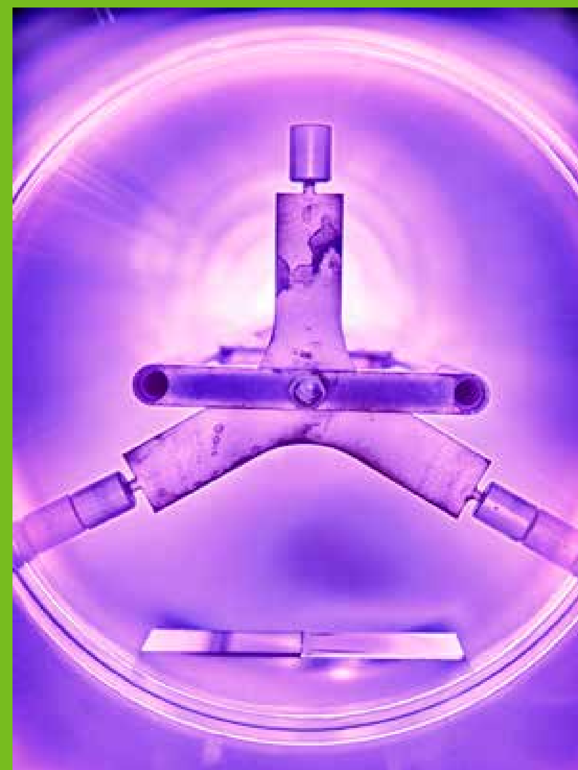
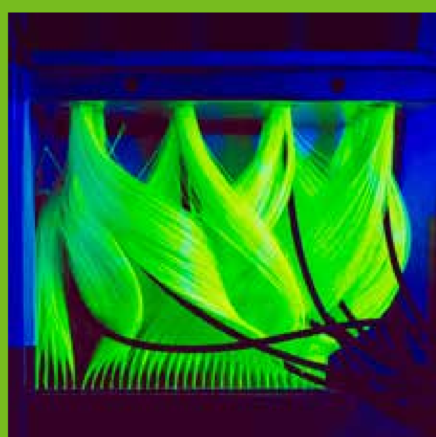
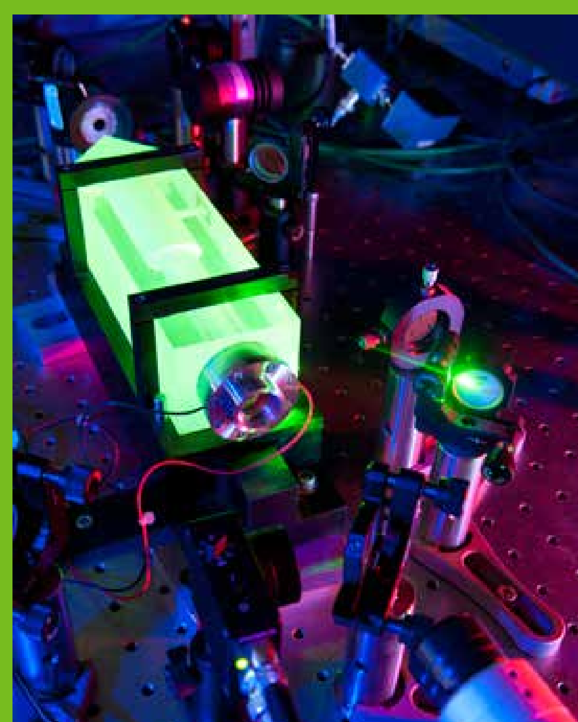
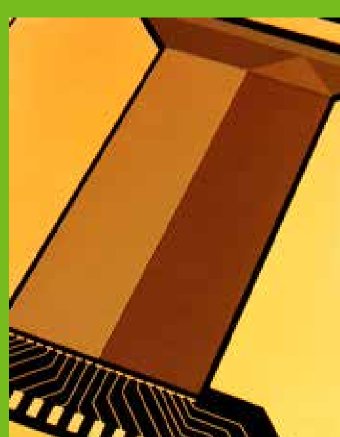
FERMILAB-FN-1015-LDRD

2015 Fermilab | Laboratory Directed Research & Development Annual Report









Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

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

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I. Executive Summary

The Fermi National Accelerator Laboratory (FNAL) is conducting a Laboratory Directed Research and Development (LDRD) program. Fiscal year 2015 represents the first full year of LDRD at Fermilab and includes seven projects approved mid-year in FY14 and six projects approved in FY15. One of the seven original projects has been completed just after the beginning of FY15. The implementation of LDRD at Fermilab is captured in the approved Fermilab 2015 LDRD Annual Program Plan. In FY15, the LDRD program represents 0.64% of Laboratory funding. The scope of the LDRD program at Fermilab will be established over the next couple of years where a portfolio of about 20 on-going projects representing approximately between 1% and 1.5% 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 with 84 new ideas put forward resulting in 36 full proposals being submitted to a selection committee. The Laboratory Director has approved the thirteen projects being funded that are the subject of this Annual Report. The funded projects are based in all of the scientific and technical divisions of the Laboratory and often help facilitate cross-divisional work.

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.

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II. Program Overview

Beginning in FY 2014, Fermilab has initiated a LDRD program as authorized by a DOE order, 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.

The FY 2015 Fermilab Annual LDRD Program Plan has been approved and used to implement the FY 2015 LDRD Program. The laboratory sought and was granted approval for an LDRD expenditure comprising up to a maximum of 1.0% ($3.5M) of the laboratory's total operating / capital budget. Actual expenditures were below the allowed maximum and came in at 0.64% ($2.1M) of the laboratory's total operating / capital budget.

