

## Fermilab Status and Strategic Plan

Summary document for the 2015 Institutional Review

Fermilab is America's particle physics and accelerator laboratory. Fermilab's over-arching strategic goal is to do great science. The lab drives discovery by

- Building and operating world-leading accelerator and detector facilities
- Performing pioneering research in collaboration with universities, other labs, and international partners
- Developing new technologies for particle physics that also support the innovation ecosystem of U.S. competitiveness in the world economy

During the past decade, Fermilab has been in transition, leveraging the capabilities developed for the successful Tevatron and NuMI programs into leadership in CMS, the Cosmic Frontier, and new accelerator-based initiatives for neutrinos and muons. The current Fermilab program exploits the many synergies of the lab's core scientific and technical capabilities, project management expertise, and operation of the world's second largest accelerator complex. With neutrinos as the new flagship, Fermilab is moving forward with new experiments, new international and national partnerships, and investments in the future. Fermilab's strategic plan is fully aligned with the P5 recommendations for U.S. HEP. This strategic plan looks out ten years for five science-based strategic themes, with clearly defined goals:

**Neutrinos.** Fermilab will become for accelerator-based neutrinos what CERN is for the Higgs boson. This goal builds from past success with the MINOS and MiniBooNE experiments, as well as the current neutrino program that includes MINERvA and the newly launched NOvA and MicroBooNE experiments. In addition to providing the world's most powerful and versatile neutrino beams, Fermilab will empower the wider neutrino community with a *neutrino platform* that supports a variety of detector R&D, target and beamline development, software, computing, and theory. Fermilab will attract the global community of neutrino physicists, and partner with CERN and other labs, to realize the coherent vision of a new short-baseline program combined with the flagship LBNF facility that hosts 40 kilotons of liquid argon detectors deep underground and uses PIP-II to provide a megawatt-class neutrino beam.

**Large Hadron Collider.** Fermilab will continue to be the leading U.S. center for LHC physics and the second leading center in the world after our partner CERN. The lab will enable leading roles for USCMS in future LHC discoveries and subsequent exploration, drive key contributions to upgrades of the CMS detectors, and supply critical technologies and components for the LHC accelerator upgrade.

**Exploring the Unknown with Muons.** Fermilab will become the world center for muon physics with the advent of the g-2 and Mu2e experiments and their exciting prospects for discovery. The lab will work with the U.S. and international communities to identify new opportunities leveraged off this program and the new capabilities provided by PIP-II.

**Cosmic Science.** Fermilab will support the diversified approach to dark matter direct detection recommended by P5, with leading roles on some projects and technologies. The laboratory is the current world leader in cosmic surveys with DES, plans a strong project role in DESI, and an important intellectual footprint in LSST. Fermilab's new involvement with the South Pole Telescope will foster a growing collaboration of labs and universities that will ensure U.S. leadership in CMB science.

**Accelerator Science.** In partnership with nearby institutions, Fermilab will support Illinois as a world center for accelerator science with a suite of unique test facilities. The lab will drive major advances in accelerator science that are tied to game-changing issues relevant to future accelerators for particle physics.

The discovery potential enabled by the current and planned Fermilab program is huge and varied. On the ten-year horizon, Fermilab, with international and national partners, will have successfully built a new billion-dollar class neutrino facility. Fermilab will continue to be in demand nationally and internationally for critical accelerator, detector, and computing capabilities needed elsewhere. Fermilab is moving to create a modern centralized campus successfully catering to a large international user community. The laboratory is working with the U.S. community and international partners on options for future high-energy colliders, including developing the physics case and pursuing detector R&D. With all of these strengths, the lab will be well positioned to advance ambitious new particle physics initiatives for the subsequent decades.

The remainder of this document outlines in more detail the recent accomplishments, status and plans for the Fermilab program, organized by the five crosscuts of the Institutional Review.

## CMS

### Introduction

Run 1 of the LHC was a great success, highlighted by the discovery of the Higgs Boson. The current long shutdown (LS1) is ending and the LHC will soon return to operation at an energy of  $\sqrt{s}=13$  TeV. The LHC long-range schedule shows Run 2 continuing into 2018, before a second shutdown (LS2), with Run 3 spanning 2020-2022. The combined integrated luminosity expected in Runs 2 and 3 is  $300 \text{ fb}^{-1}$ . Following a three-year shutdown, the High Luminosity LHC (HL-LHC) era is planned to begin in 2025. The goal of the HL-LHC upgrade is a peak instantaneous luminosity of  $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ , delivering  $250 \text{ fb}^{-1}$  per year, with the goal of  $3000 \text{ fb}^{-1}$  in a dozen years. The CMS detector must be upgraded for this extended running at high luminosity. Upgrades referred to as Phase 1 will be completed by the end of LS2, with Phase 2 upgrades to be complete before HL-LHC operation.

Fermilab is the largest group in USCMS and the second largest in all of CMS. With a staff of more than 50 scientists and more than 100 total FTE, the group is active in physics analysis, software and computing, CMS operations, construction of Phase 1 upgrades, and R&D for the Phase 2 upgrades.

### Physics

The Fermilab CMS group has been strongly engaged in physics analysis during Run 1. Many members of the group played key roles in analysis efforts in Higgs Boson physics, including the search, discovery and measurements of its fundamental properties, BSM searches (especially SUSY), and QCD and Electroweak measurements. FNAL scientists worked on the kinematic discriminant used in the  $H \rightarrow ZZ \rightarrow 4l$  analysis, measured the Higgs spin and parity in  $H \rightarrow WW \rightarrow l\nu l\nu$ , and lead the search for a high mass Higgs in  $H \rightarrow WW \rightarrow l\nu jj$ . Many scientists were active in searches for SUSY, in both hadronic and leptonic channels. Hadronic searches, using all-jets and  $\gamma$ +jets final states, included an inclusive search for gluinos and light squarks, a search for direct stop production, and a search for gauge-mediated SUSY. Leptonic searches included inclusive searches using opposite- and same-charge dileptons, and a search for direct stop production using single lepton events. These analyses were conducted in close collaboration with other U.S. universities. In numerous cases the interaction with Fermilab theorists helped in making significant progress. Several group members served as conveners of CMS physics object groups or physics analysis groups, and many more served as sub-group conveners, including five within the SUSY group. Moreover, quite a few chaired or served on analysis review committees, which scrutinize an analysis on behalf of the collaboration before publication. Currently most physicists are heavily involved with preparations for Run 2, including software development and physics analysis. The group plans to build on past experience, with improved SUSY/BSM searches in both hadronic and leptonic channels, including b-tagging, and Higgs measurements.

## LHC Physics Center (LPC)

Fermilab hosts the LPC, a regional center designed to engage members of USCMS institutions, especially those who are remote from CERN, in physics analysis of LHC data and in upgrade-related work. The LPC achieves this by lowering the barrier to remote participation, creating a vibrant environment, which is akin to being at the accelerator location. The LPC provides access to a broad range of detector and physics analysis expertise under one roof, extensive expert core and analysis software support, access to outstanding computing resources, and basic and advanced training. This creates an intellectual community that is economically attractive, relative to stationing staff at CERN.

