I. Executive Summary

The Fermi National Accelerator Laboratory (Fermilab or FNAL) is conducting a Laboratory Directed Research and Development (LDRD) program. Fiscal year 2017 (FY17) represents the third full year of LDRD at Fermilab and includes three projects approved mid-year in FY14, six projects approved in FY15, seven approved projects in FY16, and nine approved projects in FY17. The implementation of LDRD at Fermilab is captured in the approved Fermilab LDRD Annual Program Plan which appears in FY17 as an Appendix to Fermilab’s Annual Laboratory Plan. In FY17, the LDRD program represents 1.2% ($3.8M) of Laboratory funding. Due to successes, the scope of the LDRD program at Fermilab is expected to increase where a portfolio of about 25 on-going projects representing between 1.5% and perhaps eventually 2.5% of the Laboratory funding is anticipated.

This Annual Report focuses on the status of the current projects and provides an overview of the current status of LDRD at Fermilab. LDRD projects are generally initiated through a response to a Call for Proposals. The response has been outstanding to the four Calls for Proposals with 155 new ideas put forward resulting in 66 full proposals being submitted to a Selection Committee. After recommendations by the Selection Committee, the Laboratory Director has approved funding for twenty-nine projects. Of those, sixteen are on-going projects that are the subject of this Annual Report.

All indications are that LDRD is improving the scientific and technical vitality of the Laboratory and providing new, novel, or cutting edge projects carried out at the forefront of science and technology. The projects are aligned with the core capabilities of Fermilab and hence are positioned to carry out the mission and strategic visions of Fermilab and the Department of Energy.

Operated by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the United States Department of Energy.
II. Program Overview

Beginning in FY 2014, Fermilab has initiated a LDRD program as authorized by a DOE order, now DOE O 413.2C, to enhance and realize the mission of the laboratory in a manner that also supports the laboratory’s strategic objectives and the mission of the Department of Energy. LDRD funds enable scientific creativity, allow for exploration of “high risk, high payoff” research, and allow for the demonstration of new ideas, technical concepts, and devices. LDRD also has an objective of maintaining and enhancing the scientific and technical vitality of Fermilab.

LDRD is able to fund employee-initiated proposals that address the current strategic objectives and better position Fermilab for future mission needs. The request for such funds is made in consideration of the investment needs, affordability, and directives from DOE and Congress. Our implementation of LDRD also allows for the Laboratory Director, for instance, initiating a proposal from a Principal Investigator (PI) who is a strategic hire or otherwise working in a strategically important area.

The FY 2017 Fermilab Annual LDRD Program Plan (as reviewed as part of the Annual Laboratory Plan) has been used to implement the FY 2017 LDRD Program. The laboratory sought and was granted approval for an LDRD expenditure comprising up to a maximum of 1.5% ($4.5M) of the laboratory’s total operating / capital budget. Actual expenditures were below the allowed maximum and came in at 1.2% ($3.8M) of the laboratory’s total operating / capital budget. Being below the maximum allowed was due in part to alleviate budgetary pressure on other parts of the Fermilab program and the fact that projects generally have spent below initial maximum approved amounts as those often include project contingencies or a project becomes stretched over an additional fiscal year.

Following an approved FY 2017 Annual LDRD Program Plan, a call for proposals was issued and 37 preliminary proposals were received. These preliminary proposals were typically one or two pages in length and required supervisory and divisional concurrence as to the proposed scope of effort and materials. An LDRD Selection Committee reviewed these preliminary proposals and PI’s were advised of their approximate competitive standing along with feedback should they wish to submit a full proposal.

In response to the preliminary proposal stage, a total of 15 full proposals were prepared, submitted, and fully evaluated by the LDRD Selection Committee. Each PI made a brief presentation to the Selection Committee. The LDRD Selection Committee evaluated the full proposals on a 5-point rating scale across 10 scoring criteria. The scoring criteria included an evaluation of the scientific or technical significance, innovativeness / novelty, the qualifications of the PI, the overall quality of the proposal, the likelihood of success, mission relevance, and relevance to the initiative as spelled out in the call for proposals, the strategic fit, enduring capability, and the likelihood to enhance the laboratory’s reputation. In short, the scoring criteria encapsulated the key objectives and aspects that LDRD has as its purpose.
In consideration of the scope of proposals received, the LDRD selection committee made a recommendation to the Laboratory Director who approved the funding of the nine new LDRD projects at Fermilab. Table 1 shows the flow down for proposals and funded projects for FY14, FY15, FY16, and FY17.

Table 1: Number of LDRD proposals received in response to the annual Call for Proposals, the number of full proposals prepared, and the number of awarded and funded LDRD Projects

<table>
<thead>
<tr>
<th>Fiscal Year</th>
<th>Preliminary Proposals</th>
<th>Full Proposals</th>
<th>Funded LDRD Projects</th>
<th>Completed by Oct 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY14</td>
<td>50</td>
<td>29</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>FY15</td>
<td>34</td>
<td>12</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>FY16</td>
<td>34</td>
<td>15</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>FY17</td>
<td>37</td>
<td>15</td>
<td>9</td>
<td>-</td>
</tr>
</tbody>
</table>

The twenty-nine LDRD approved projects have internal laboratory project and task numbers assigned with budgetary information recorded such that financial tracking of effort and spending could be monitored. On roughly a monthly basis, project financial information is compiled, shared with the PI and the LDRD Coordinator. Each PI has also been asked to provide a short progress report to the LDRD Coordinator on approximately a monthly basis. In December 2014, August 2015, 2016, and 2017, the LDRD selection committee has conducted mid-year reviews of each of projects and recommended project continuation that was subsequently approved by the Laboratory Director. Occasionally, a project has been recommended to be reduced in scope. Each PI provides the Project Summary contained within this document with minor edits applied.

III. LDRD and Laboratory and Agency Mission

Department of Energy Mission

The mission of the Energy Department is to ensure America’s security and prosperity by addressing its energy, environmental and nuclear challenges through transformative science and technology solutions.

Fermilab Mission

Our mission is to drive discovery in particle physics by
- building and operating world-leading accelerator and detector facilities
- performing pioneering research with global partners
- developing new technologies for science that support U.S. industrial competitiveness

The Mission statement of Fermilab reflects the pursuit of excellence in scientific research in the area of particle physics. Particle physics addresses scientific mysteries in matter, energy, space and time through cosmic science, Large Hadron Collider (LHC) science, neutrino science, and precision science. In addition to particle physics, Fermilab has core
capabilities in accelerator science and technology, advanced computer science, and large-scale user facilities. Fermilab’s Mission statement reflects Fermilab’s role in support of the overall mission of the Department of Energy. In particular, “transformative science and technology solutions” in the area of particle physics will be furthered through the use of LDRD. LDRD provides flexibility and efficiency that enables investigators to carry out creative new projects in forefront areas that enrich the current Fermilab program and strategically put Fermilab in a better position to deliver the mission objectives of DOE and Fermilab for the future. The Project Summaries describe the relevance of each project to the missions of Fermilab and DOE.

IV. Summary of Fermilab LDRD Costs

The costs associated with the Fermilab LDRD program are reported as part of the annual Chief Financial Officer, CFO, database upload required at the beginning of each fiscal year. Costs associated with the administration of LDRD are absorbed into the Laboratory’s overhead. Table 2 shows a list of projects approved in FY14 and the spending for each project during FY17. Tables 3, 4, and 5 show the similar list of projects approved in FY15, FY16, and FY17.

Table 2: List of FY14 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY17. Note that the three projects with FY17 spending have all been completed within the 36 month performance period (2014-012 was granted a ~3 month extension).