Following an approved FY 2015 Annual LDRD Program Plan, a call for proposals was issued and 34 preliminary proposals were received. These preliminary proposals were typically one page in length and required supervisory and divisional concurrence as to the proposed scope of effort and materials requested by the PI. 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 12 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 six new

LDRD projects at Fermilab. Table 1 shows the flowdown for proposals and funded projects for FY14 and FY15.

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

Fiscal Year	Preliminary Proposals	Full Proposals	Funded LDRD Projects
FY14	50	29	7
FY15	34	12	6

The thirteen 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 both December 2014 and August 2015, the LDRD selection committee conducted mid-year reviews of each of projects and recommended project continuation that was subsequently approved by the Laboratory Director. At the August mid-year review, the PI provided updated budget information for the following fiscal year. Each PI provided the Project Summary contained within this document. One of the original FY14 projects has been completed shortly after the beginning of FY15.

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 competetiveness*

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 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 FY15. Table 3 shows the similar list of projects approved in FY15.

Table 2: List of FY14 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY15 and uploaded to the CFO database.

LDRD Project Number	Project Name	FY2015 Spending
FNAL-LDRD-2014-010	Cosmic Microwave Background Detector Development at Fermilab	$442,591
FNAL-LDRD-2014-012	Development of HTS Based Rapid-Cycling Accelerator Magnets	$152,869
FNAL-LDRD-2014-016	High Frequency Gallium Nitride Driver	$187,365
FNAL-LDRD-2014-025	The Sinuous Target	$26,314
FNAL-LDRD-2014-027	From Magic to Method: Characterizing High Voltage in Liquid Argon Time Projection Chambers with the Breakdown in liquid argon cryostat for high voltage experiments	$400,349
FNAL-LDRD-2014-028	Deployment and operation of prototype CCD array at Reactor Site for detection of Coherent Neutrino-Nucleus Interaction	$111,363
FNAL-LDRD-2014-038	Application-Oriented Network Traffic Analysis based on Graphical Processing Units	$236,271
FY 14 Totals		**$1,557,121**

Table 3: List of FY15 Fermilab LDRD Projects and the associated spending with each project. Shown is the actual spending in FY15 and uploaded to the CFO database. The total FY2015 spending for all on-going projects (FY14+FY15) is also shown.

LDRD Project Number	Project Name	FY2015 Spending
FNAL-LDRD-2015-009	High Energy Physics Pattern Recognition with an Automata Processor	$158,929
FNAL-LDRD-2015-010	Dark Energy Survey and Gravitational Waves	$51,112
FNAL-LDRD-2015-020	Off-the-Shelf Data Acquisition System	$264,640
FNAL-LDRD-2015-021	Transverse and Longitudinal Profile Diagnostics for H- Beams using Fiber Lasers and Synchronous Detection	$33,382
FNAL-LDRD-2015-029	Nb_3Sn Superconducting RF Cavities to Reach Gradients up to 90MV/m and Enable 4.2K Operation of Accelerators	$124,828
FNAL-LDRD-2015-031	A Comprehensive Investigation of a Transformational Integrable Optics Test Storage Ring as a "Smart" Rapid Cycling Synchrotron for High-Intensity Beams	$0
FY15 Totals		**$632,890**
FY14 + FY15 Totals		**$2,190,011**

Note: that while approved in FY15, one project FNAL-LDRD-2015-031 will formally commence in FY16 once a postdoctoral researcher is hired.

V. Project Summaries

Each of the thirteen on-going and recently completed 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. There is a description of initial results and accomplishments of each project along with a list of publications (if any) that have been produced.

Project Number and Title: FNAL-LDRD-2014-010
Cosmic Microwave Background Detector Development at Fermilab

Authors: (PI) Bradford A. Benson (Fermilab); John Carlstrom (University of Chicago), Clarence Chang (Argonne National Lab), Hogan Nguyen (Fermilab)

Project Description:
This project proposes to perform research and developing to demonstrate the production of arrays of superconducting transition-edge sensors (TES) detectors for future CMB experiments. This proposal supports the design and development of new TES detector technologies, the assembly of prototype modules of TES detector arrays, and the construction of a unique high-throughput testing capability, to characterize large arrays of detectors for future CMB experiments.

Relevance:
Fully realizing the scientific potential of CMB polarization will require new detector technology that enables instruments with >10 times more sensitivity than current experiments. The technological challenges for future CMB experiments are well matched to, and solely filled by national labs like Fermilab. This proposal explicitly follows the P5 report's recommendation to: "***Increase particle physics funding of CMB research and projects in the context of continued multiagency partnerships***." The instrumentation developed will lead to CMB experiments that aim to answer some of the most exciting questions in cosmology and that are at the heart of the high-energy physics mission: to constrain inflationary physics at grand-unified theory energy scales (~ 10^{16} GeV), to measure the sum of the neutrino masses at a level below the minimum mass expected from neutrino oscillations (< 0.06 eV), and to precisely constrain the relativistic energy density of the universe and any "dark radiation" component.