The LPC has a long history of providing engagement opportunities for the USCMS community with many notable contributions to CMS. Under the leadership of the present LPC coordinators, the LPC has evolved to create new opportunities during LS1 and to prepare for the significantly higher LHC energy in Run 2. To conduct first class research requires an LPC community not only with expertise in detector construction, physics object reconstruction and its identification, but also full engagement in the main physics that the LHC will address at 13 TeV. The CMS Data Analysis School and the Hands-on Advanced Tutorial Sessions (HATS) are signature initiatives of the LPC which provide training on CMS analysis software. The HATS are unique within CMS, acting as a forum to share experience in advanced analysis methods, detector techniques, and upgrade projects. Due to the LPC's unique access to facilities and broad range of expertise, it promotes a wide range of opportunities for interaction and dialogue between LPC scientists and the theory community, with significant involvement of the Fermilab theory group. The Topic of the Week seminar, organized together with two members of the theory group and university members of the LPC, fosters discussion between expert theorists and experimentalists from CMS and ATLAS. At the bi-weekly LPC Physics Forum two scientists, either two CMS experimentalists or an experimentalist and a theorist, give blackboard presentations on their work, promoting discussion and collaboration among groups. Based on a recent survey of all 50 USCMS university groups, 100% are engaged with the LPC, about 50% of USCMS members are using it as a resource on Hardware or Software, 50% on Physics, and about 70% on Computing.

## Theory

Fermilab theorists have been major contributors to calculations, tool development, novel search strategies, and new physics interpretations for the LHC program. This work ranges from Higgs physics as a tool for discovery, to dark matter and new particle searches. In Higgs physics, members of the group performed precision studies of the production of Higgs boson decays into Z and W pairs far above the resonance region and provided fast, efficient code used by CMS to directly bound the Higgs width. Working with CMS collaborators, they were the first to study the power of using the full matrix element information in the  $H \rightarrow ZZ \rightarrow 4l$  channel. As a Fermilab Graduate Student Fellow, Northwestern student Roberto Vega-Morales worked directly on Higgs analyses with CMS physicists through the LPC; his contributions were recognized by the 2014 Sakurai Dissertation Award, and his name was added to the author list of the CMS Higgs properties paper. Fermilab theorists have proposed new ideas to scrutinize Higgs properties and are also studying the implications of precision Higgs physics for a wide range of new physics models. They have proposed benchmark scenarios to study the complementarity between Higgs properties and searches for additional Higgs bosons. ATLAS and CMS through the LHC Higgs Cross Section working group are using these new benchmarks to present their analysis interpretations in SUSY and two Higgs doublet models. Beginning already with CDF, Fermilab theorists have been leaders in new ideas for collider dark matter searches, sparking a flurry of activity in both CMS and ATLAS using mono-X searches to set limits on dark matter couplings and masses, and consulting with both collaborations on these searches.

## USCMS Program Management

As the host national laboratory for the U.S, effort on CMS, Fermilab is the nexus of management activities for multiple facets of the USCMS program. The DOE expectations regarding the roles and responsibilities of

the National Labs have been explicitly delineated, with particular mention of leading in management, design, construction, and operations, fostering cross-cutting activities between experimental research, theory, and computation, and exploiting unique infrastructure to develop future apparatus. The Fermilab CMS group is clearly fulfilling all of these expectations. Fermilab provides the leadership and management infrastructure for the Operations Program as well as both the Phase 1 and Phase 2 Upgrades, which were called out as the highest near term priority in the recent P5 report. The Operations Program is currently gearing up for the start of the LHC Run 2, the Phase 1 Upgrade recently received CD-2 and CD-3 approval and is transitioning to production mode, and Phase 2 is actively pursuing R&D in anticipation of CD-0 in the coming year. The upgrades make extensive use of the technology base at FCC, SiDet, and in Wilson Hall, as well as the PPD Test Beam Facility, to continue to push detector techniques to meet the demanding challenges of the LHC. Fermilab CMS actively seeks participation from all of USCMS, making sure that management structures have room for adequate representation at all levels from a large number of institutions supported by either DOE or NSF; this includes leveraging institutional strengths such as the silicon fabrication facilities at Nebraska and Purdue in the upgrades, and providing Fermilab as a welcoming and supportive site for a critical mass of collaborators to work on common topics, both detector and analysis based.

### Software and Computing

Software and computing are fundamental parts of the scientific process of the CMS experiment. Fermilab is involved in all aspects of maintaining and evolving the software and computing infrastructure to enable CMS's scientific success in LHC Run 2 and beyond. The CMS software framework is the basis of all data and Monte Carlo (MC) production, processing both online and offline, and analysis. Its maintenance and evolution is of crucial importance to the success of the experiment, and Fermilab experts lead and are at the heart of the development team.

The computing infrastructure is of equally crucial importance. Fermilab hosts the only Tier-1 site in the U.S. and the most reliably available Tier-1 site in the world. CMS relies heavily on the resources at the lab for the most difficult and demanding work, such as the resource intensive Phase II Upgrade MC workflows. Local experts are leading the development of computing tools for CMS, and are lead developers of the most critical parts of the infrastructure, namely the Tier-0 and central processing infrastructure and the metadata catalog. Fermilab experts are involved in the complex operation of the diverse components and workflows that enable CMS to rapidly and efficiently extract physics results.

U.S. physicists rely heavily on Fermilab's interactive and batch computing resources at the LPC. Experts from the Tier-1 team and the software and computing development and operations teams support these systems. Fermilab is generally considered by the collaboration as the best place in the world to efficiently and quickly analyze CMS data. All this is possible because of the excellent coordination between LPC leadership and Tier-1 facility management, aided by the close connection between scientists in SCD and PPD at Fermilab. A recent reorganization in SCD strengthened the connection between SCD and CMS with key personnel involved in the leadership of Fermilab scientific computing and USCMS; this benefits the whole computing landscape at Fermilab.

### Hadron Calorimeter (HCAL)

The Fermilab group played a major role in designing, developing, and operating the CMS HCAL during Run 1. The electronics department developed the readout electronics used during Run 1 and the ASIC department developed the QIE readout chips. Fermilab scientists have held leadership positions throughout the project, including management of the Phase 1 upgrade, and the group played a leading role in the installation and commissioning of the readout electronics with a strong presence at CERN.

Fermilab scientists developed the SiPM-based readout for the Phase 1 HCAL upgrade, and led the hardware installation effort during LS1. ASIC developers, supported by Detector R&D funding, are working on the next generation of QIE chips (QIE10/11), a joint project with ATLAS, electronics engineers are developing

and prototyping the front end readout electronics, and mechanical engineers are developing the cooling and mechanics of the readout boxes. Fermilab is playing a major role in the electronics integration testing for Phase 1 and has established a test stand for this. There is a close collaboration with several university groups, facilitating their involvement and helping new faculty members to establish key roles within CMS.

