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PNNL-35518

Developing a Cyclotron Radiation Emission Spectroscopy Detection System

December 2023

Noah S. Oblath
Daniel Cain

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Abstract

Cyclotron Radiation Emission Spectroscopy is a new technique for ultra-precise spectroscopy of low-energy electrons. This project aimed at developing capabilities that would be useful to a future CRES experiment. The recent results from the Project 8 and He6-CRES collaborations indicate that CRES has a promising future, but will need advancements to continue developing. In this report we cover the four tasks that comprised the project: data acquisition, data management, updating the raw-data format, and cloud computing.

Summary

- Project 8 and He6-CRES have both produced significant results recently and are planning the next phases of their operations. Under this project we aimed to develop several capabilities that would allow us to continue to support those experiments or other future CRES experiments: data acquisition (DAQ), data management, a new data file format, and the potential to use AWS cloud computing.

- The data-acquisition task comprised adapting firmware from the Project 8 Phase II DAQ system to a new hardware platform. The firmware was ported under this project, but testing was not completed.

- The data-management task consisted of studying and implementing a solution for handling the data from an experiment like Phase III of Project 8. The study of the software platform was conducted and initial work done to implement the system at PNNL. However, due to technical challenges, we determined that the platform would not work for us.

- The update to the raw-data file format is due to incompatibilities between the Project 8 Phase II DAQ and library for writing those files. We evaluated a new data file format to use, and began the process of replacing the old file format with the new one.

- We explored the possibility of using cloud computing to fill a gap in computing resources between working on one's own machine and using HPC systems. With cloud computing, on-demand compute resources are available to collaborators who want to use them, and they would have access to the data repositories. We created a demonstration of the ability to use a Jupyter-like Python notebook environment, which could be applied to any CRES analysis work.

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Acronyms and Abbreviations

AWS – Amazon Web Services
CASPER – Collaboration for Astronomy Signal Processing and Electronics Research
CCA – Cavity CRES Apparatus
CRES – Cyclotron Radiation Emission Spectroscopy
DAQ – Data Acquisition

Contents

1.0 Introduction

Phase II of the Project 8 experiment recently demonstrated [1] the ability to use Cyclotron Radiation Emission Spectroscopy [2] to measure the electron energy spectrum from tritium beta decay and place a limit on the absolute neutrino mass. PNNL's RF-engineering and computing capabilities were critical contributions to the success of that experiment. PNNL is also involved in the He6-CRES experiment, which recently published its first CRES results [3]. Buoyed by these successes, both collaborations are planning the next advances in the use of CRES. Project 8 is seeking to advance the ways in which CRES experiments are conducted by developing the ability to perform a CRES measurement with a resonant RF cavity. This project was aimed at developing capabilities that will enable future CRES experiments.

The first task in the project was to develop the data acquisition system for a future CRES experiment. The second task was to explore a possible data-management platform that could be used for a future CRES experiment to catalog data and handle automated data processing. The third task was to update the data format used by Project 8 to fix issues that were experienced during Phase II. And the fourth task was to explore the possibility of using cloud computing as a resource for collaborators on a future CRES experiment. Progress on those tasks is described in the sections below.

2.0 Data Acquisition

Phase II of Project 8 used the ROACH2 [4] as the hardware platform for the experiment's data-acquisition system. It was recognized that a future CRES experiment would want to take advantage of more recent advances in RF data-acquisition hardware, while still benefitting from the firmware that was used for Project 8 if the requirements of the future experiment are appropriate.

The goal of this task was to transfer the firmware used on the ROACH II board to a Xilinx RFSoC board. The Project 8 group at PNNL already had a Xilinx ZCU216 RFSoC board, which was used for this task. Fortunately, the CASPER collaboration [5], which developed the ROACH II board and the firmware that was used by Project 8, already had experience using Xilinx ZCU boards, so we had confidence that the porting of the firmware should work.