Results and Accomplishments:
In FY15, this proposal helped fund the development of new capabilities at the Silicon Detector Facility (Sidet) at Fermilab, and achieved several milestones in CMB related detector research and development. These included:

1) Increased capability of a CMB detector test cryostat (purchased in FY14 of this LDRD) in Lab A at Sidet, including: the installation of new cryogenic wiring, which will enable the readout of ~3000 transition edge sensor (TES) detectors, and a new sub-Kelvin mechanical stage.
2) At Sidet, the first ever tests of superconducting quantum interference devices (SQUIDs). These measurements characterized a new SQUID design by NIST-Boulder that is aiming to increase the trans-impedence over their standard SQUID arrays.
3) At Sidet, the first ever tests of micro-fabricated superconducting inductor and capacitor elements for a new frequency multiplexed SQUID readout system. These tests characterized a new design from UC-Berkeley / LBL, which is attempting to increase the detector multi-plexing by a factor of 1.5 over currently demonstrated technology.

4) At Sidet, the first ever test of a prototype CMB detector array of antenna-coupled TES detectors fabricated by Argonne National Labs (ANL).
5) The design, construction, and initial testing of a high-throughput fourier transform spectrometer (FTS), to characterize the mm-wave spectral response of prototype CMB detectors.
6) The packaging and wire-bonding of twelve prototype TES-detector arrays fabricated at ANL, a process developed in FY14 as part of this LDRD, in support of a joint R&D effort to develop detector arrays for next-generation CMB experiments.
7) Continued efforts by Fermilab scientists and technicians to simulate and design prototype antenna-coupled TES detectors.

Publications:

Posada, C. M., et al., "Fabrication of large dual-polarized multichroic TES bolometer arrays for CMB measurements with the SPT-3G camera", Superconductor Science and Technology, Volume 28, Number 9 (2015)

Benson, B. A., Ade, P. A. R., Ahmed, Z., et al. 2014, "SPT-3G: A Next-Generation Cosmic Microwave Background Polarization Experiment on the South Pole Telescope", Proceedings of the SPIE, 9153, 91531P

Project Number and Title: FNAL-LDRD-2014-012
Development of HTS Based Rapid-Cycling Accelerator Magnets

Authors: (PI) Henryk Piekarz, James Blowers and Steven Hays

Project description:
The goal is design, fabricate, and test a short-sample rapid-cycling superconducting accelerator magnet using a combined novel core and power cable designs. The power cables are based on a high temperature superconductor (HTS) to expand the working temperature margin. These unique core and cable designs will minimize limitations with the normal conducting (copper cable) rapid-cycling magnets due to high power loss induced by the eddy currents and magnetic hysteresis. They will potentially pave the way for extended capabilities in ramp rate, lower power, and long-term operation of such magnets. The rapid-cycling test magnet will be coupled to a 500 Hz ringing mode power supply and to a 20 Hz white circuit power supply to achieve 2000 T/s and 20 T/s ramp capabilities, respectively.

Relevance:
Rapid-cycling magnets constitute a critical component of many particle accelerator systems including fast-cycling synchrotrons such as Booster, Main Injector, SPS and FAIR. The key limitations in achieving high beam intensities in these accelerators are due to power losses induced by a high ramp rate of the magnetic field. Successful R&D in this area would provide extended capabilities for possible new magnet and new

synchrotron designs for Fermilab future accelerator complex and other facilities within DOE, as well as HEP facilities elsewhere, e.g. CERN in Europe, CEPC in China.

Results and accomplishments:
Our studies of magnetic core and power cable arrangement lead to a novel design of a dual C -shaped magnetic core with both beam gaps placed in the vertical plane. In this design the power cable coil is wounded vertically and both beam gaps are open to air on the same side of the core allowing products of beam particle decays, or beam loss itself, to be emitted away from the cable winding thus suppressing potential for radiation damage of the cable. With a single coil winding a single power system accelerates simultaneously two beams cutting by half the required ramping power per beam. The engineering design of magnetic core is completed and a stack of fifty 100 µm thick steel laminations was successfully cut with the water jet using the designed dual beam gap core profile. The vendors were inquired about delivery of 100 µm thick Fe3%Si laminations. The engineering design of HTS cables including splicing connections to the current leads is also completed and the strands were purchased. The supporting cryogenic system for the magnet test was designed and components mostly fabricated. Cryogenic plant at MDB enclosure will be used to provide the supercritical liquid helium for the cooling of HTS coil and current leads. The HTS magnet test area at MDB was designated and fenced-off.

Publications:
A Milanese [1], H. Piekarz [2] and L. Rossi [1], "Concept of a Hybrid (NC + SC) Bending Magnet for (80-100) km Hadron/Lepton Colliders, TUOCB01, Proceedings of IPAC-2014, Dresden, Germany ([1] CERN, [2] FNAL)

Project Number and Title: FNAL-LDRD-2014-038
HF GaN Driver

Authors: (PI) Gregory Warren Saewert

Project Description:
The purpose of this project is to develop an electronic switch that has certain abilities that are not available commercially. The performance objectives are to be able to switch on in the 1 to 2 nanosecond (ns) range and operate in the 500+ voltage range. The switch is to be DC coupled to its load in order for it to deliver a totally arbitrary switching pattern. The width of pulsed voltage must range from as narrow as a couple of nanoseconds to as wide as many microseconds in the same waveform while also potentially switch on and off at rates of tens of megahertz. Recently available GaN FET transistors on the commercial market make such performance feasible, so this LDRD's goal was to build a switch demonstrating these capabilities.