<table>
<thead>
<tr>
<th>LDRD Project FNAL-LDRD-</th>
<th>Project Name</th>
<th>FY2017 Spending</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014-010</td>
<td>Cosmic Microwave Background Detector Development at Fermilab</td>
<td>$445,227</td>
<td>*</td>
</tr>
<tr>
<td>2014-012</td>
<td>Development of HTS Based Rapid-Cycling Accelerator Magnets</td>
<td>$537,361</td>
<td>*</td>
</tr>
<tr>
<td>2014-016</td>
<td>High Frequency Gallium Nitride Driver</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2014-025</td>
<td>The Sinuous Target</td>
<td>$213,112</td>
<td>*</td>
</tr>
<tr>
<td>2014-027</td>
<td>From Magic to Method: Characterizing High Voltage in Liquid Argon Time Projection Chambers with the Breakdown in liquid argon cryostat for high voltage experiments</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2014-028</td>
<td>Deployment and operation of prototype CCD array at Reactor Site for detection of Coherent Neutrino-Nucleus Interaction</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>2014-038</td>
<td>Application-Oriented Network Traffic Analysis based on Graphical Processing Units</td>
<td>-</td>
<td>*</td>
</tr>
<tr>
<td>“FY14 Project” Totals</td>
<td></td>
<td>$1,195,700</td>
<td></td>
</tr>
</tbody>
</table>
### Table 3: List of FY15 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY17 and uploaded to the CFO database.

<table>
<thead>
<tr>
<th>LDRD Project</th>
<th>Project Name</th>
<th>FY2017 Spending</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015-009</td>
<td>High Energy Physics Pattern Recognition with an Automata Processor</td>
<td>$50,399</td>
<td>*</td>
</tr>
<tr>
<td>2015-010</td>
<td>Dark Energy Survey and Gravitational Waves</td>
<td>$2,232</td>
<td>*</td>
</tr>
<tr>
<td>2015-020</td>
<td>Off-the-Shelf Data Acquisition System</td>
<td>$158,157</td>
<td>*</td>
</tr>
<tr>
<td>2015-021</td>
<td>Transverse and Longitudinal Profile Diagnostics for H- Beams using Fiber Lasers and Synchronous Detection</td>
<td>$17,085</td>
<td></td>
</tr>
<tr>
<td>2015-029</td>
<td>Nb$_3$Sn Superconducting RF Cavities to Reach Gradients up to 90MV/m and Enable 4.2K Operation of Accelerators</td>
<td>$293,291</td>
<td>*</td>
</tr>
<tr>
<td>2015-031</td>
<td>A Comprehensive Investigation of a Transformational Integrable Optics Test Storage Ring as a &quot;Smart&quot; Rapid Cycling Synchrotron for High-Intensity Beams</td>
<td>$169,508</td>
<td></td>
</tr>
<tr>
<td><strong>“FY15 Project” Totals</strong></td>
<td></td>
<td><strong>$690,672</strong></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4: List of FY16 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY17 and uploaded to the CFO database.

<table>
<thead>
<tr>
<th>LDRD Project</th>
<th>Project Name</th>
<th>FY2017 Spending</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016-001</td>
<td>Beam Precision Time Profile Monitor</td>
<td>$100,135</td>
<td></td>
</tr>
<tr>
<td>2016-004</td>
<td>Development of an ultra low energy threshold particle detector</td>
<td>$96,543</td>
<td></td>
</tr>
<tr>
<td>2016-007</td>
<td>Tuning Axion Detectors with Non-Linear Dielectrics</td>
<td>$132,651</td>
<td></td>
</tr>
<tr>
<td>2016-008</td>
<td>Novel Methods for High Performance Superconducting Coating on Copper</td>
<td>$356,512</td>
<td></td>
</tr>
<tr>
<td>2016-010</td>
<td>Preparing HEP reconstruction and analysis software for exascale era computing</td>
<td>$190,974</td>
<td></td>
</tr>
<tr>
<td>2016-032</td>
<td>Implement open source HEP NoSQL database</td>
<td>$130,272</td>
<td></td>
</tr>
<tr>
<td>2016-034</td>
<td>Instrumentation for the Initial set of Critical Scientific Experiments in IOTA and the FAST Injector</td>
<td>$83,733</td>
<td></td>
</tr>
<tr>
<td><strong>“FY16 Project” Totals</strong></td>
<td></td>
<td><strong>$1,090,820</strong></td>
<td></td>
</tr>
</tbody>
</table>
Table 5: List of FY17 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY17 and uploaded to the CFO database. The total FY2017 spending for all on-going projects (FY14+FY15+FY16+FY17) is also shown.

<table>
<thead>
<tr>
<th>LDRD Project FNAL-LDRD-</th>
<th>Project Name</th>
<th>FY2017 Spending</th>
<th>Completed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2017-003</td>
<td>Optical Microwave Kinetic Inductance Detectors for future cosmic surveys</td>
<td>$27,964</td>
<td></td>
</tr>
<tr>
<td>2017-010</td>
<td>Training Deep Neural Networks for Neutrino Identification in the Cloud</td>
<td>$45,645</td>
<td></td>
</tr>
<tr>
<td>2017-011</td>
<td>LArCADe _ Liquid Argon Charge Amplification Devices</td>
<td>-</td>
<td>To start in FY18</td>
</tr>
<tr>
<td>2017-014</td>
<td>Cryogenic photon sensors for the low mass frontier</td>
<td>-</td>
<td>To start in FY18</td>
</tr>
<tr>
<td>2017-019</td>
<td>First demonstration of conduction cooled SRF Cavity</td>
<td>$332,793</td>
<td></td>
</tr>
<tr>
<td>2017-020</td>
<td>Development of next-generation Nb3Sn superconductors for accelerator magnets</td>
<td>$92,555</td>
<td></td>
</tr>
<tr>
<td>2017-027</td>
<td>Silicon precision timing detectors for minimum ionizing particles</td>
<td>$107,939</td>
<td></td>
</tr>
<tr>
<td>2017-028</td>
<td>Increasing the photon detector light efficiency in a liquid argon detector</td>
<td>$128,374</td>
<td></td>
</tr>
<tr>
<td>2017-038</td>
<td>Quantum Computing using SRF Technology</td>
<td>$61,705</td>
<td></td>
</tr>
<tr>
<td>“FY17 Project” Totals</td>
<td></td>
<td>$796,975</td>
<td></td>
</tr>
<tr>
<td>FY17 Total</td>
<td>includes FY14-FY17 projects</td>
<td>$3,774,168</td>
<td></td>
</tr>
</tbody>
</table>

V. Project Summaries

Each of the on-going LDRD projects are described in the following Project Summaries. The project number and title, key authors including the PI are listed. A short project description is provided along with a statement addressing the relevance of the project to the Laboratory. A description follows of initial results and accomplishments along with a list of publications (if any) that have been produced.

Project Number and Title: FNAL-LDRD-2015-021
Transverse and Longitudinal Profile Diagnostics for H- Beams using Fiber Lasers

Authors: (PI) Victor Scarpine, Jinhao Ruan

Project Description:
This research project is to develop the concept of a combined transverse and longitudinal H+ beam profiling instrument utilizing a low-power, high rep-rate fiber laser with optical fiber transport to the accelerator and synchronous signal detection. Traditionally, beam
profile measurements of H- beams is accomplished with high-power lasers and signal detection through the collection of electrons. However, a low-power laser will produce far fewer photo-disassociations and, hence, a smaller signal. This project will detect this small signal through narrow-band synchronous detection of a low-power modulated laser pulse train. In addition, this project will test the concept of acquiring these beam profiles by measuring reduction in H⁻ beam current, as opposed to electron collection. The final goal of this proposal is the construction and operation of a R&D profiling instrument that can study low-power photo-disassociation signals and laser and instrumentation systematic issues, as well as make initial beam profile measurements.