Fermilab scientists have leading roles in R&D and planning for the Phase 2 upgrade, including simulation and studies of endcap options. Scientists are involved in radiation testing of scintillator materials to understand the aging mechanisms, development of new rad hard scintillator materials in collaboration with the Fermilab Detector R&D group, specification of the readout electronics, and mechanics and cooling. The PPD Test Beam Facility has been essential for qualification and testing of front-end electronics and measuring the performance of new detector concepts as part of Phase 2 R&D.

Throughout the project, the LPC has been effective at concentrating expertise and providing a focal point for university HCAL groups, allowing them to more effectively participate in hardware and software projects. Fermilab has been a major center for universities participating in HCAL software development, calibrations and monitoring, and Fermilab scientists established remote monitoring shifts at the Fermilab Remote Operations Center (ROC) to provide prompt feedback on data quality.

## Tracker

The CMS tracking effort at Fermilab includes activities in operations, detector construction, off-line beam spot workflow, and detector R&D. Construction of the present Forward Pixel detector (FPIX) was centered at Fermilab, utilizing the facilities and technical expertise at the Lab. Technicians and engineers continue to service parts of FPIX to maintain the detector performance. Fermilab scientists led the R&D for the Phase 1 Upgrade FPIX by coordinating the work of scientists, engineers, and technicians from 15 US institutions and Fermilab to design, simulate, and prototype a proposed upgrade. Following successful NSF and DOE reviews of the USCMS Upgrade Project, Fermilab will lead and host the construction of the Phase 1 Upgrade FPIX. Fermilab mechanical engineers have designed new low mass carbon fiber and cooling supports, while electrical engineers have designed much of the on- and off-pixel module electronics. Detector components machined in-house and parts made or assembled at other collaborating institutions and vendors will arrive at Fermilab to be tested, graded, and assembled into the final detector. Teams of university collaborators working at Fermilab's SiDet facility will do the testing and assembly of the final detector.

Fermilab scientists have lead roles in the R&D and planning for a Phase 2 upgrade of the CMS tracking system. 22 US institutions including Fermilab are engaged in the R&D and scope planning, and in the TDR preparations for an upgrade to the pixel and Outer Tracker detectors. Fermilab has an organizational and planning role, and is also involved in many aspects of the R&D. These include studies of the radiation tolerance of electronics, high performance readout circuit development, sensor design, beam tests of sensors and readout chips, development of high rate low power optical links, development of mechanical and thermal support structures, module and tracker integration, construction database, and simulations. These activities bring together expertise from different areas of Fermilab in collaboration with universities. They also make use of the Test Beam Facility, the large computing resources for simulations, SiDet for prototyping and design, and various Fermilab technical facilities for prototyping and other R&D work.

## Trigger

To exploit the upgraded detector in the HL-LHC era, the trigger system must be able to cope with increased luminosities. The chief strategy for reducing the trigger rate and preserving efficiency is to execute precision tracking in the Level 1 trigger and matching the tracks to objects in the calorimeter and muon systems. Fermilab is leading R&D to address the main challenges of implementing tracking in the Level 1 trigger for CMS. A Fermilab scientist coordinates the CMS L1 track trigger project, with the collaboration of several USCMS institutions. Fermilab scientists and electrical engineers are developing the dedicated ATCA-based hardware to perform pattern recognition and track fitting, with the initial goal of a vertical slice

demonstration system planned for 2016. The first prototype of Fermilab's VIPRAM (Vertically Integrated Pattern Recognition Associative Memory) chip was designed, produced and fully tested in 2014.

Simultaneously, Fermilab is engaged with maximizing the performance of the Level 1 trigger for Run 2. The existing Global Calorimeter Trigger, which reconstructs jets, energy sums, taus, and electron/photon objects, will be replaced in 2015 with contemporary FPGA-based cards which can perform more sophisticated reconstruction (such as pileup subtraction) within the same rate and latency budgets. A Fermilab physicist is manager of the project, which includes universities in both the US and UK, and Fermilab physicists and engineers are tasked with delivering FPGA firmware. Besides enhancing the physics potential of CMS in 2015, the upgrade will exercise many technologies needed for future trigger and front-end electronics upgrades in CMS: high-speed FPGAs, micro-TCA DAQ, and high-throughput optical I/O.

## LARP at Fermilab

DOE initiated the LHC Accelerator R&D Program in 2003 to participate in the commissioning of the US-built LHC triplet magnets, bringing together and coordinating resources from four U.S. laboratories. The program also focused, from the very beginning, on the design of improved focusing quadrupoles for the low- $\beta$  insertion regions during HL-LHC operation. LARP@FNAL goals for the FY15-FY17 periods include construction of test models and pre-production prototypes, in anticipation of delivering 50% of the low- $\beta$  quadrupoles as a U.S. in-kind contribution to HL-LHC. This contribution to the LHC accelerator is of crucial importance to continued U.S. participation in the ATLAS, CMS, and LHCb physics programs. Additional details are presented in the Technology R&D chapter of this document.

## CMS Summary

As described above, the Fermilab CMS group is active in physics analysis, software and computing, CMS operations, construction of Phase 1 upgrades, and R&D for the Phase 2 upgrades. The group builds on its past strength and expertise, choosing projects that are important to CMS and USCMS, while taking advantage of the unique facilities of the lab. Fermilab partners with USCMS collaborators, many hosted at the LPC, to maximize the collective impact on CMS. Fermilab CMS activities are integrated with the theory, computing, and detector R&D activities of the lab, in ways that strengthen all of these efforts.

## Neutrinos

### Neutrino landscape and P5

The discovery that neutrinos can change from one type to another and hence have mass has been one of the most surprising and important developments in particle physics in recent times. We have built a simple three-flavor paradigm to describe this phenomenon, but many aspects of neutrino mixing are puzzling and important questions remain. These questions were identified as high priority items in the Snowmass community planning exercise, and reinforced by the P5 recommendations for U.S. HEP.

P5 presented four recommendations concerning neutrino oscillation physics: (1) that the U.S., in collaboration with international partners, develop a coherent short- and long-baseline program hosted at Fermilab, (2) form a new international collaboration to design and execute a highly capable Long-Baseline Neutrino Facility (LBNF) hosted by the U.S., (3) upgrade the Fermilab proton accelerator complex to provide more than 1 MW by the time of first operation of the new long-baseline neutrino facility, and (4) select and perform a set of short term, small scale short-baseline experiments to conclusively address experimental hints of physics beyond the three-neutrino paradigm. P5 also specifically recommended that some of these small-scale experiments “use liquid argon to advance the technology and build the international community for LBNF at Fermilab”. Fermilab is vigorously working to execute the P5 plan.

The P5 plan sets a trajectory for Fermilab to host the world-leading accelerator-based neutrino facility. Fermilab is already unique in that it is the only laboratory in the world that simultaneously operates two



accelerator-based neutrino beams, thus allowing a dynamic program of both short and long-baseline neutrino research. Making use of these two intense neutrino sources, Fermilab is currently operating an ensemble of experiments that include:

**NOvA (long-baseline, NuMI):** the most powerful accelerator-based long-baseline neutrino experiment ever built. Sending neutrinos from the Main Injector 810 km to a massive detector in northern Minnesota, NOvA will address the core scientific issues of neutrino mixings and mass orderings, and at the same time, may provide an early glimpse at CP violation in the neutrino sector. Furthermore the NOvA near detector, located about 1 km away from the target, provides additional opportunities for neutrino physics as well as for dark sector searches. Beginning operations last year, NOvA sets the stage for the future LBNF program, which will send neutrinos across an even longer baseline.