Both the operating voltage requirement as well as the potential of very high repetition rates demands the final switch be constructed of multiple FETs connected in series. Voltage must be shared among these transistors – particularly when switching. The objective of this LDRD is to develop a GaN FET driver circuit, identical for each stage, consisting of several sub-systems: an isolated trigger system, the GaN FET along with circuitry that drives it on and off, and isolated DC power. There are no off-the-shelf commercial components that can provide these functions capable of these switching speeds and isolation – thus the need for development of discrete circuits.

Relevance:
This LDRD proposal addresses the need to deliver high voltage pulses for accelerator applications that include driving particle beam kickers operating on a bunch-by-bunch basis, for one example. Other applications could be to drive electron device electrodes or Pockel Cells driving laser Q switches. Switching devices built for accelerator systems have always taken advantage of semiconductor technological advances. When building switch systems that take advantage of speeds made possible by GaN FETs, certain design issues present themselves for which there no commercial solutions. This project will pursue development of solutions in order to advance accelerator technology.

Results and Accomplishments:
In 2015 I pursued the possibility of isolating trigger signals using high speed laser diodes (as a transmitter) and photo detectors (a receiver) in a free-space communications scheme. I developed sufficiently fast transmitter and receiver circuits. I then tested several each of readily available laser diodes and photo detectors in combination. A couple of issues encountered made it difficult to anticipate using this scheme for our requirements. I thus abandoned this approach in favor of the transformer-coupled approach I had used last year – after improving it a bit.

In 2015 I was able to test the first 650 V rated GaN FETs available from a new vendor rather than continue with lower voltage rate GaN FETs I used in 2014. Reaching 500 Volts should be now more readily achievable. (There are however always trade-offs.) I laid out printed circuit boards (PCB) after redesigning the driver circuit for the new GaN FET. I custom ordered ferrite cores for the trigger signals and the AC power delivery circuit to allow PCBs to be closely spaced. I also needed to redesign the DC power delivery system due to the higher power demands of this 650 V GaN FET.

I put together a three-stage, low-side switch after matching turn-on delay, turn-off delay, rise time and fall time among the individual stages. I matched their timing to about 0.1 ns using provisions in the driver circuit design for this purpose.
Operational results were positive. I operated this three-stage, low-side configured switch up to the DC power supply limit of 630 Volts in December. I connected it to a 500 Watt rated, 185 Ohm load to handle both voltage and power above 300 Volts. I encountered two problems showing up above 200 Volts that were resolved with the addition of proper shielding. The particular GaN FET driver stage design I employed is limited to producing turn-on times just under 3 ns, 5-95%, for a 3 Amp load. This switch can be triggered to produce pulses as narrow as 2 ns at flattop. The widest pulse is essentially unlimited.

The turn-off time of this switch is about 10 ns, 95-5%, without applying any speed-up techniques. The turn-off time is dominated by parasitics, since the FET itself is turned off in about 2 ns. I tested one technique and decreased turn-off time about 25%. Further effort will be worth pursuing to reduce turn-off time further.
Testing revealed this particular GaN FET is capable of turning on at least twice as fast when driven with higher gate current. To that end, I pursued another circuit design, completed a PCB layout and had boards made. The very small transistors employed in this design require a PCB assembly house to mount them. We ended December before finishing the PCB assembly and evaluation.

The year ended only beginning to investigate high repetition rates at 500 Volts. I started this testing very cautiously, and initially generated short bursts at 35 MHz at 500 Volts. Die heating effects were observed that affected transition timing – in the sub-nanosecond level. Reducing these thermal effects at high repetition rates is the primary motive to further reduce turn-on times. Further testing is needed to quantify this affect and determine ultimate switching rate limits.

Project Number and Title: FNAL-LDRD-2014-025
The Sinuous Target

Authors: (PI) Robert Zwaska

Project Description:
The project is to generate a new, engineered material for use in high-power accelerator targets. The sinuous material will be composed of a multitude of interlaced rills: wires of small dimensions. The sinuous bulk material will have improved resistance to thermal shock due to the very low effective modulus of elasticity. Furthermore, the interlaced nature of the wires makes it resilient to individual wire failures. The material will enable targets to accommodate higher incident beam power with more efficient secondary beam production. This project will develop production techniques of several matrixing approaches to the material, and test the mechanical and thermal properties of the engineered bulk.

Relevance:
A high-power target is an integral part of a neutrino beam, muon beam, other intensity frontier beams for high energy physics as well as neutron and rare isotope beams outside of high energy physics. Thermal, mechanical, and radiation effects limit the degree to which targets can be subject to high incident beam power. If successful, the material developed has applications at accelerators at Fermilab and within the DOE complex (including beam facilities for NP, BES, FES, and other areas). The most proximal application of this technology will be for the production of multi-megawatt neutrino beams at Fermilab.

Results and Accomplishments:
A number of analogue, manufactured materials have been identified to act as reference materials: metal foams, flexible graphite, and reticulated metal foams and glassy carbon.

A number of prototype are being procured and will be subjected to mechanical experiments and inspection. A suite of tests is being designed for these materials.

