the frequency spectra are analyzed for high-power signals that indicate the potential presence of an electron.
4. Tracking: potential electron signals are tracked over their lifetimes in the detector, changing the beamforming parameters as the electrons physically move within the experiment.
5. Data reduction: The size of the data stored for each event must be smaller than the full bandwidth over the lifetime of the electron, so a smaller frequency range in the immediate vicinity of the electron track is kept. Track parameters are calculated and stored with the power information.

The data rate is one of the primary challenges for this system. Due to the particular characteristics of the beamforming process, the full data rate will be present all the way through stage 4. The trigger and tracking stages require all of the data (full frequency range) from all channels for a given period of time. This process cannot be parallelized by antenna channel or even beamformed "channel" (physical location). These requirements lead to three guidelines that we will follow in our initial design process:

1. Data will be moved within the system as little as possible (e.g. data resides on a single compute node, but we may do multiple operations to it);
2. Data will be divided in time so that each compute node is considering a single chunk of time;

3. We will explore as many trigger/reconstruction/analysis algorithms as possible and optimize the compute hardware based on the algorithm(s) chosen for use.

Architecture The basic architecture for the system, driven by the guidelines laid out above, consists of the front-end components (including the digitizers), a layer of broker servers in the middle, and finally a set of compute servers. We need to keep the data rates at levels that can be handled by a dedicated high-speed ethernet network. In the process of going from the front-end components to the compute servers, the data needs to be effectively rebinned in time to get larger time chunks. Data will come off the front-end components as "records," which are sized to fit in a single UDP packet and are significantly smaller than the typical event. Records must be combined to form blocks, which are significantly larger than a single event. Blocks will overlap with one another, with the end of a given block reserved for finishing existing events without triggering new ones. Each broker will handle incoming data from a specific subset of the antenna channels such that it can handle the incoming data rate. The brokers will rebin the data into blocks, and send the blocks to the compute servers. The brokers will coordinate with each other and with the compute servers to know where to send each block. All of the brokers send data from a given block (i.e. period of time) to a single compute node, and the number of compute nodes can be scaled to handle the data rate according to the number of channels and the speed of the analysis. Each compute node therefore ends up with the data from all channels for a given block. Furthermore, it performs all analysis, both triggering and tracking for that block, thereby minimizing the movement of data.

Analysis The detection of sinusoidal signals in noise is a well-studied problem [6]. In the context of Project 8, the challenge is to maximize the likelihood of identifying faint electron signals, and minimize the detection of random noise fluctuations. There are currently a few different algorithms under consideration for performing the triggering and track-reconstruction analysis. The algorithm(s) that is eventually selected will need to operate in real time and have a well-understood efficiency. The options currently under development are:

1. The trigger used during Phase II was a simple search for high-power bins in each frequency spectrum, resulting in a "trigger" for a given set of sequential spectra with high-power bins;
2. The offline analysis used during Phase II improved on option (1) by taking advantage of the straight-line characteristic of the tracks in time-frequency space. This resulted in a significant reduction in false events due to random noise fluctuations;
3. Real-time machine learning (ML) is currently of interest in the TDAQ community, and could be applied to Project 8. We are currently developing a ML analysis of Phase II data to determine how it performs compared to the production Phase II track reconstruction;
4. Instead of analyzing the frequency spectra, we can consider analyzing the time-domain data, taking advantage of the high precision in time. We would use the phase information in the data to look for the presence of continuous signals that are the result of electron events.

The Phase III DAQ system will be the result of combining these aspects of development into a unique apparatus. We will demonstrate the ability to reliably detect faint electron signals from a large-volume CRES source. Based on what we learn in Phase III, the eventual Phase IV DAQ system will go on to form a crucial piece of the final iteration of the Project 8 experiment.

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