Relevance:
Beam profile measurements in high-intensity, superconducting H⁻ accelerators are driving the need for non-invasive measurements of both transverse and longitudinal profiles. The technique of photo-disassociation of H⁻ is generally the technique used for non-invasive profile measurements. Usually this requires the use of high-power, low rep-rate lasers, increased beam line space and complicated light transport systems which lead to slower profile measurements, higher costs and accelerator and laser safety issues.

The beam profiling technique of this project has a number of new and novel features. The primary advantages of this approach are:

1. Safer and easier transport lower-power laser light, with optical fibers, through the accelerator system with no risk of damage to optical vacuum windows.
2. A combination of both transverse and longitudinal profile measurements in one system.
3. The use of amplitude modulation of the laser pulse train with synchronous lock-in amplifier detection and oversampling techniques, which will enable the detection of the very small signals and faster profile measurements.
4. The measurement of profiles, by a reduced beam intensity method, which will allow for minimizing the required accelerator beam line space by removing the requirement to collect photo-disassociated electrons.

Results and Accomplishments:
At the end of this LDRD project, delays in design and infrastructure construction have prevented operation of the fiber-based laser profiler in the PIP2IT (Proton Improvement Plan II Injector Test) beamline. However, much progress has been made toward construction and operation of the laser profiler with the following accomplishments.

- Design and procurement of the 2W fiber-based Ytterbium laser. The laser is undergoing testing at Fermilab.
- Demonstration of laser amplitude modulation and 2W operation into optical fiber.
- Construction of the laser vacuum chamber. It is awaiting installation into the PIP2IT beamline.
- Simulation, design and construction of the electron deflection magnets.
- Procurement of the electron collection system.
Successfully delivered 2.1 MeV H\(^-\) beam at PIP2IT, that will be used for beam measurements for this project.

- PIP2IT laser hut design completed and is under construction.

Overall, effort on the project has continued as the system looks promising to provide information for the PIP2IT beamline. The integration of components into the final system is proceeding with the goal to produce measurement results at PIP2IT in the summer of 2018. The key deliverables for this project will be the construction and operation of a test fiber laser-based beam profiler and initial beam measurements. This profiler will be available for future testing and development beyond this project.

**Publications:**

“An Overview of Beam Instrumentation Results and Commissioning from the PIP-II Injector Test Accelerator at Fermilab.” Submitted to 2017 International Beam Instrumentation Conference.

**Project Number and Title:** FNAL-LDRD-2015-031

* A comprehensive investigation of a transformational integrable optics storage ring as a “smart” rapid cycling synchrotron for high-intensity beams

**Authors:** (PI) Alexander Valishev, Jeffrey Eldred (Fermilab), Swapan Chattopadhyay (Northern Illinois University/Fermilab)

**Project Description:**

This project seeks to enhance Fermilab’s strategic vision via engaging in a comprehensive feasibility study and investigation of an integrable optics “smart” rapid cycling synchrotron (RCS) as an essential component of a potential future multi-megawatt (MW) facility to advance neutrino science. The high-level project objective over a 3-year period is a full analytical, computational and technical evaluation of a scenario for multi-MW neutrino facility based on an innovative high intensity RCS.

**Relevance:**

A future multi-MW accelerator would be an enabling new device for research at the forefront of the intensity frontier with possible application to high luminosity hadron machines at the energy frontier. If successful, the study will result in significant cost reduction for a planned new RCS aimed to attain the beam power more than 2 MW for the future long baseline neutrino program.

**Results and Accomplishments:**

The second-year objectives were to a) evaluate the space charge mitigations using analytical approach; b) develop tools and establish procedures for simulations of space charge compensation; c) propose validation experiments to be carried out in the IOTA ring. Following this plan, and using the scenarios developed in year one, the space charge effect modeling in the new iRCS design was done both numerically with the Synergia code as well as analytically. The simulations guided the design of a new higher-periodicity lattice, which demonstrates a better degree of integrability at higher beam intensity. Along
objective c) the iRCS performance was compared to the space charge dynamics in IOTA and the effect of initial beam distribution is evaluated in order to provide useful input for future effort. The results of these studies were reported in talks at: Fermilab Accelerator Physics and Technology Seminar, Budker Seminar, IOTA Collaboration Meeting, Workshop in Intense Beams Dynamics, Space Charge Workshop, Center of Bright Beams Workshop.

Publications:


Project Number and Title: FNAL-LDRD-2016-001
Beam Precision Time Profile Monitor

Authors: (PI) Eric Prebys, Dave Hedin, Andrei Gaponenko

Project Description:
The goal of this project is to measure the fraction of beam that falls outside of nominal beam bunches, with a sensitivity of at least $10^{-5}$. The general problem of such measurements is the large dynamic range required to directly measure the beam intensity. Our proposed technique uses a statistical method, in which a charge telescope is used to monitor beam scattering off of an existing multi-wire or multi-foil installed in the beam line. An accurate time profile will then be built by integrating over many bunches. The sensitivity is expected to be at least two orders of magnitude better than that which can be achieved with traditional techniques, such as resistive wall monitors. We will initially use the Recycler primary collimators to scatter particles, to evaluate the 2.5 MHz Recycler bunches. The detector consists four arms of four detectors each. The sensitive element of each detector is a 1” cube of Quartz, which will generate Cherenkov light when a charged particle passes through. Cherenkov light is used because it is insensitive to soft backgrounds, and does not suffer from the “afterglow” problems of scintillators.

Relevance:
Longitudinal beam tails have significant implications for beam and acceleration efficiency, and are therefore an important consideration for all experiments where beam loss is a factor. At Fermilab, this will be particularly important as we increase the intensity of the Main Injector in the coming years. In the near term, this measurement is
important to the Mu2e Experiment, which has very stringent limits for out-of-time beam. This detector will use the Recycler beam scrapers to scatter particles, to evaluate the 2.5 MHz Recycler bunches. The results can be directly compared with simulations, which is in itself of fundamental interest to the accelerator community. These measurements will also provide valuable insight into Recycler operation for future experiments.

Results and Accomplishments:
The first arm of the spectrometer was installed in the Recycler tunnel last year. We were able to see the 53 MHz beam structure for NuMI Booster batches. Preliminary attempts were made to observe g-2 bunches before the summer shutdown, but the early unreliability of the g-2 beam made this difficult. Studies since the shutdown have been slowed down by the departure of Eric Prebys for UC Davis, but studies continue and it is hoped that we will make conclusive measurements in the next few months, which we ultimately plan to publish.

In addition, the additional Cerenkov radiators and PMTs were assembled and tested at NIU, and the design of the final support structure was completed. All electronics for the final (16 channel) readout system have also been purchased.

Due to the departure of the PI for UC Davis, the LDRD project will be completed in FY18. The lasting detectors that have been assembled should be useful in their own right and will have future impact at Fermilab.

Publications: none at this time.

Project Number and Title: FNAL-LDRD-2016-004
Development of an ultra-low energy threshold particle detector

Authors: (PI) Javier Tiffenberg, Yann Guardincerri, Christopher Bebek, Jeremy Mardon, Rouven Essig, Tien-Tien Yu, Tomer Volansky

Project Description:
Development and construction of a prototype new generation CCD-based particle detector with an ultra-low energy threshold. We’ve successfully build the first instrument with discrete sub-electron counting capability that can be reproducibly achieved over millions of pixels on a stable, large-area sensor. This leap in technology allow us, for the first time, to reach the theoretical limit of 1.1 eV in energy threshold, set by the silicon band gap. The sensor is pixelated with an spatial resolution of 15 micron and is capable of discriminating and counting individual electrons on each of its 4 million pixels.