Publications:
The Sinuous Target, IPAC 2015, May, 2015. FERMILAB-CONF-15-261-AD

Project Number and Title: FNAL-LDRD-2014-027
From Magic to Method: Characterizing High Voltage in Liquid Argon TPCs with Breakdown in liquid argon cryostat for high voltage experiments

Authors: (PI) Sarah E. Lockwitz, Brian Rebel, Hans Jostlein

Project Description:
Liquid argon is a popular detector medium for neutrino and dark matter experiments due to its ionization detection ability and its relative affordability compared to other noble liquids. Producing strong signal in such experiments requires a high electric field, yet achieving and maintaining voltages for such fields continues to challenge experimentalists. The goal of this project is to better understand the conditions related to dielectric breakdown in liquid argon by focusing on two key areas: the dielectric strength of liquid argon, and the performance of insulating materials under electrical stress in liquid argon. The experiments have been carried out in two stages: first, in an open cryostat where preliminary tests were performed, and then in a closed cryostat where refined testing has been able to take place in ultra-pure argon similar to the conditions of a liquid argon experiment. A better understanding of these parameters would lead to a more efficient design process for high voltage components in liquid argon experiments in effect taking the approach from magic to method.

Relevance:
This project is relevant to the DOE's Office of Science in that it helps to support the Fermi National Accelerator Laboratory's (FNAL) mission to build and operate world-leading detector facilities and perform pioneering research. Successfully defining the design and operation parameters leading to stable high voltage operation in liquid argon would enable FNAL to efficiently design and use robust, cutting-edge liquid argon detectors in particle physics experiments with minimal downtime, and reduced risk of damaging components due to high voltage failures. These detectors have the potential to unlock the mysteries related to the ubiquitous yet elusive neutrinos and dark matter thereby increasing our understanding of the fundamental components of the universe. This detector technology has already been chosen for the DUNE project and the additional Short Baseline Neutrino detectors at FNAL.

Results and Accomplishments:
In 2015, we completed open cryostat insulator testing and found a number of interesting results: (1) in contrast with near-universal experience, the breakdown voltage along the surface of insulators in liquid argon has a very weak, if any, dependence on the length of the insulator; (2) the effect of adding grooves to the surface of insulators also has little

effect on electrical performance; (3) the permittivity of the insulator appeared to be a primary parameter of performance. These findings support a streamer propagation model of breakdown suggested in the literature that motivates feedthrough design to focus on preventing initiation (i.e. reduce the peak electric field in liquid argon). These findings should greatly improve feedthrough design, which was previously littered with apocryphal requirements, by basing it on solid principles. The results have been submitted to JINST and presented at a conference.

In the past year, we also put forth a Herculean effort to get a new cryostat delivered, installed, and through all safety reviews. In parallel, we designed and made a new apparatus for use in the cryostat to determine whether the electrically stressed volume or area is the parameter of concern for predicting dielectric breakdown through liquid argon, and how the behavior changes as a function of argon purity. These are basic parameters for predicting the breakdown voltage of a given geometry in liquid argon and can inform all future liquid argon time-projection chamber designs. The first tests were done in December, and the results are currently being analyzed. We will complete planned tests in the cryostat, and then allow it to be used by the community for other high voltage in liquid argon testing.

Publications:

S. Lockwitz, and H. Jostlein. "A Study of Dielectric Breakdown Along Insulators Surrounding Conductors in Liquid Argon." Submitted to JINST. [arXiv:1506.04185 [physics.ins-det]]

Project Number and Title: FNAL-LDRD-2014-028
Deployment and operation of a prototype CCD array at Reactor Site for detection of Coherent Neutrino-Nucleus Interaction

Authors: (PI) Juan Estrada, Gustavo Cancelo, Javier Tiffenberg

Project Description:

Neutrinos are one type of the elementary particles that make up our universe. These weakly interacting subatomic particles have no electric charge. The detection of neutrinos is an experimental challenge because of their low interaction probability. The state of the art to address this challenge is based on very massive particle detectors with the capability to identify signals from secondary particles generated in a neutrino interaction. This project has the goal of developing a new way of detecting neutrinos, based on the direct observation of their elastic collisions with nuclei. The very small signal produced by these low energy nuclear recoils is typically below the detection threshold. For this project we establish a much lower detection threshold by using extremely sensitive charge couple devices (CCDs). We use a 4 gigawatt nuclear power plant as a source of neutrinos to test this detector concept. The cosmic and environmental radiation is suppressed using a polyethylene and lead radiation shield. The array of CCDs is located 30 meters away from the core of the reactor, inside the radiation shield.

Relevance:

The elastic collisions of neutrinos and nuclei is theoretically well established, but has escaped detection until now. At low energies the probability of this interaction is expected to increase due to the large number of elementary particles inside a nucleus (coherent interaction). The successful detection of this process will validate for the first time this important aspect of our understanding of elementary particles. This neutrino detection technique could also open a new window to physics beyond our standard model of particles and their interactions, looking at processes that are enhanced at low interaction energies in the neutrino sector. A compact detector capable of identifying neutrinos produced in a reactor could also be used as a tool for monitoring the operations in nuclear power plants.

Results and Accomplishments:
The CONNIE prototype was installed at the Angra-2 Nuclear power plant in Brazil during September-October 2014. It has been running with engineering detectors since December 2014 with a total active mass of 8g. The detector is running inside a conditioned shipping container installed at a distance of 30m from the core of the 4GW nuclear reactor. The operation of the experiment is based at Centro Brasileiro de Pesquisas Fisicas (Rio de Janeiro, Brazil). The full shield was completed in July-August 2015.

The success of the installation and run of the CONNIE prototype, has demonstrated the feasibility of operating a CCD array at the Angra-2 nuclear power plant as a detector for coherent neutrino scattering. The results of the engineering run will be published early in 2016.