**MINERvA (short-baseline, NuMI):** the first precision neutrino scattering experiment with multiple nuclear targets. Sitting upstream of the MINOS near detector, MINERvA provides an important basis for future oscillation experiments by measuring neutrino interactions on a variety of nuclear targets ranging from helium to lead. This experiment is the neutrino version of the Jefferson lab electron-nucleus scattering program. MINERvA data produces cross-section measurements in the important energy range of the LBNF 1<sup>st</sup> oscillation maximum.

**MINOS+ (long-baseline, NuMI):** a continuation of the MINOS program in the medium energy NuMI beam. MINOS+ will explore new phase space and produce stringent tests of non-standard neutrino interactions, sterile neutrinos, and extra dimensions. Running through 2016, it will provide a strong conclusion to the distinguished MINOS program.

**MicroBooNE (short-baseline, BNB):** the first large scale liquid argon TPC built in the United States. Positioned on the Booster neutrino beam, MicroBooNE will produce the first measurements of low energy neutrino interactions in argon, investigate the excess of electromagnetic events observed by MiniBooNE, and provide a step towards the construction of future massive kiloton-scale liquid argon TPCs. MicroBooNE data will produce cross section measurements in the important energy range of the LBNF 2<sup>nd</sup> oscillation maximum. It will also become part of the new SBN short-baseline program.

Together, these experiments will study the detailed properties of neutrinos at both low and high energy, short and long distances, and propel us into the next decade.

## Recent Scientific and Technical Accomplishments

In 2014, Fermilab-based neutrino experiments published or submitted for publication a total of 9 physics results, each of which form the building blocks that the current and future generation of neutrino experiments will need. Last year alone MINOS/MINOS+ produced the most precise value of the largest neutrino mass squared splitting, and MINERvA and ArgoNeuT provided new inputs on the hadronic side of quasi-elastic interactions. Both experiments also released a suite of charged current pion production measurements. Together, these channels make up the bulk of the neutrino events that the NOvA experiment is measuring today and that ELBNF will measure in the future. MINERvA also published a surprising measurement of the EMC effect in neutrino scattering, which shows that the effect of the nuclear environment on neutrino scattering cannot be predicted from charged lepton measurements alone.

Fermilab scientists have been involved with these publications at all levels: from contributing new capabilities to identify final state particles in neutrino interactions, developing completely new observables to constrain theoretical models, to providing oversight and intellectual leadership to guide analyses as co-spokespeople, analysis coordinators, and paper reviewers. Fermilab plans to continue this intellectual leadership in the future, with expected first physics results from NOvA and MicroBooNE.

## Neutrino Division and the Current Program

Neutrino experiments have played a large part in Fermilab's past and present, and they will now be an even bigger part of Fermilab's future. To enable the Laboratory's goal of leading the world in accelerator-based neutrino physics, the Director announced in July 2014 the formation of a new **Neutrino Division**.

The initial mission of this new organization is to provide a visible home with administrative and technical support for the Laboratory's current and planned neutrino experiments. In October 2014, about 70 staff, guest scientists and International Fellows became the first members of this new division. The organization has two well-defined elements to its mission. The first is to focus on operating the experiments in the NuMI and Booster Neutrino beams (NOvA, MINERvA, MINOS+ and MicroBooNE). The second is aligning with the P5 plan by nurturing and hosting, in a coordinated way, a world-leading program of short and long baseline neutrino experiments.

There are at present more than 550 unique users from universities and other external institutions who participate in neutrino experiments and detector tests (MicroBooNE, NOvA, MINERvA, MINOS+, LArIAT, SBN, and LBNF). There are also a number of programs that attract students and other researchers to the lab. More than 38 URA scholarships have been awarded since 2008, and 19 Intensity Frontier Fellowships since 2013. Special programs for Indian students and students from Latin America also bring added global focus to the lab, with more than 10 Indian and 36 Latin American students. These students benefit not only from the vibrant neutrino community active at Fermilab, but also the active mentoring efforts of many of the Fermilab postdocs and staff scientists.

At present, most of the Neutrino Division staff are Fermilab scientists or guest scientists, working on the current and planned experiments. The Division also hosts the LBNF project team as well as the nascent ELBNF user community that will be joining this effort. Most of the scientists in the Division are in the Neutrino Physics Department. This department is structured by experimental groups representing both the current and future experiments. Most of the scientists engaged in the currently running experiments are also playing active roles in the development of the future SBN and LBNF detectors or beams.

Neutrino Division includes a Technical Support Department, which includes the Liquid Argon Detector Group, a team of engineers specializing in cryogenic systems to operate and design the liquid argon neutrino detectors for both the SBN and LBNF programs. This detector engineering team needs to expand as the new projects mature and require more design effort. In addition to adding several more engineers with cryogenic expertise, conventional mechanical, electrical and process engineers are also needed. The Neutrino Division and Particle Physics Divisions are working together to optimize utilization of engineering and technical resources.

The Technical Support Department additionally includes the Operations Support Group (OSG), which supports running and future experiments either directly or as experiment liaisons with the other divisions of the Laboratory. Currently identified areas receiving support include NOvA operations and controls, support for MicroBooNE and commissioning, and support for a MINERvA DAQ upgrade for higher intensity and the MINERvA test beam experiment. The group expects to take a proactive approach to involvement in the SBN program, with early involvement in infrastructure and conceptual DAQ work. Additional opportunities to support the current and future experiments will arise as some current projects related to MINOS and MINERvA ramp down in the first half of 2015.

The Neutrino Division, working with the University of Minnesota, also coordinates operations at the Soudan and Ash River laboratories, which host the MINOS and NOvA far detectors respectively.

## Fermilab Neutrino Platform

The **Fermilab Neutrino Platform** is a new concept to describe the activities upon which we are supporting the current and future neutrino program. These activities range from experiment design, construction and operation to analysis and final publication of results. The activities of the Neutrino Platform support multiple experiments and can be divided into four general areas – neutrino beam support, detector R&D,



software and computing, and theory. In all aspects of the platform, Fermilab scientists work closely with university and other lab researchers enabling and empowering the wider neutrino community.

The activities of the Fermilab Neutrino Platform span four different divisions at the laboratory with the Neutrino Division playing the central coordinating role. The Neutrino Division ensures that the work is coherent across the laboratory and broader community as well as integrated with the activities in the universities and other laboratories both in the US and abroad.