This innovative readout technology has a negligible impact on CCD design and fabrication, and has nearly immediate implications for a wide range of scientific disciplines, from biological imaging to fundamental physics. Specifically it has immediate applications on neutrino and Dark Matter direct detection experiments.

Relevance:

FY2017 Fermilab LDRD Annual Report
The energy threshold of 50 eV of existing detectors precludes access to very low energy interactions. By reducing the energy threshold to 1.1 eV we are now able to investigate a new regime of interactions and provide the technology needed to build the next generation of neutrino and Dark Matter (DM) experiments that will be at the forefront of exploring physics beyond the Standard Model.

This LDRD completed in FY18 and we’ve been granted private funding from the Heising-Simons Foundation to build a larger version of our prototype system to conduct the first search of DM using this technology and explore a large number of currently inaccessible physics theories that are beyond the Standard Model of Particles. The construction of an even larger version of the detector with a target mass of 10kg is being considered to detect low energy neutrinos from Nuclear Power plants and could be an important tool for Non-Proliferation Treaty verification and the understanding the fundamental nature of neutrinos.

We are also exploring imaging applications that could have a major impact in astronomical instruments and microscopy.

Results and Accomplishments:
We’ve accomplished all the objectives of the project by successfully building the first instrument with discrete sub-electron counting capability that can be reproducibly achieved over millions of pixels on a stable, large-area sensor. The results of the project have had a big impact on several areas of the scientific and technology communities. A new experiment based on the technology developed within this LDRD has been identified as the priority by the Physics Community during the “Cosmic Visions” process organized by DOE in 2017. The next step of the project has obtained private funding from the Heising-Simons Foundation and we are currently on the process of building a science grade system that will be deployed by the end of 2018 at the MINOS underground facility, a shallow underground laboratory located on Fermilab grounds. The results of the project, published in Physical Review Letters, were highlighted by the editors as a major contribution that impacts many areas of research.

Publications:


Project Number and Title: FNAL-LDRD-2016-007
Tuning Axion Detectors with Non-Linear Dielectrics

Authors: (PI) Andrew Sonnenschein, Daniel Bowring, Shashank Priya, Alvin Tollestrup

Project Description:
Our LDRD proposal focuses on exploiting the novel electronic properties of non-linear dielectric materials such as strontium titanate (SrTiO$_3$) to build more sensitive detectors for axion dark matter particles. The expected properties of axion particles make them extraordinarily difficult to observe, as their interactions with ordinary matter and light would be negligible. However, in the presence of intense magnetic fields, axions may convert into ordinary photons, producing a weak electromagnetic signal that could in principle be observed. Detection of this signal will require large arrays of microwave resonator structures precisely tuned to a common frequency. The existing schemes for doing this require a large number of mechanical actuators operating at a temperature of just a fraction of a degree above absolute zero. Our proposed scheme would greatly simplify the problem by substituting solid state electronic tuning elements for mechanical actuators, making possible detectors with orders of magnitude larger detector volume and greater sensitivity.

Relevance:
Our long term goal is to discover a new elementary particle making up the “dark matter” believed to constitute most of the mass of the universe. Fermilab is the lead lab for the DOE’s ADMX-G2 experiment, which is now the most sensitive in the world to axion dark matter. However, the current generation experiment is sensitive to axions only within a limited mass range. The technology being developed using this LDRD grant would allow us to extend the range of mass sensitivity.

Results and Accomplishments:
We have built two devices which are being used to characterize the properties of SrTiO$_3$ films and demonstrate the principle of voltage-controlled frequency tuning of axion detectors. The first is a small diameter (<1 inch) probe containing a 6 GHz coplanar waveguide resonator that can be inserted into the bore of a high field magnet. The temperature of the probe can be adjusted from 6 Kelvin to room temperature. This probe is ideal for the rapid characterization of thin, planar samples at a fixed frequency. The second device, recently completed, is a 3D cavity resonator with a 50 mm diameter and hexagonal cross section. It contains a tuning rod controlled by a piezoelectric actuator capable of tuning from 4.5-6.5 GHz. Dielectric samples can be mounted on the inner walls of the resonator and exposed to the combination of the cavity microwave field and a high voltage DC electric field for fine tuning. This 3D resonator has all the essential features that would be required for axion detection and can be considered a single unit prototype for the array of resonators needed for future experiments. The resonator has demonstrated a quality factor of $10^3$ in room temperature operation, with cold testing planned for the near future.

We have produced and tested a number of thick film SrTiO$_3$ film samples on quartz and sapphire substrates using several film deposition techniques. A frequency shift in the
cavity resonance due to the STO film is clearly evident and the shift increases as the
temperature is lowered and the dielectric constant of the film increases. We have
performed simulations of our resonators using the COMSOL and HFSS microwave
simulation packages and the results of these simulations have been used to relate the
magnitude of the observed resonance shifts to the change in dielectric constant with no
electric field. The next anticipated steps are to repeat these measurements in the presence
of an electric field of up to 50 kV/cm and magnetic fields up to 7 Tesla. We are also
continuing to explore other film preparation methods, including the use of a composite
material made by mixing sub-micron SrTiO$_3$ particles in an epoxy matrix.

Publications: none at this time.

Project Number and Title: FNAL-LDRD-2016-008
Novel Methods for High Performance Superconducting Coating on Copper

Authors: (PI) Genfa Wu

Project Description:
Superconducting thin film cavities have the potential to save tens of millions of dollars in materials costs for superconducting accelerators. This project seeks to develop innovative approaches to generate superconducting coatings on cheaper substrate such as copper cavities that will match or exceed performance of bulk niobium cavities. The unique approach of this proposal is to dramatically increase film’s thickness using high quality high-speed deposition to achieve a film that is in the range of 50-100 micron in thickness. When using after-coating furnace annealing and chemical etching, one can truly obtain a coating that is closer or better than bulk material.

Relevance:
As the copper based film cavity performs, no one will ever make SRF cavities using expensive solid niobium. The film cavity will be able to take advantage of the very high thermal conductivity of the materials such as copper that can support high gradient operation more easily. The practical importance of the film based cavity is the cost savings, where copper costs less than a tenth of that of niobium. The successful outcome of this R&D project can directly benefit future HEP particle accelerators such as Proton Improvement Project (PIP3). If PIP3 will be built based on bulk superconducting technology, then it is estimated that ~ $20M of niobium material will be needed. If SRF cavities could be built with comparable performance out of microns’ thick niobium films on copper, then the cost savings would be of the order of $15M just for the PIP-3 project. Another example of important application for this technology would be Future Circular Collider (FCC) that would need significant more niobium material compared to PIP3. The benefit of coated cavity extends beyond the high energy physics that includes other department of energy programs such as nuclear energy physics, basic energy science as well as particle accelerators for industrial applications.

Results and Accomplishments:
  1. Major components for ECR coating are in place.
All components are in place that included vacuum system, magnet system, electron gun and RF system. Commissioning is in progress.

2. HiPIMS Design
   Vacuum system is shared with ECR coating. And its design was completed. Magnetron prototype design is completed and a journal paper is submitted. Optimization was completed. Procurement is in progress.

Publications:


Project Number and Title: FNAL-LDRD-2016-010
Preparing HEP reconstruction and analysis software for exascale-era computing

Authors: (PI) Marc Paterno, Christopher Green

Project Description:
The project is to produce a prototype software system suitable for moving high energy physics (HEP) experiment event data through multiple processing stages in an exascale-class computing facility. There are two critical components to be demonstrated: a) high-performance input and output (I/O) to a parallel filesystem and b) communication of event data through node interconnects rather than through the filesystem. Simulated and experimental HEP data will be used for the I/O implementation studies, the data store methods for a high-core-count, low-memory per core system, and studying the scaling performance.