The CONNIE Collaboration in planning an upgrade to a detector with 100g of active mass in Summer 2016. With a background 600 events/kg/day/keV a 3 sigma detection significant of the SM coherent scattering is expected in 36 days of running. The current background achieved at the reactor site with partial shielding is ~6000 events/kg/day/keV, giving a 3 sigma detection in one year. We believe this is a conservative estimation because we expect an improvement in the background level when the full shield is assembled.

Publications:
A. Anuilar-Arevalo, et al, "Results from engineering run of the Coherent Neutrino Nucleus Interaction Experiment (CONNIE)," LDRD Final Project Report in preparation.

"Charge Coupled Devices for the Detection of Coherent Neutrino-Nucleus Scattering", G.F. Moroni, Juan Estrada, Gustavo Cancelo, Eduardo Paolini, Javier Tiffenberg, Jorge Molina. Physical Review D 91 (2015) 7, 072001.

Project Number and Title: FNAL-LDRD-2014-038
Application-Oriented Network Traffic Analysis Based on GPUs

Authors: Philip DeMar (PI), Dr. Wenji Wu

Project Description:
The project seeks to develop a network traffic analysis platform that provides a generalized framework for real time traffic pattern identification. The platform is intended to be capable of supporting these services within advanced, high-performance networks that utilize 40GE and 100GE network technologies. Existing packet capture and analysis tools do not perform adequately in such advanced network environments. The project platform will consist of a lossless packet capture engine, and a set of basic GPU libraries for manipulating and analyzing the captured data packets with GPUs. The development use case will be the identification of high impact, large-scale science data flows. A customized set of GPU libraries will be developed to perform the specific traffic characterization services that detect and identify high-impact data flows of interest. While this project is specifically targeted at identification of high-impact data flows, the platform design is intended to be adaptable a wide range of traffic detection and identification capabilities, including security tools and “middle-box” traffic modification functions. In the final stage of the project, an interface for the platform to an OpenFlow network controller will be developed to demonstrate proof-of-concept reconfiguration of network infrastructure to accommodate specifically identified traffic.

Relevance:
The Department of Energy’s (DOE) Office of High Energy Physics (HEP) has heavily invested in US participation in the Large Hadron Collider (LHC) experiments. The LHC experiments have distributed computing models of global scale, and move extreme volumes of data among collaborating sites, including DOE-funded National Laboratories and research university HEP programs. This project is targeted at helping facilitate use of emerging network technologies, such as Software-Defined Networking (SDN), that will be needed to effectively support this extreme scale data movement. The focus of our project is on identification of high-impact traffic flows for network traffic engineering purposes. We target those purposes to be: (1) provision of adequate network resources for the specified flows; (2) isolation of the specified data flows from general Internet traffic; and (3) facilitation of custom computer security risk profiles for the specified traffic. We envision interfacing our product to SDN controllers, in order to enable efficient use of high performance network infrastructure, such as 40GE and 100GE, to optimize LHC data movement.

Results and Accomplishments:
The project has four components: (1) a high-performance packet capture engine; (2) a set of general GPU libraries that manipulate the captured packets for GPU analysis; (3) a set of custom GPU libraries that perform the traffic analysis and classification; and (4) an output engine that interfaces to SDN controllers for manipulating network services based on identified traffic. The four components must be integrated into a single software platform that seamlessly coordinates their respective functions. Component (1) has been

completed with 10GE network interface cards (NICs) and is currently in a test & evaluation stage with 40GE NICs. Component (2) has been completed. A prototype version of component (3) is now also finished. Integration work is currently under way using components (1), (2), and (3). Component (4) is not scheduled to be worked on until the final stages of the project later this year. A non-provisional patent on the algorithms developed for component (1) has been filed with the U.S. Patent Office.

Publications:
ACM/IMC 2014; Vancouver, British Columbia: "WireCAP: a Novel Packet Capture Engine for Commodity NICs in High-speed Networks" - Dr. Wenji Wu and Philip DeMar (Fermilab)

Project Number and Title: FNAL-LDRD-2015-009
High Energy Physics Pattern Recognition with an Automata Processor

Authors: (PI) Michael Wang, Christopher Green

Project Description:
This project investigates the effectiveness of the Micron Automata Processor (AP) in pattern recognition applications in High Energy Physics experiments (HEP). The first year involves demonstrating a proof-of-concept based on a simplified computer model of the pixel detector of the Compact Muon Solenoid (CMS) experiment at the CERN Large Hadron Collider (LHC). The AP is used to find charged particle trajectories in the pixel detector associated with single, energetic electrons that potentially point to new and interesting physics. Upon successful completion of the first year, the second year focuses on pulse shape recognition applications useful for track reconstruction in the Liquid Argon Time Projection Chambers (LArTPCs) of future neutrino experiments at Fermilab.

Relevance:
Pattern recognition is a fundamental task in HEP experiments that has become more challenging with each new generation of experiments and more difficult to address with conventional computing technologies as we approach the end of Moore's law. The Micron AP offers a unique solution based on a novel architecture ideally suited to such applications and which scales well to meet increasing demands. Being a commercial, off-the-shelf product, it does not require the significant investments in capital and manpower that custom hardware solutions entail. A successful proof-of-concept demonstration based on the AP will provide the CMS experiment at Fermilab's Energy Frontier with a practical solution that will meet its growing pattern recognition needs well into the high luminosity era. It will also provide a future-proof pattern recognition solution for experiments like DUNE and Mu2e at Fermilab's Intensity Frontier.