We set requirements for the performance of the DAQ based on the first Project 8 Phase III demonstrator, the Cavity CRES Apparatus (CCA), since the CCA is a concrete example of an upcoming CRES experiment, and it will be able to take immediate advantage of this capability. The Phase II firmware was the starting point for the CCA firmware because the DAQ requirements were similar, in particular regarding the target frequency and bandwidth. Modifications compared to the Phase II system include reducing to a single channel (the Phase II DAQ had three channels) and widening the bandwidth.

Work on this task was performed by electrical engineer Daniel Cain. The firmware was ported to the RFSoC board and elements of it were tested. A problem arose with the integration of the network connection, which ended up delaying the task such that the work was not completed before the end of FY23.

D. Cain also led the design and construction of an enclosure for the RFSoC board, which is otherwise a bare circuit board. The enclosure was completed, so the RFSoC board will be able to be easily deployed to the CCA experiment when the firmware is completed.

3.0 Data Management

PNNL provided the bulk of computing and data management for Project 8 Phase II. That system was implemented with a platformed called DIRAC, which provided data cataloguing, and workload management. However, we no longer have the expertise at PNNL to run DIRAC, and it was a complicated system to maintain. With this project we sought to develop the capability to provide the same capabilities to a future CRES experiment. We sought a different solution for CRES data management.

The test case for this work was the CCA. We compiled the requirements on data management for the CCA and evaluated options for implementing a data-management system, including estimated data rates and volumes, and the need for automated transfer and processing of the data. The data and associated metadata must be catalogued in a way that can be accessed and searched by Project 8 collaborators.

The platform initially pursued under this task is called RUCIO [6]. It is developed by CERN and used by various experiments in the same and adjacent field as Project 8. Ian Smith lead the team of Research Computing engineers to implement this system. We collaborated with Project 8 collaborators at Yale University who were also involved in data management, focused on simulations. In the end, we were unsuccessful in getting RUCIO running. However, we did establish a basis for using Globus [7] for data transfer and have a path forward to deliver a functioning data-management system in FY24 under funding for Project 8 from the DOE Office of Nuclear Physics.

4.0 Raw Data File Format

The Project 8 experiment created a file format called Egg v3 for use during Phase II. This format was based on the industry-standard HDF5 file format [8]. The Egg v3 standard defined certain requirements for formatting the data and metadata within the files in a way that's useful for a CRES experiment. During Phase II, Project 8 had trouble with the data-acquisition system crashing, which was eventually traced to an issue with the use of HDF5 for the Egg v3 format: HDF5 cannot be used in a multithreaded way, and the Project 8 data-acquisition system used multiple threads when interacting with the files it was writing.

For future CRES experiments, a new underlying data file format would be needed that's compatible with the multi-threaded nature of the Project 8 data-acquisition system. We settled on the Zarr format [9] as a good candidate. Ray Dunn led this task, studying the Zarr format and analyzing how the C++ library used to read and write Egg files (Monarch [10]) would need to be modified to use the Zarr format. He was able to complete approximately one third of the worked on the Monarch library by the time this project ended. Work will continue under DOE Office of Nuclear Physics funding.

5.0 End-User Cloud Computing

Project 8, during their Phase II efforts, identified a computing need that would be relevant for future CRES experiments: there was a gap in computing resources between a collaborator performing analysis on their own machine, and production data analysis and simulations performed with HPC resources. Cloud computing was identified as a possible way to fill this gap, providing both access to large data stores and flexible compute capabilities.

We decided to pursue this capability under this LDRD project in the hope that the cloud setup we produced could be used by future CRES experiments. We chose AWS as the cloud provider. Mohammad Rammah recommended the use of SageMaker as a platform where CRES-experiment collaborators could develop analysis code and deploy that code on a variety of compute resources. He put together an interface layer in AWS that would create a SageMaker notebook on request from a user, setting up permissions, data access, etc. as needed. If an experiment like Project 8 were to opt in to use AWS cloud computing, this product could be used directly.

6.0 References

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