Relevance:
HEP experimentation requires advanced computing capabilities and often breakthroughs in experimentation are the result of advances in computing. Current HEP projects take advantage of “high throughput computing” (HTC) which utilize an architecture not compatible with the new “high performance computing” (HPC) machines that will make available factors of 10s and 100s more processing power. This project will perform research and development on the architectures required for HEP data to make use of HPC machines.

Results and Accomplishments:
In the first year, we focused on the encoding of HEP data into several formats, based on the Hierarchical Data Format (HDF5) system. HDF5 is developed and maintained by the HDF Group, and is the premier data file format used at HPC centers. It supports parallel filesystems (which are in use at all large HPC centers) and parallel I/O. We drafted a
Fermilab technical publication enumerating the several processing contexts in which HEP I/O is required, identifying the majority of contexts which require event-by-event reading (as opposed to analysis contexts, in which small parts of events are read). Using quick prototype Python implementations, we evaluated multiple organizations for the run/subrun/event/data product hierarchy, and chose two for further development and performance characterization in C++. We also worked with the HDF Group to identify three data products, from the Deep Underground Neutrino Experiment (DUNE), which span the range of complexity of such products.

We have also begun the investigation of a distributed C++ runtime system, Charm++, to evaluate its suitability for use as a basis of an HEP event-processing framework. Charm++ has been used in a variety of traditional HPC problem domains. We have met with the main the Charm++ designers to discuss possible program organization, and are now working on the first demonstration of a conceptual HEP event-processing framework using Charm++.

**Publications:** Fermilab technical publication on event storage requirements, being prepared.

**Project Number and Title:** FNAL-LDRD-2016-032  
Implement open source HEP NoSQL database

**Authors:** (PI) Oliver Gutsche (Fermilab), Igor Mandrichenko (Fermilab), Jin Chang (formerly Fermilab PI, now Caltech), Jim Pivarski (Princeton University)

**Project Description:**
Efficient management of “big data” is critical to the overall success of many high energy physics experiments at Fermilab. From the initial event reconstruction to data analysis, scientists spend much time in sorting out the computing details of searching and correlating interesting events before being able to focus on the research.

The purpose of this project is to implement an open source HEP NoSQL database and computing framework that can be used as a broader data analysis service for multiple HEP experiments. We believe such a platform will offer greater flexibility and significantly reduce the overall efforts required for data analysis than currently used object-oriented file-based technologies. The proposed platform is well aligned with Fermilab’s participation in Big Data R&D following research directions in industry and DOE ASCR extreme scale science.

**Relevance:**
One of the main challenges in managing high energy physics data is making the data accessible to a large number of data analysts with different interests. The dataset is large, but also generic because it contains information for any possible analysis. Every data analyst must therefore filter and transform the data in different ways. Moreover, this process has to be repeated many times to find optimal data selection criteria to produce the most accurate physics results.
Given this challenge, most physicists resort to making private copies of the data with fewer events ("skimming") and/or fewer variables ("slimming") than the original dataset. This compounds the problems of computing resource utilization and data versioning and provenance. Our goal is to short-circuit this process with a responsive query system that quickly finds and serves physics data on demand, eliminating the need to copy data.

We are doing this by storing the data in a NoSQL database and use caches to provide a mechanism to find and deliver relevant data to the analysis process with a columnar data representation.

**Results and Accomplishments:**
In FY17, we developed a format of HEP data representation suitable for storing data in a no-SQL databases in a way which would support efficient and scalable parallel data analysis. We call the format “Striped Data Representation”, or ”Striped”. The Striped format is a variation of a columnar data representation. Major features of this format are its suitability to represent complex data structures used in HEP; its support of efficient partial reads of records; and its compatibility with any key-BLOB data storage, covering a wide range of open-source and commercial no-SQL database management products as well as POSIX file systems. It uses the open-source community package numpy as internal data representation. This significantly reduces data decoding overhead during the analysis using Python as the analysis language.

We conducted comparison analysis of several no-SQL database products (Cassandra, AeroSpik, MongoDB, CouchBase) and concluded that most of them would be able to support Striped data representation, and selected CouchBase because it has some attractive features such as direct management of the RAM cache, completely symmetrical architecture, low deployment and support cost.

For performance testing, a test cluster was built including a 12 TB data storage cluster out of 15 decommissioned farm nodes and a 2-node, 32 core computing cluster. As a user test case, we converted CMS Dark Matter Search dataset into Striped format and stored the data into the development cluster. We used the CMS Dark Matter Search dataset to plot dimuon invariant masses to show the Z boson peak as the demo analysis problem and to measure the performance of the Platform. Our measurements show that for this simplified analysis use case, we can process up to a million events per second using our 30 cores cluster. The performance is scaling with adding more nodes to the Platform. Our results were presented in ACAT 2017 (FERMILAB-CONF-18-016-CD).

In FY18, we are expanding our use cases to test the system under different conditions. We presented our system to members of several collaborations: US CMS, NOvA, MicroBooNe, and DES. We obtained samples of their data and analyzed how easy it would be to convert their data to the Striped format. The goal is to work with the collaborations to enable them to perform data analysis using the Striped Data Representation.

**Publications:**

**Project Number and Title:** FNAL-LDRD-2016-034
**R&D and Experimental Instrumentation for the Initial Set of Critical Scientific Experiments in IOTA and the FAST Injector**

**Authors:** (PI) Swapan Chattopadhyay

**Project Description:**
This project involves conceiving, designing, building and commissioning experimental diagnostics and instrumentation to observe and understand the unique behavior of an intense beam of charged particles (e.g. protons) interacting with each other very strongly via self-generated electric and magnetic fields and moving under very special nonlinear magnetic focusing forces that confine the beam in stable orbits in a specially designed storage ring, called IOTA. For this experiment to be meaningful, one must follow the beam and its characteristics, first as it is injected into the circular ring and then, to follow its evolution over time via special diagnostic instruments that record its properties in subsequent time as the beam circulates in the ring. The necessary diagnostic to measure the beam dynamical properties during evolution is a Gas Jet Monitor, where a weak jet of gas intersects the beam and scatters off it, giving us an image as well as velocity profile of the beam. A second experiment involves a very precise pencil-like electron beam that interacts with itself via a self-generated optical feedback loop and gets damped in its transverse motion. This experiment will require some special-purpose nonlinear optical elements to be designed and built and very fast laser-based diagnostics and light detectors. The LDRD project is to conceive, design procure, and commission the above special-purpose diagnostic equipment to enable the first set of high-impact experiments to be conducted in the IOTA ring.

**Relevance:**
The IOTA /FAST accelerator complex is a test facility to test and develop novel ideas, which can be experimentally tested as a prototype, to help pave the way in generating much more intense proton beams than have been produced to date historically in a cost-effective manner, without employing high-cost superconducting radio-frequency linear accelerator technology. Intense beams of such high strength are required for future experimentation in high energy physics in general, but especially critical for high intensity neutrino beams relevant to neutrino physics being pursued by DOE at Fermilab in the flagship international experiment, DUNE. Thus, this LDRD project is tied to the core mission and strategic future of DOE and Fermilab in the energy and intensity frontiers for high precision science.