Results and Accomplishments:
Over the course of the first year, we have developed a computer model of the CMS pixel detector and generated simulated collisions with realistic topologies under the expected conditions at the High Luminosity LHC. A track finding algorithm based on the AP has been designed and tested on the simulated collisions to identify tracks from energetic,

isolated electrons that are used to distinguish them from photons. The results demonstrate the effectiveness of the AP in track pattern recognition and its ability to perform within the stringent time constraints found in online HEP applications. A paper draft describing our work has been prepared and comparisons with other platforms like GPGPUs are being completed. Our project was showcased in Fermilab's electronic poster at the 2015 Supercomputing Conference. A presentation of the project was also given by one of us at a special session arranged by Micron Technology during SC15.

Publications:
Paper being prepared for submission to Nuclear Instruments and Methods in Physics.

Project Number and Title: FNAL-LDRD-2015-010
Dark Energy Survey and Gravitational Waves

Author: (PI) Marcelle Soares-Santos

Project Description:
The project is to perform a feasibility study of using the Dark Energy Survey (DES) to make an optical identification of a source of gravitational waves triggered by gravitational wave (GW) detectors that started taking data in 2015. GW detectors are able to determine only with moderate precision the location of their sources. A dedicated search by DES which has a wide field of view and sensitivity in the near infrared optical bands may result in a pinpoint precision of the source of the gravitational waves allowing for much improved measurements of their properties that would otherwise be lacking.

Relevance:
Gravitational waves from coalescing neutron star binaries or black hole-neutron star pairs are potential new probes for dark energy and the physics of spacetime – areas of study directly related to the mission of Fermilab. This project leverages existing DOE investment in the Dark Energy Survey Camera (DECam) and, if successful, will be a demonstration of a new kind of probe relevant for high-energy particle astrophysics and cosmology.

Results and Accomplishments:
Key accomplishments in the first year of this project include:

1. Modeling of potential optical signatures
   We produced a semi-analytic model for the optical counterpart of GW events resulting from mergers of two neutron stars or a neutron star and a black hole. We use simulations reported in the literature to tune our model. The model predicts sources that would be detectable in typical DES-like exposures in the wavelengths from 0.7 to 1 micron. We used these models to guide the design of our observing strategy.
2. Development of image processing pipeline
   We built a pipeline to process individual images taken in the region of interest and subtract them from templates in search for candidate sources.

This pipeline is a generalized version of the pipeline that DES uses for supernova searches. While the original pipeline was restricted to 10 specific supernova fields and offered little flexibility to perform "on demand" searches, this generalized version is capable of performing subtractions at any position in the sky using any DECam image as a template. We have made this pipeline available to the DES Collaboration for use in other projects that might benefit from difference imaging in areas outside of the supernova fields (e.g. searches for supernovae gravitationally lensed by galaxies, discovery of new solar system objects).

3. <u>Increase of DES telescope time allocation</u>
   Through a competitive call for proposals, we obtained 3 nights of time on DECam. Those nights were added to the nominal DES allocation of 105 nights in the 2015-2016 observing season. This allowed us to perform observations for this project without causing a negative impact on the mainline DES program.
4. <u>Optimization of observing strategy</u>
   We developed an observing strategy that takes into consideration the source model, the GW sky map of localization probability, and our telescope time budget to plan a sequence of observations that maximizes our chance of detection. We also further optimized this plan to ensure that our images are compatible with the DES observing strategy, so images taken for this program can also be added to the pool of DES images available for any DES analysis.
5. <u>First observing campaign</u>
   We set up a system to receive alerts from the GW detectors and perform our observing campaign in the 2015-2016 observing season.

Publications:

DES Collaboration, 2016. "The Dark Energy Survey: more than dark energy - an overview", Section 5: "Searches for optical counterparts of gravitational waves", submitted to MNRAS and ongoing peer-review. ArXiv:1601.00329

Project Number and Title: FNAL-LDRD-2015-020
Off-the-Shelf Data Acquisition System

Authors: (PI) Ryan Rivera, Kurt Biery, and Mark Bowden

Project description:

Define and evaluate a low-cost, scalable data acquisition (DAQ) system architecture based on commercial technology being developed for the emerging "Internet of Things" (IoT). This approach connects intelligent front-end digitizers directly to a standard network without additional layers of custom readout electronics. The same network is used for data acquisition, event building, detector controls, online and offline data storage/processing, and control room interfaces. The system is scalable from a few MBytes/sec to hundreds of GBytes/sec using inexpensive commodity networking equipment and interface modules. The software will leverage already existing software developed at Fermilab to form a comprehensive data acquisition and processing infrastructure for current and future experiments. As part of this proposal we will include drivers for these generic network-attached digitizer interfaces. The goal is to define a complete and scalable "off-the-shelf" DAQ (*otsdaq*) system for use in a wide range of experiments and studies.

Relevance:
A wide range of experiments and studies rely on data acquisition systems that in the past were often based upon relatively expensive and short-lived technologies. As experiments are reluctant to subsidize the development of niche standards, an off-the-shelf DAQ enabled by the IoT has the potential to satisfy the requirements of a large range of experiments and studies at a very modest cost. We expect DAQ experts and novices to be able to re-use pieces of the *otsdaq* framework and make new contributions, in open source fashion, so that future DAQ work might be more efficient.