Fermilab supplies neutrino beams to the user community. Currently this means the Booster Neutrino (BNB) and NuMI with the future addition of the beamline for LBNF. Neutrino beams to experiments, by their very nature, always put a heavy tax on the “proton economics” of the machines: the proton intensity is the most important parameter, not beam energy. In addition, there are other programs at the lab that require proton resources, further straining the budget. Fermilab will realize proton “economic growth” with a set of accelerator improvements over the next decade: the Proton Improvement Plans or PIP. The first of these improvements, PIP, is being implemented now. Completion of PIP will more than double the available protons through the Booster, to  $>2 \times 10^{17}$  per hour and allow the Main Injector to deliver 700kW of proton beam power to NuMI. After PIP, the present accelerator complex will be at its limit, and the front-end (source through Linac) will need to be replaced. PIP-II will replace the Linac with a new superconducting RF Linac using cavities developed at Fermilab, resulting in another doubling to 1.2MW at 120 GeV in proton intensity before 2025. The need for accelerated protons will not end and more powerful beams are envisioned beyond PIP-II, in excess of 2 MW at 120 GeV.

The newly formed Neutrino Beam Group within the Neutrino Division is charged with developing neutrino beam concepts capable of using these delivered protons. The Neutrino Beam Group will work closely with the External Beams and High Power Targetry Groups within Accelerator Division (AD). Currently the design of the LBNF beamline and upgrade of the BNB to a 2-horn system are high priority items for the beam group, along with the support of the simulations of all beamlines. The target group has also embarked on a dedicated R&D effort to more fully understand how high energy beams affect potential target materials. This is important work prior to designing a target for 1.2MW and essential work prior to designing a 2+MW target. An LDRD proposal was funded in FY14 to develop targets that can withstand the high power of future neutrino and muon beams.

Another key aspect of the Neutrino Platform is Fermilab’s support of detector R&D. There are three main facilities relevant here: The Proton Assembly Building (PAB), the PC4 building, and the newly refurbished MCenter experimental area in the Fermilab Test Beam Facility (FTBF). The scientific personnel supporting these areas come, for the most part, from the Detector R&D group within Neutrino Division. Presently MCenter is host to LArIAT, a LAr TPC that will characterize the response to charged particles in the energy range relevant to current and upcoming neutrino experiments ( $\sim 200$  MeV – 2 GeV). The FTBF-MTest is also hosting the MINERvA test beam effort to characterize detector performance at the higher energies being collected in the NuMI medium energy mode. The PC4 facility hosted the LAPD system that demonstrated that high purity argon could be achieved in a cryostat without evacuation. Currently PC4 hosts the 35 ton LBNE prototype, a small scale test of many of the design aspects proposed for the large TPCs of ELBNF. PAB has hosted multiple cryogenic test stands over the last few years including a materials test system (MTS) for assessing the impact of various materials on the electron drift lifetime in liquid argon, a cryostat system used for studies of light collection and the effect of contaminants on light production and transmission (TallBo), and a cryostat in which high voltage breakdown in liquid argon can be studied. The high voltage effort was made possible by LDRD awarded in 2014.

The software activities of the Neutrino Platform fall largely under the Scientific Computing Division (SCD). The artdaq framework used for data acquisition in the current generation of neutrino experiments is a key element of this support. Fermilab has also invested strongly in the GENIE neutrino generator and intends to extend that support in the future. LArSoft is the framework designed to be used in all analysis of LAr data and is built on SCD’s ART framework. Fermilab has also become a center for GEANT4 development via its CMS computing commitment, and this investment is now valuable also for the neutrino experiments.

Theoretical physicists have had and continue to have a significant influence on the Fermilab neutrino program. Members of the Fermilab Theoretical Physics Department have been engaged in neutrino phenomenology and the lab's experimental strategy for many years and have impacted the current short and long baseline neutrino programs, and the plans for the future programs. They collaborate closely and continually with experimental colleagues. They have also had a major influence on the global neutrino program. There is a recent effort to use the lab's lattice QCD expertise to calculate the nucleon axial-vector form factor, which is relevant for the neutrino-nucleon cross section.

Fermilab has begun investing in efforts to build predictive models of neutrino-nucleus interactions. The lab has sponsored long term visits by a number of world experts in the field trying to strengthen the connections between their work and the needs of the future experimental program. Recently, the lab has embarked on a collaboration with several of the world's experts in nuclear structure calculations for electron scattering with a view to applying their considerable success in that field to the field of neutrino-nucleus scattering. The Theoretical Physics Department is supporting these efforts.

### New Programs in Short and Long Baseline Neutrinos

With the Fermilab Neutrino Platform providing a strong foundation upon which to build the future program, the laboratory has engaged with the international neutrino community to aggressively pursue the next generation of long and short baseline experiments.

**SBN** is the next-generation short-baseline neutrino program. This program brings together an international team that will add two additional liquid argon TPCs to the Booster neutrino line, one each at a near and far location relative to MicroBooNE. This three-detector suite (LAR1-ND, MicroBooNE, ICARUS T600) will definitively address the physics of short-baseline neutrino oscillations, with the potential to make a groundbreaking discovery in neutrino physics: namely, the discovery of a possible fourth type of neutrino. The program foresees installation of both the near and far detectors during 2017 culminating in the three detector configuration ready for beam data-taking in the spring of 2018. This program will also offer the chance to test specific design elements being considered for ELBNF detectors. It exactly satisfies one of the P5 recommendations.

**LBNE and ELBNF:** Following the P5 recommendation to “reformulate the long-baseline neutrino program as an internationally designed, coordinated, and funded program with Fermilab as host,” Fermilab is working with the global neutrino community, CERN and other funding agencies to establish a new scientific collaboration and a new project structure that encompasses groups from around the world who want to do this science. To guide this process, the Fermilab Director established an Interim International Executive Committee comprising leaders of the global neutrino community and representatives of relevant funding agencies. Building on the technical and engineering work done by the LBNE Project, the LAGUNA-LBNO design study, and other groups, Fermilab, working with international partners, plans to host the Long-Baseline Neutrino Facility (**LBNE**), which will comprise the neutrino beamline, the conventional facilities for the beamline and the near detector at Fermilab, the conventional facilities for the far detector at the Sanford Underground Research Facility (SURF), and the cryostat and cryogenic systems necessary for the liquid argon TPC far detector.

A new international collaboration, currently referred to as **ELBNF** has been formed to design and build the near and far detectors and conduct scientific research with them. A Letter of Intent was endorsed by Fermilab PAC proposing to pursue an accelerator-based long-baseline neutrino experiment, as well as neutrino astrophysics and nucleon decay, with a 40-kt (fiducial mass) modular liquid argon TPC detector located deep underground and a high-resolution near detector, with a goal to implement a first 10 kt module on the timescale of 2021. The first collaboration meeting has been held and the process of electing spokespersons and providing other machinery for organizing the collaboration has been launched. In parallel with the process to establish the new LBNE project and ELBNF collaboration, technical progress continues in key areas that will underpin the new project, including far detector prototyping, cryostat and cryogenics system design, beamline design, and conventional facilities design.