**Results and Accomplishments:**
The project involved effort equivalent to 1 Full Time Equivalent (FTE) of a post-doctoral research fellow, Ben Freemire, funded fully by other DOE sources at a collaborating
university (NIU), in developing the designs in collaboration with other Fermilab and university researchers. The Gas Jet monitor has been designed and its vacuum parts and other components including the test chamber, movable 3-dimensional positioners and CCDs are under procurement. The special optical beamline has been designed and special purpose magnets and vacuum parts are under procurement.

**Publications to date:**

Proceedings of IBIC'17: "Gas Jet Halo Profile Monitor for Use in IOTA Proton Beam", S. Szustkowski, S. Chattopadhyay, D. Crawford, B. Freemire

Proceedings of NuFact'17: "Accelerator R&D at Fermilab's FAST/IOTA for Future High Intensity Proton Accelerators", B. Freemire for the FAST/IOTA Team

Submitted to Proceedings of IPAC'18: "Simulations of the Electron Column in IOTA", B. Freemire, S. Chattopadhyay, C.S. Park, G. Stancari

Submitted to IPAC'18: "Development of a Gas Sheet Beam Profile Monitor for IOTA", S. Szustkowski, S. Chattopadhyay, D. Crawford, B. Freemire


**Project Number and Title:** FNAL-LDRD-2017-003

**Optical Microwave Kinetic Inductance Detectors (MKIDs) for future cosmic surveys**

**Authors:** (PI) Juan Estrada

**Project Description:**

MKIDs are single photon detectors taking advantage of kinetic impedance in superconducting thin films. Photons incident in the superconductor film change the surface impedance through the kinetic inductance effect, giving a detectable signal proportional to the energy of the photon. MKIDs have the great advantage of being easily multiplexed in the frequency domain, allowing for the development of very large arrays of superconductor detectors (20,000 pixels arrays has been tested in telescopes). MKIDs have the potential of reaching a photon energy resolution $R = E/\Delta E \sim 100$ in the blue edge of the visible spectrum, the current performance achieved in these sensors is $R \sim 15$. This project consists on sensor R&D focused in the understanding the current limitations of the MKID energy resolution.

**Relevance:**

In the coming decade the observational cosmology community will build and operate the most ambitious astronomical imaging surveys ever. The Large Synoptic Survey Telescope (LSST) will produce imaging for half of the sky in 5 optical and near-IR
filters, a database with approximately 3,000,000,000 galaxies. These maps will allow measurements of the large scale structure of the universe with very high angular precision to study Dark Energy. However, the information along the line of sight in these surveys is diluted by the uncertainty in the redshift estimations based on multi filter observations. Typical redshift uncertainty of $\sigma_z/(1 + z) \sim 0.1$ are produced by the imaging surveys, which correspond to a line of sight distance uncertainty $\sigma_d \sim 300$ Mpc. Spectroscopic follow up observation for all the galaxies in these data sets will not be possible with the technology currently available. MKIDs could provide a tool for low resolution ($R = E/\Delta E \sim 30 - 100$) wide field spectroscopic follow up of DES and LSST with the goal of reducing by a factor of 10 the redshift uncertainty. MKIDs have been identified by the High Energy Physics community as a technology that could allow billions of galaxies found in LSST to be used for wide field and low resolution Redshift Space Distortions measurements, as stated in the last P5 Report.

**Results and Accomplishments:**

Project started in April 2017. Two visiting students joined the effort right away for Universidad de Guanajuato, Mexico (one of them was supported by the LDRD and the other supported by his home institution). A visiting scientist from CBPF (Brazil) also joined the effort in summer 2017 (partially supported by LDRD). The visitors got fully trained at the Pritzker Nanofabrication Facility located at U.Chicago to fabricate MKIDs. Together with the University of Chicago (Prof. Erik Shirokoff) we designed and fabricated our first MKIDs during summer 2017. We used Atomic Layer Deposition (ALD) to produce the thin superconducting film, in order to have full control of the properties of the MKIDs. The sensors have been characterized at FNAL as a function of temperature and operating power. The uniformity in the ALD fabrication process produced very consistent performance in the MKIDs. This is an encouraging result giving the experience with other fabrication processes. We have also demonstrated high sensitivity and low noise in the sensors. The final results of energy resolution in this R&D sensors is expected for fall 2018.

Two additional MKID fabrication runs were completed in early 2018. We completed one run with a lower critical temperature MKIDs, for higher energy resolution. An additional fabrication run was completed with a modified design for testing some modeling issues for the sensors. The characterization of these sensors will start in spring 2018.

**Publications:**


**Project Number and Title:** FNAL-LDRD-2017-010  
**Training Deep Neural Networks for Neutrino Identification in the Cloud**  
**Authors:** (PI) Evan Niner, Alex Himmel
Project Description:
Deep learning has great potential for the neutrino physics and HEP community at large to improve the way we reconstruct and classify particles and interactions inside detectors. This LDRD builds on the work already done for NOvA, developing and optimizing new deep networks to identify substructure in the events, i.e. individual particles, rather than classifying the overall neutrino interaction and also to reduce the computing burden of the experiment from cosmic ray background interactions. We will also pioneer a new way to access the required GPU resources: using off-site commercial resources via HEPCloud. Training networks is a great example of high “peak” demand and low average demand, making it well suited to the HEPCloud approach.

Relevance:
Both in the physics community and the world at large the applications of machine learning to solve problems has become increasingly widespread. Fermilab and NOvA have been at the forefront of developing deep learning applications and NOvA published the first HEP result in 2017 to employ a deep convolutional neural network. As these applications become widespread it is important to develop efficient workflows for training these networks and pooling GPU resources. The HEPCloud has proven successful in the standard computing workflow of experiments and is a natural candidate to expand the pool of GPU resources. In NOvA this project is designed to address the specific problems of particle identification with an application to neutrino cross section physics and cosmic rejection where a neural network that can reduce background events early in the workflow independent of calibration and reconstruction would significantly reduce the computing load for the rest of the experiment workflow.

Results and Accomplishments:
We have established the required GPU resources and integrated into the existing Fermilab computing infrastructure. We have used these resources to develop neural networks both for the application of particle identification and rejection of cosmic ray backgrounds in the NOvA experiment. We have piloted submission of network training jobs via the HEPCloud and worked with the Scientific Computing Division to pilot the use of Singularity, a portable software container system, to expand the computing resources available for network training. In addition to network optimization for physics performance, we are establishing groundwork to understand how network optimization on GPUs translates in computational run-time performance in the large-scale CPU processing that is part of standard experimental workflow. In FY18 we will be evaluating trained particle identification networks in NOvA and applying them to understand simulation model biases from training information and the application of measuring neutrino cross sections. Development on algorithms for early rejection of cosmic ray backgrounds in the analysis stream will continue. We will be working with the computing division to tie the GPU resources at Fermilab into the HEPCloud to streamline the training process.

Publications: none at this time.

Project Number and Title: FNAL-LDRD-2017-011

FY2017 Fermilab LDRD Annual Report
LArCADe _ Liquid Argon Charge Amplification Devices

Authors: (PI) Angela Fava

Project Description:
This project has started in FY18. There were no FY17 costs.

The primary goal of LArCADe Project is to multiply electron charge generated by ionizing particles passing through liquid argon medium directly in liquid at the end of the drift path.

The feasibility of this idea is investigated by the experimental characterization of the behavior of micrometric tungsten tips in liquid argon, exploiting small drift chambers available at Fermilab and properly modified.

Systematic measurements of the ratio between collected and produced charge for different geometric features of the tips and as a function of the applied biasing voltage to the electrodes will be complemented by software simulation for improving the understanding of the behavior of liquid argon in presence of local electric fields between hundreds of kV/cm and MV/cm, where the proportional multiplication should occur before reaching the breakdown limit.