Results and accomplishments:
We are eleven months into the proposed two year work plan for the Off-the-Shelf Data Acquisition System, and we have made good progress on the first-year goals. We have surveyed the IoT market for candidate boards and selected a low-, mid-, and high-performance board to populate the initial menu of supported hardware. We have developed and tested Ethernet firmware solutions for each of the boards on the initial menu. We have centralized the relevant source code into a common repository and compiler environment. We have created a sandbox environment for the public webpage that will be used to facilitate selections from the menu of supported *otsdaq* items. And finally we have created several proof-of-concepts that we will look to integrate into the final system: JavaScript and HTML5 graphical user interface, secure user login, arbitrary digital waveform generator, firmware customization scripting, power over Ethernet, point-to-point synchronization protocol, and temperature-voltage-current monitor over Ethernet.

Project Number and Title: FNAL-LDRD-2015-021
Diagnostics for H- Beams Using Fiber Lasers and Synchronous Detection

Authors: (PI) Victor Scarpine, Jinhao Ruan

Project Description:
This research 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 these 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 is generally used for non-invasive 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 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 laser light, with optical fibers, through the accelerator system with no damage to optical vacuum windows.
2. A combination of both transverse and longitudinal 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:

This project has a number of specific components necessary before beam profile measurements can occur. The initial year of this project has been focused on three primary areas, (1) the design of the laser system, (2) the design of the beamline vacuum hardware and (3) understanding and optimizing the transport optical fibers. The design of the laser system has gone through a number of revisions. We are in discussion with the laser vendor to procure the fiber laser in FY2016. In addition, the laser modulation system has been purchased and is being tested. The design of the accelerator vacuum hardware is proceeding with construction and installation into the PXIE accelerator beamline later this year. The development of the transport optical fibers has been slowed by concerns of damage to the fiber due to high optical power density at the fiber tips. This issue is being pursued and various options are being evaluated. Delays in the transport optical fiber development will not cause delays in other areas of the project.

Project Number and Title: FNAL-LDRD-2015-029
Nb_3Sn superconducting RF cavities to reach gradients up to 90 MV/m and enable 4.2 K operation of accelerators

Authors: (PI) Sam Posen, Alexander Romanenko

Project Description:

Superconducting radio frequency (RF) cavities are structures that transfer energy to beams of charged particles as they traverse through. Traditional cavities are fabricated from the superconductor niobium, but recent advances have brought performance close to the fundamental limits of this material. This has led researchers to study alternative materials, one of the most promising of which is Nb_3Sn. A recent proof-of-principle demonstration at Cornell University by S. Posen et al showed (1) Nb_3Sn cavities with reproducible quality factors at 4.2 K comparable to those obtained in bulk Nb at 2 K (cryogenic plant efficiency is 3-4 times higher at 4.2 K) and (2) that Nb_3Sn cavities hold a potential for accelerating gradients up to 90 MV/m, nearly twice that of niobium. However, the achievable gradient was limited to ~12 MV/m due to cavity surface defect, and the performance was very sensitive to additional surface treatments and cooling procedure. The objective of this project is to address these extrinsic limitations uncovered in Cornell's pioneering work and develop an optimized production-ready Nb_3Sn layer forming technique for any future SRF-based project at Fermilab and around the world.

Relevance:
The increase in performance of Nb_3Sn SRF cavities compared to traditional niobium cavities has the potential to bring about substantial cost reductions for state-of-the-art particle accelerator facilities. The demonstrated increase in cryogenic efficiency could reduce the considerable cryogenic plant costs for SRF linacs with high duty factor. The predicted increase in ultimate accelerating gradient could dramatically reduce the length of high energy accelerators. If successful, the cavities developed would have applications at many accelerators within the department of energy (including accelerator facilities for HEP, NP, BES, and other areas) and in small- and medium-scale industrial applications, where the ability to operate at 4.2 K could enable low-maintenance cryocooler-based SRF accelerators. At Fermilab, the significant advantages of Nb_3Sn cavities would be beneficial for producing multi-megawatt neutrino beams.

Results and Accomplishments:
A coating apparatus has been designed for fabricating Nb_3Sn films on niobium substrates even as large as the 650 MHz 5-cell cavities designed for the PIP II accelerator. Engineering simulations were performed for thermal and mechanical stability, and a design review was held. Niobium has been purchased for use in the coating chamber, which is currently in the fabrication process at a vendor. Modifications to the furnace are currently in procurement. These developments are critical to developing Nb_3Sn fabrication capabilities at Fermilab. First coatings are planned for the coming year. In addition to these activities, a Nb_3Sn cavity coated at Cornell University was brought to Fermilab, and tested with temperature map to study dissipation over the surface. Coupons were the cut from the cavity and microscopic analysis was performed. Regions of high dissipation were correlated with local areas of unusually thin Nb_3Sn film. Additional studies are underway to understand how to avoid similar problems in future coatings.

Publications:
Fermilab Nb_3Sn R&D Program. International Conference on RF Superconductivity 2015, September, 2015. Accepted for contribution.
Cutout Study of a Nb3Sn Cavity. International Conference on RF Superconductivity 2015, September, 2015. Accepted for contribution.

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

Project Description:
This proposal 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 in excess of 2 MW for the future long baseline neutrino program.

Results and Accomplishments:
The project start date is delayed until a new postdoc can be hired. There were 27 applications from which a short list and interview process continues. It is expected an offer will be made by the end of Sept. 2015. In addition, a student has been identified at Northern Illinois University who will be preparing for coursework. Initial pre-project groundwork by the PI and co-PI's should allow for the project to start promptly when the postdoc arrives.

VI. 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.