## A Coherent Neutrino Program

Fermilab is managing this future neutrino program as a coordinated effort, involving universities and laboratories from around the world, to enable efficiencies and knowledge transfer in scientific efforts and technical developments from separate physics collaborations and projects that are working towards similar goals. Although the Fermilab-managed SBN and LBN programs involve multiple collaborations that have independent scientific goals, synergies in liquid argon time-projection chamber technology and personnel provide near and longer-term coherence. The two programs together provide a coordinated approach to addressing some of the most fundamental questions about neutrinos but also provide a means to grow the technical expertise needed to be successful in this exciting and challenging research. Using the Fermilab Neutrino Platform, the SBN will train junior researchers in the technology while the LBN program is evolving. Since many Fermilab neutrino scientists are involved in multiple collaborations, knowledge transfer occurs as each experiment develops. Improvements in liquid argon TPC technology evolves as components such as cold electronics are managed on successive detectors with the same personnel and lessons learned are integrated into the next generation detector. Efficiencies in support technology such as cryogenics are being managed in a joint Fermilab-CERN engineering team responsible for cryogenic technology for both the Fermilab-hosted short and long baseline neutrino programs. Coordinated approaches through Fermilab SCD to software and computing builds on knowledge from past neutrino experiments and provides an early means to grow the expertise necessary for the LBN experiment. The integrated program managed by Fermilab and enabled by facilities and staff in the Fermilab Neutrino Platform will provide exciting research during an intermediate neutrino program while also developing the expertise, technology, and computing required for the long-term program.

## Muon Program

The current Muon Program at Fermilab is composed of the Muon g-2 and Mu2e experiments, both of which are in the project phase with data taking expected to begin in the next 2-5 years. Both projects have completed baseline reviews and expect DOE CD-2 to be finalized this year. Each experiment will significantly improve the current state-of-the-art and each offers discovery sensitivity to interesting regions of new physics parameter space. Both experiments are identified as a high priority for the U.S. HEP community in the recent P5 report, which recommended the completion of both projects in all budget scenarios considered. Since the last Fermilab S&T review in November of 2013 both projects have made significant progress, and both collaborations continue to grow. These experiments form a major part of the Fermilab physics program in the 2017-2025 timeframe.

Muon g-2 will probe new physics at the Terascale by measuring the muon magnetic moment with a precision 4 times better than BNL E-821. The former antiproton production complex is in the process of being reconfigured for muon production. The polarized muon beam will be delivered to the new MC1 building that houses the E-821 storage ring. The muon production rate in this complex will be roughly 20 times higher than the production rate for BNL E-821. The highest energy positrons are used to track the muon spin precession, and precision NMR probes are used to map the free proton spin precession. The ratio of these two quantities is proportional to g-2. The storage ring will be cooled down and powered for the first time beginning March 2015, at which time the measurement of the proton spin precession will begin. Accelerator and detector construction will continue through 2016 and 2017, with the first muon beam expected in March 2017. Once commissioned, it will take approximately a month to acquire a data set equivalent to the BNL experiment, so first results could be as early as 2018.

Mu2e will search for charged lepton flavor violation with a sensitivity  $10^4$  times better than SINDRUM-II and will probe for new physics at effective mass scales in the  $10^3$ - $10^4$  TeV range. Mu2e will use 8 GeV protons from the Booster, rebunch them in the Recycler, and then store them in the Delivery Ring (DR). The protons

in the DR will be resonantly extracted to the Mu2e production target every 1695 ns. This pulsed proton structure is key to achieving the target physics sensitivity. The Mu2e apparatus consists of a system of 3 solenoids - a production solenoid (PS), an “S”-shaped transport solenoid (TS), and a detector solenoid (DS) – that will work together to deliver the world’s most intense muon beam. A graded magnetic field, starting at 4.6 T in the upstream part of the PS and decreasing to about 1 T in the downstream part of the DS, is important for mitigating backgrounds to an acceptable level. The key active detector components include a straw-tube tracker, a crystal calorimeter, and a scintillator-based cosmic-ray veto system. A dedicated pixel telescope, located near the PS, will measure the number of out-of-time protons. Mu2e is scheduled to begin commissioning with beam in 2020.

### Synergies and commonalities

Common resource and technology requirements of the two muon experiments have been exploited to achieve major cost savings and efficiencies. They share a common beam delivery scheme, office space, Fermilab personnel resources, collaborators, etc. They are located in close proximity on the new Muon Campus, located just south of Wilson Hall. The shared elements of the g-2 and Mu2e beam lines and infrastructure have been collected into a common set of Accelerator Division projects – the Muon Campus Projects - which are managed by the laboratory for the benefit of both experiments. Fermilab scientists have led the design of the straw tracking detectors for both experiments and have converged on several common features for the two experiments minimizing design and infrastructure costs. Organizational changes within the laboratory have occurred in order to collect personnel with expertise relevant to these experiments in common departments. The identification and exploitation of these synergies has helped realize significant efficiencies. For example, by identifying common solutions for g-2 and Mu2e into the Muon Campus Projects over \$100M has been saved relative to each experiment pursuing separate solutions. By collecting the responsible personnel into a common Muon Department in the Accelerator Division the relevant interface issues are readily addressed. Currently there is an effort to extend this model to operations. Discussions are underway to identify common operational elements (e.g. the need for cryogenic operations technicians, control room) and to develop an operations model that will reduce the lifetime costs across the program.

### Integration across the laboratory

Both the g-2 and Mu2e projects benefit from strong support across Fermilab divisions. Scientists and engineers in the Particle Physics Division (PPD), the Accelerator Division (AD), the Technical Division (TD), and the Scientific Computing Division (SCD), all play major roles. The laboratory has been responsive to the resource needs of both projects and has provided the personnel from all four Divisions necessary to make the required progress. In instances where significant shortfalls existed, the laboratory worked to address them. For example, additional cryogenic engineering resources were aggressively recruited in TD and AD to address shortfalls across the laboratory that affected Mu2e. Fermilab is responsible for the solenoid system for the Mu2e Project. Over the last five years Fermilab TD has developed detailed reference designs for all three solenoids, interacting with the experimenters to refine the functional requirements and conducting extensive design studies.

The SCD ART framework is used by both experiments as the basis for their simulation and reconstruction software. The SCD expertise in simulations has been especially useful as the collaborations pursue final design work. The Fermilab computing facility and services provide comprehensive resources for simulation production and analysis, as well as expertise in exploiting opportunistic resources when necessary. Particle Physics Division hosts the PPD Muon Department, as well as the Test Beam Facility used to develop straw tracker prototypes through test beam experiment T1042. Most recently the laboratory has begun working with the PPD Muon Department to develop plans for additional office space to house the two growing collaborations, and to develop an operations plan that exploits commonalities.

The execution of these projects is managed through a set of meetings that includes the g-2 Project Management Group (PMG), the Mu2e PMG, the Muon Campus PMG, the Fermilab Performance Oversight Group (POG), the Fermilab Proton Planning Management Group (PPMG), and the Integrated Project Team (IPT), which includes representation from the Department of Energy. Conflicts are usually first identified in the individual PMG meetings, but then elevated as appropriate to oversight meetings with representation from projects and experiments across the laboratory – namely the POG and PPMG. There is a good working relationship between the leadership of the experiments, projects, and the laboratory, and they work together to address common concerns.