Relevance:
The primary motivation of LArCADe Project is to make single-phase Liquid Argon Time Projection Chamber detectors sensitive to energy deposition O(10 keV), 100 times smaller than the state of the art.

The impact on Particle Physics of low energy rare events is potentially dramatic, mainly in searches for coherent neutrino scattering and Dark Matter interactions characterized by O(100 keV) experimental signature and $O(10^{-40} \text{ cm}^2)$ cross section.

Interdisciplinary applications in telescopes for Gamma-rays polarization measurements and in high resolution Compton spectrometers for medical imaging or identification of explosive devices are also possible.

Results and accomplishments:
The Project start date has been delayed until December 2017 due to time for on-boarding of the requested manpower (one post-doc at 30% of his time).

However, this initial deadlock has been proficiently mitigated by putting effort in developing the expertise for producing the tungsten, W, tips within Technical Division at Fermilab. A setup for electrochemical etching of W wires, exploiting a solution of 8 g of Sodium Hydroxide (NaOH) in 100 g of distilled water with 4 V applied voltage, has been prepared and optimized, leading to the production of the first tip by December 2017.
The procedure for Quality Control of production has also been defined, with measurements of the geometrical properties of the tips (curvature radius at the apex and at the base of the conic tip, as well as aperture angle of the cone) performed with a scanning electron microscope (SEM).

**Publications:** none at this time.

**Project Number and Title:** FNAL-LDRD-2017-014

**Cryogenic photon sensors for the low mass frontier**

**Authors:** (PI) Aaron Chou

**Project Description:**
This project is expected to start in FY18 once an order for a dilution refrigerator is placed.

**Project Number and Title:** FNAL-LDRD-2017-019

**First Demonstration of conduction cooled SRF cavity**

**Authors:** (PI) Jayakar Charles Tobin Thangaraj; (Co-PI) Thomas Kroc; Ram Dhuley, Michael Geelhoed

**Project description:**
Superconducting radio frequency (SRF) cavities in particle accelerators operate at liquid helium temperatures, which requires bulky and complex cryogenic infrastructure. This LDRD project aims to demonstrate operation of a SRF cavity conductively cooled by a compact cryogenic refrigerator (cryocooler) that eliminates the need for liquid Helium. Specific aims of this project are to: (1) design and build thermally conductive cryogenic links for cooling a SRF cavity using a commercial cryocooler, (2) build a test stand for RF testing of the conduction cooled cavity, and (3) demonstrate RF operation of the cavity at practical accelerating gradients.

**Relevance:**
The cost and complexity of designing, building, and safely operating SRF based particle accelerator is escalating. In all modern SRF accelerator, the Niobium cavities are immersed in large baths of liquid helium – the primary driver of cost and complexity of the cryogenic infrastructure. By exploring conduction cooling with modern cryocoolers, our work will substantially reduce cost and complexity of future SRF accelerators. Successful execution of this project will replace complex cryogenic modules with much simpler liquid helium free versions. It will also enable SRF accelerators for the first time to enter the industrial accelerator arena with the potential to create presently unavailable high-efficiency, compact, MW class electron accelerators.

**Results and accomplishment:**
In FY17, this project completed its first goal stated in Project Description:
- Based on extensive literature review of cryogenic material properties, we selected high purity aluminum as the material for conduction links. We identified
appropriate vendor, procured the aluminum, and measured its thermal conductivity using an in-house built cryocooler based test setup. Based on the measured data, we designed geometry of the conduction link for a niobium SRF cavity.

- SRF cavities intended to be cooled by liquid helium carry no provision for connecting our conduction link to the cavity. We engineered electron-beam welded rings around the cavity ellipses that provide a uniformly plane surface on the cavity to anchor the conduction link. We note that this is an innovative design for thermal link based on Fermilab IP.

- By following systematic surface cleaning procedures and contact resistance measurements, we designed technique for interfacing the aluminum conduction link with the ring-welded niobium cavity.

Employing the outcomes of the above activities, we cooled a single cell 1.3 GHz and a single cell 650 MHz cavity to 4 K using a cryocooler. The cooldown time was less than a day.

We have also made significant progress towards the second goal listed in Project Description:

- A new single cell 650 MHz cavity has been designed and ordered for fabrication.
- A low level radio frequency (LLRF) for RF testing the cavity is under procurement.
- A new multi-watt cryocooler has been purchased and a test-rig is being set-up for its commissioning.
- A new cryostat is under design that will house the new cavity, its conduction link, and the cryocooler. The cryostat will be magnetically shielded and will ultimately enable RF testing of the cavity under low ambient magnetic fields.

Publications:


Project Number and Title: FNAL-LDRD-2017-020
Development of next-generation Nb₃Sn superconductors for accelerator magnets

Authors: (PI) Xingchen Xu

Project Description:
This project aims to develop a new generation of Nb₃Sn superconductors with significantly enhanced critical current density ($J_c$) for accelerator magnets. Nb₃Sn is the workhorse conductor to fabricate magnets >10 T. Boost of fields of magnets requires increase of superconductor $J_c$s. This LDRD project is based on a novel technique.
invented by the PI, which forms ZrO$_2$ particles (<10 nm) in Nb$_3$Sn via internal oxidation of Nb-1%Zr. These ZrO$_2$ particles can refine Nb$_3$Sn grain size from 100-150 nm to 35-50 nm and improve $J_c$ (as $J_c$ is inversely proportional to grain size). This project aims to develop this new technique, solve issues such as low upper critical field ($B_{c2}$) seen in previous samples, and transform it into magnet-grade Nb$_3$Sn conductors.

**Relevance:**
Study of new physics needs proton-proton circular colliders with higher collision energy, which requires accelerators with higher magnetic fields for bending particle beams. The magnetic field generated by a coil is determined by the coil width $W$ and the $J_c$ of Nb$_3$Sn conductors. Because magnet cost increases dramatically with $W$, higher field relies on higher $J_c$. Taking the planned future circular collider (FCC) as an example, to achieve the targeted 16 T, it requires Nb$_3$Sn conductors with 50% higher $J_c$ than the present state of the art. However, the $J_c$ of Nb$_3$Sn has plateaued for decades. The novel technique in this project is expected to deliver a new generation of Nb$_3$Sn conductors with significantly higher $J_c$. Such conductors can not only increase the achievable field of accelerator magnets (to 16 T and above) for future p-p circular colliders (such as high-energy LHC and FCC), but also greatly reduce their costs by billions of dollars. This effort aligns very well with the P5 strategic plan and Fermilab’s missions and competencies.

**Results and Accomplishments:**
In the past year great progresses have been made. First, significant efforts were made to optimize recipe of the powder-in-tube conductors based on this new technique, including optimizing Sn/Cu/SnO$_2$ ratios, size of Nb-1%Zr tube, powder packing density, and powder mixing and filling methods, etc. Over ten multifilamentary wires have been fabricated, with wire quality improved greatly over time. Second, ternary additives (tantalum and titanium) were introduced. These efforts lead to improvement of 4.2 K Nb$_3$Sn $B_{c2}$ from 20 T to 25 T (which is similar to present regular Nb$_3$Sn conductors) – this solved a big problem because previously the major concern for this technique had been that it might improve pinning at the expense of $B_{c2}$. Thanks to the great improvement of conductor quality and $B_{c2}$ in the past year, the 15 T non-Cu $J_c$ was improved from ~350 to nearly 900 A/mm$^2$, and the improvement is still ongoing. Root causes for issues limiting the non-Cu $J_c$ have been identified and solutions have been developed. Moreover, the point pinning behavior of the new conductors developed in this project was discovered, which leads to several important properties (such as much lower magnetizations at low fields).

**Publications:**

**Project Number and Title:** FNAL-LDRD-2017-027  
SiCN  
**Silicon precision timing detectors for minimum ionizing particles**

**Authors:** (PI) Artur Apresyan, Lindsey Gray
Project Description:
The project aims to develop over two years the technology that achieves the level of 20-30 picoseconds (ps) for single minimum ionizing particle detection, and implement it in a detector comprised of around 30 individual readout channels. Precision timing devices based on silicon sensors with internal gain will be used to provide a radiation tolerant, cost-effective, large area timing system with resolution $O(20 \text{ ps})$. An exhaustive characterization of the available single-channel sensors, and their radiation tolerance will be performed, which will aid in the design of the following production runs for larger area sensors. Sensor readout and data acquisition systems will be developed for characterization studies, and a versatile testing system will be designed and installed at SiDet for sensor characterization.

Relevance:
The next generation of detectors being built for particle physics experiments at colliding beams will face enormous challenges in terms of beam intensity and the volume of the detectors themselves. Without a significant improvement in the timing capabilities of these future detectors the quality of the data taken will degrade significantly. Detectors with timing resolution of about 30ps could reveal the time-evolution of electromagnetic and hadronic showers, and discriminate particles that originate from a hard scatter event from those in overlapping proton-proton collisions (pileup/PU). Both ATLAS and CMS are considering dedicated timing detectors as extensions to their HL-LHC upgrade plans, where PU larger than 200 is expected. The capabilities of the upgraded CMS and ATLAS detectors would be significantly enhanced by adding a dedicated timing detector. Looking beyond the HL-LHC, the eventual 4D-tracking and 4D-calorimeter detectors resulting from this research will provide the capability for precision physics to be done in extreme PU environments.

Results and Accomplishments:
In FY17, this proposal helped fund the development of new capabilities at the Silicon Detector Facility (Sidet) at Fermilab, develop the test stand for precision characterization of silicon sensors, perform test beam and laboratory measurements, and to design the next generation of precision timing detectors. These include the following:

- Design and production of a 4-channel printed-circuit board (PCB) with fast amplifiers and low noise. These boards were used in multiple measurements at Fermilab, and have been distributed to multiple collaborators in US universities.
- Design and construction of a cold-running testing box, capable of maintaining -30C temperature, with remotely controlled internal motion stages, and multi-signal patch-panel. This box was used to test in the laboratory and the Fermilab test-beam for studies of irradiated sensors.
- The PCB boards designed at FNAL were used to test in the laboratory at SiDet, and at the Fermilab test beams to characterize new and irradiated silicon sensors.
- Measurements of sensors produced by two vendors were performed at FNAL, and demonstrated excellent uniformity of signal size and time resolution across large-area silicon sensors.
- Single channel, irradiated sensors were shown to sustain excellent time resolution, and sensors from one of the vendors were shown to maintain highly uniform
response across sensor area. Based on the measurements at Fermilab, the design of the sensor from the other vendor was modified for the next production, in order to achieve similar uniformity.

- Based on the studies supported by this LDRD, the design of the next round of radiation hard, multi-channel sensors has been finalized with three manufacturers, and we expect the next round of large-area sensors to arrive by Summer 2018.

Publications:

Project Number and Title: FNAL-LDRD-2017-028
Increasing the photon detector light efficiency in a liquid argon detector by an order of magnitude

Authors: (PI) Gustavo Cancelo, Flavio Cavanna, Adam Para, Carlos Escobar, Ettore Segretto, Ana Machado, Ernesto Kemp, Stuart Mufson, Denver Whittington, Laura Paulucci, Norm Buchanan, David Warner.

Project Description:
The technical objective of the current work is to achieve a photon detection efficiency higher than 1% in LAr scintillating detectors.

Relevance:
This is of paramount importance for detectors such as the DUNE Photon Detector (PDS). A high light detection efficiency will allow the PDS the determination of a time stamp (T0) for non-beam events for proton decay candidates and atmospheric neutrinos with 90% efficiency. For supernova physics it should allow a T0 with high efficiency to improve the energy resolution on supernova burst neutrino (SNB) events. An SNB event will generate low-energy (5–50 MeV) events [1]. A high light detection efficiency is also important in background rejection as explained in the next section.

Scintillation events in Ar produce 127nm photons. The light is converted to ~450mn to be observed by SiPMs. Our work has developed a light trapper named ARAPUCA and a novel active ganging architecture of SiPMs. The ARAPUCA devices will increase the light collection while the active ganging of SiPMs will increase the detection area while keeping a low number of channels and cost.

The ARAPUCA is based on two wavelength shifters a filter a highly reflective box and Silicon photon sensors. A shifter on the external side on the external face of the filter converts LAr scintillation light to blue light that travels through the filter. The shifter on the internal side converts the light to green photons that bounce off the filter and get trapped in the reflective box.

Results and Accomplishments:
During the 1st year we have improved the ARAPUCA and active ganging of SiPMs designs. We have performed optical measurements using short pulses from UV LEDs and
performed runs in liquid argon (LAr) using radioactive sources and cosmic rays. We have explored and narrow down the selection of dichroic filters based on quality and cost. We developed techniques to analyze data from LAr experiments. We have also validated or improved existing measurements on wavelength shifter photon absorption and emission. We have also developed procedures to improve adherence of wavelength shifters to the dichroic filter and base material.

In the ganging on SiPMs we have developed an ultra low noise preamplifier capable of summing the action of many photon sensors in a single channel. The current results of efficiency for ARAPUCA with passive ganging are over 0.5% and will be improved to our goal of over 1% during the 2018.

**Publications:**

**Project Number and Title:** FNAL-LDRD-2017-038
Quantum Computing Using SRF Technology

**Authors:** (PI) Alexander Romanenko

**Project Description:**
The project is focused on designing, manufacturing, and studying single and multiple unit quantum computing structures based upon a combination of ultra-high Q superconducting radio frequency (SRF) host cavities and embedded Josephson junction qubit(s). The goal of this work is to achieve within the next few years a working high coherence multiple qubit quantum system suitable for various tasks including quantum computing and quantum memory.

**Relevance:**
Quantum computers propose to provide a new degree of computational power that potentially could revolutionize certain calculations that are relevant for High Energy Physics (HEP). Current limitations include lifetime and de-coherence issues with storing quantum information. This project will utilize existing expertise in High Energy Physics in SRF technology, cryogenics, and other technical abilities to help overcome the limitations and position HEP to be a contributor to this possible computing revolution.

**Results and Accomplishments:**
In the first year of this LDRD project, a very large state-of-the-art dilution refrigerator to enable measurements of SRF cavities down to temperatures less than 10 mK has been procured, installed, and commissioned. Required microwave measurement and single qubit control equipment has been procured as well. The first near-quantum regime
measurements have been performed and showed a record high photon lifetime of 122 ms in the quantum regime, factor of > 50 improvement over the state-of-the-art.

Publications:
“Ultra-high Q > 10^{10} superconducting 3D cavities for quantum computing and quantum memory”, A. Romanenko et al, 2018 APS March meeting invited presentation

VI. Notes on Completed Projects
Each Fermilab LDRD project that is completed will have a Final Report written and submitted to the DOE Office of Scientific and Technical Information.

VII. Conclusions
Fermilab is successfully conducting a LDRD program in accordance with the terms of its authorization. The current portfolio of approved projects are addressing R&D in several areas of scientific and technical expertise that exist at the Laboratory. All projects are aligned with the mission of the Laboratory and DOE and have begun to making good progress. Already, there have been several publications that are related to the LDRD work and a provisional patent that has been generated. The number of proposals already submitted and subsequent discussion with those who have submitted the proposals also indicate that the LDRD program is strengthening the scientific and technical vitality of Fermilab.