### **Involvement of the HEP community**

The Muon g-2 Collaboration consists of 155 scientists from 23 universities and 11 laboratories from the U.S., Italy, the United Kingdom, Russia, China, and Korea. Over the last year the collaboration has grown by 17%, admitting 1 new institution. The collaboration makes strong contributions to the g-2 Project and to the simulation and test beam studies needed to guide the final design efforts. Scientists and engineers from collaborating institutions hold 58% of the management positions in the project work breakdown structure. Major sub-systems are being constructed in 17 collaborating institutions. The calorimeters, associated readout electronics, and the entire data acquisition system are funded through an NSF Major Research Instrumentation Award (MRI), co-managed through the University of Washington and Cornell University with sub-contracts to the University of Kentucky, University of Illinois, University of Virginia, and James Madison University. This effort is also supported by several Italian institutions, Shanghai Jiao Tong University, and JINR, Russia. Cornell University and Brookhaven have major responsibilities for accelerator components within the storage ring. Argonne, University of Massachusetts, and University of Washington are refurbishing NMR equipment from BNL E-821, and Argonne is hosting a large bore MRI magnet test facility for quality control during construction and systematic studies during the experiment. Boston University, NIU, University of Liverpool, University College London, and Oxford are constructing the tracking detectors and associated readout electronics. NIU is providing the slow control infrastructure. Students and postdocs at over 10 institutions are actively developing common simulation tools hosted at Fermilab, and are performing systematic studies to inform the design and prepare for analysis. During the past three years g-2 has benefited from over \$200k in Intensity Frontier Fellowships, URA Visiting Scholar Fellowships, and DOE Office of Science Graduate Student Research Awards.

The Mu2e Collaboration is composed of about 170 scientists from 23 universities and 8 laboratories from the U.S., Italy, and Russia. Over the past year seven new institutions have joined the collaboration: Argonne, Minnesota, INFN Genova, Novosibirsk, Louisville, Southern Alabama, and Yale. In addition, the research groups at existing institutions have also grown, adding new faculty, post-doctoral researchers, and graduate students to Mu2e. Taken together the collaboration has grown by about 20% since the last S&T review in November 2013. The collaboration makes significant contributions to the Mu2e Project and to the simulation and test beam studies needed to guide the final design efforts. Jim Miller (Boston) is the co-spokesperson of the collaboration. The simulation and physics studies of the experiment are organized into four analysis working groups. Dave Hedin (NIU) and Iuri Oksuzian (Virginia) lead the Neutron Working Group, charged with developing cost effective shielding solutions that sufficiently reduce the neutron and photon rates in the detectors to acceptable levels. Dave Brown (LBNL) leads the Calibrations Working Group, charged with developing the analysis strategies required to calibrate the response of the detectors to the required precisions. Dave Brown (Louisville) plays a leadership role in the Simulations Working Group as the Geometry Czar, charged with ensuring the geometry description in the simulation package is accurate. Craig Dukes (Virginia) is the L2 manager for the Cosmic Ray Veto system. Stefano Miscetti (Frascati) is the L2 manager and David Hitlin (Caltech) the deputy L2 for the Calorimeter system. Nine university collaborators serve as L3 managers across the project. Recent test beam efforts have been led by Peter Kammel (Washington) for AICap, a joint effort between the Mu2e and COMET collaborations, and Ivano Sarra (Frascati) for the calorimeter. Over the past three years Mu2e has benefitted from about \$260k

in support from three Intensity Frontier Fellowships and three URA Visiting Scholar Fellowships. These awards bring collaborators to Fermilab for extended stays and foster close cooperation between the project and the experiment. These awards include a recent Intensity Frontier Fellowship for a postdoctoral theorist working with Andrejz Czarnecki (Alberta), who will spend several months at Fermilab to complete a calculation of radiative corrections to the dominant Mu2e background process.

### Contributions of Fermilab scientists

The nine Fermilab scientists on the Muon g-2 Collaboration make significant contributions to the project and to the simulation and test beam studies that guide the final design effort. We call out all nine here to illustrate how Fermilab scientists in general integrate with a project and a collaboration: Chris Polly is the project manager. Mary Convery of Accelerator Division is the deputy project manager, L2 for accelerators, and project manager for the Muon Campus Project. Brendan Casey is PPD Muon Department head and L2 for Detectors and received an Early Career Award to design and prototype the tracking detectors. Adam Lyon, head of the Systems for Scientific Applications group in the SCD, serves as the g-2 SCD liaison and is leading a large team of collaborators developing the ART-based simulation and reconstruction software. Fifth year postdoc Mandy Rominsky has constructed several rounds of straw tracker prototypes, is L3 manager for the tracker, and is Spokesperson of test beam experiment T1042. Lederman Fellow Brendan Kiburg is L3 manager for shimming and is designing and constructing instrumentation to make the first measurements of the proton spin precession that will begin Spring 2015. Hogan Nguyen is L2 for the ring and is leading efforts to simulate the magnetic field. Emanuela Barzi is leading R&D efforts for a superconducting inflector magnet upgrade. First year postdoc Tammy Walton is leading a team of post docs and grad students who are developing the tracking code for the experiment.

The 40 Fermilab scientists on the Mu2e Collaboration make significant contributions to the project and to the simulation and test beam studies that guide the final design effort. Fermilab scientists serve as a co-spokesperson of the collaboration, the deputy head of the PPD Muon Department, the project manager, and the deputy project manager. A Wilson Fellow leads the Background Working Group charged with performing the simulation and analysis studies needed to estimate the expected sensitivity of the experiment. A Fermilab SCD scientist serves as the Mu2e SCD liaison and leads the Mu2e Offline and Simulations Working Group charged with developing the ART-based Monte Carlo and reconstruction software required for analysis. Another Fermilab scientist co-led the Neutron Working Group from its inception in 2012 until 2014. Fifteen Fermilab scientists serve as L2 or L3 managers across the project.

Fermilab theorists have been engaged with these experiments. They made significant contributions to the Charged Lepton sections of the 2013 Snowmass study. Lattice theorists are leading Fermilab efforts to use lattice QCD to compute the hadronic contributions to the muon g-2. Two new theory postdocs have been hired to assist with these calculations. Fermilab scientists and postdocs have worked on papers that explored the sensitivity of Mu2e to the flavor structure of the Higgs couplings and to models of Split Supersymmetry motivated by the Higgs discovery. They explored the constraints placed by the muon g-2 measurement on leptophilic dark matter and are investigating its impact on Higgs coupling measurements. Fermilab theorists have led efforts to engage the community in these experiments by initiating joint efforts with other lattice QCD collaborations, by organizing an academic lecture series that focused on the muon program, by leading the Project X Physics Study, and by organizing the “Lattice Meets Experiment” workshop, which covered topics including g-2, Mu2e, neutrinos, and more.

Seven scientists in the PPD Muon Department are also playing leading roles publishing legacy results from the Tevatron experiments; they are primary contributors to over a dozen papers on Higgs searches, dibosons, top quark properties, the W mass, and b hadron lifetimes and rare decays. Their efforts have supported the highly productive overall output of the CDF and D0 collaborations, with about 80 papers published per collaboration over the past three years, and well over 50 new PhDs defended.



## Near term goals and objectives

The primary goals for g-2 in the coming year are to cool and power the ring, which is a prerequisite for CD2/3 approval. Construction is ramping up on all subsystems, and installation will take place in 2016/17 with the first beam in March 2017. The analysis framework is mainly in place, and the collaboration is rapidly expanding analysis preparations. The Fermilab group plans to deploy four postdocs throughout the span of the experiment. The senior postdocs will play leading roles in both the measurements of the muon precession frequency and the proton precession frequency, while the junior postdocs will play leading roles operating the tracking detectors and the precision field measurement apparatus.

The primary goals for Mu2e in the coming year are to obtain DOE CD-2/3b approval, which is expected sometime in spring, and to complete the final design and begin construction in early 2016. CD-3b approval will allow fabrication of the 27 superconducting modules needed for the transport solenoid and the construction of the experimental hall on the Muon Campus to begin. Mu2e received DOE CD-3a approval in mid 2014, which authorized the fabrication of roughly 75 km of superconducting cable required to wind the three solenoids. The completed cable begins arriving in 2015 and a significant effort is required to perform all the necessary QC testing. A prototype TS module was fabricated last year and arrived at Fermilab for testing in December. More details about the solenoids are in the Technology R&D chapter.

The Mu2e tracker will complete a full-sized panel prototype in February and will operate in vacuum. This will be an important proof-of-principle for the straw tube technology choice. There are also important R&D milestones for the calorimeter and cosmic ray veto systems. As a whole, the project is aiming to complete final designs in 2015 and to conduct a DOE CD-3c review in early 2016 to authorize a full-scale construction start. Planning for data taking operations (both online and offline) has begun with the relevant laboratory divisions. The resulting plans will become more formalized over the coming year.

## Longer Term Strategic Vision

Fermilab is positioned to become the premier center for precision muon physics in the world. We are working to build a strong scientific staff that can act as an anchor to collaborations, and we strive to make Fermilab the intellectual hub of the program. The facilities currently under construction will produce leading physics results well into next decade and are ideally suited to receive beam from the PIP-II accelerator upgrade. Through the Snowmass process, several Fermilab scientists played leading roles in envisioning what is possible with increased beam power to the campus. While the current program is clearly the priority, scientists in the PPD Muon Department continue to investigate other scientific opportunities for the future; these include Mu2e upgrades, negative muon running for g-2, a dedicated muon EDM run for g-2, and a storage ring proton EDM experiment.

## Muon Program Summary

The Fermilab muon program offers compelling physics that the HEP community is excited about. The g-2 and Mu2e projects have made significant progress over the last year and expect to achieve significant milestones in the coming year. The projects are supported by talented, dedicated, diverse international collaborations that are committed to the success of the experiments. The muon program is a Fermilab priority and enjoys strong support from the laboratory Divisions, with Muon Departments in both PPD and AD, and major contributions from TD and the Fermilab Computing Divisions. The shared elements of the g-2 and Mu2e beam lines and infrastructure have been collected into a common Muon Campus; other commonalities between the two experiments, involving operations and computing, are being exploited to produce further efficiencies. The experiments enjoy strong ties to the theory community, who not only provide compelling physics motivations for pursuing these measurements, but also make contributions to the ultimate success of the experiments. The Fermilab computing facility and services provide comprehensive resources for simulation production and analysis; the SCD ART framework is used by both experiments as the basis for their simulation and reconstruction software. The PPD Test Beam Facility plays

an essential role in straw tracker detector R&D. First results from these experiments are expected by the end of the decade.

## Cosmic Frontier Program

Astrophysics at Fermilab started in the 1980's with the establishment of the Theoretical Astrophysics Group, a pioneer of new "Inner Space/Outer Space" connections between fundamental physics and cosmology. In the 1990's, laboratory capabilities in project management, mechanical and electrical design and data handling launched precision cosmology with the Sloan Digital Sky Survey, and with CDMS, the first in the modern program of experiments aimed at direct detection of WIMP dark matter. In the last decade, Fermilab has applied its expertise on silicon vertex detectors to build the Dark Energy Camera, and deployed a variety of new particle detector technologies in the search for dark matter. Fermilab scientists have also played leading roles in data analysis on these experiments, leading to major science results. The future program extends these investigations of dark matter and cosmic acceleration, and adds a new direction that merges scientific and technical aspects of both: a deep and detailed study of the cosmic microwave background.

### Current Program: Operating Cosmic Experiments

#### **Dark Energy Survey (DES)**

The main Fermilab dark energy effort after SDSS has been the Dark Energy Survey. Fermilab led the foundation of the project and collaboration, and the construction of its main instrument, the Dark Energy Camera. Fermilab, as the leading institution, continues to provide scientific leadership, technical and computing support for the collaboration, as well as management of survey operations. The survey will finish its second year of data taking in 2015, and conclude survey operations in 2019. It is the world's leading imaging survey until the Large Synoptic Survey Telescope starts operations in the 2020's, and will significantly advance the frontier of precision cosmological measurement. During these years, DES science will be the main science focus of Fermilab's dark energy team. The DES Director is Fermilab theorist Josh Frieman, and the DES operations manager is also a Fermilab scientist.

#### **Cryogenic Dark Matter Search (CDMS/SuperCDMS)**

CDMS has long been a leader in dark matter direct detection, with Fermilab a leading institution in this experiment since 1997. Currently, Fermilab operates the G1 experiment at the Soudan Underground Laboratory in Minnesota. A new detector design ("iZIP", for interleaved z-sensitive ionization and phonon detection in the ultra-cold silicon and germanium target masses) now provides active discrimination against surface background events. In addition, a new mode of operation for CDMS detectors, called CDMSlite, has provided greatly improved sensitivity for low-mass WIMPs. These new technologies will both be deployed with much larger germanium and silicon target mass in a G2 experiment called SuperCDMS SNOLAB, in Canada. This project is in the design phase and will be constructed during 2016-2018. In four years of operation, it aims to definitively explore the low WIMP mass region  $< 20$  GeV, down to the ultimate background from solar neutrino interactions. This low-mass region is particularly favored in 'dark sector' models that posit a family of dark matter particles with behaviors resembling those of normal matter. Fermilab will partner with SLAC in managing the SuperCDMS SNOLAB project and will continue to play leading scientific, technical and management roles in the experiment. Both the Project Scientist and the Project Manager are Fermilab scientists.

#### **Dark Matter searches using Superheated Liquids (COUPP/PICO)**

Together with the University of Chicago, Fermilab pioneered the resurrection of the bubble chamber as a tool for dark matter direct detection searches. Target liquids containing nuclei with large spin produce world-leading sensitivity to spin-dependent WIMP-nucleus scattering. Superheated liquids provide extraordinary rejection of electromagnetic backgrounds, since those interactions do not provide sufficiently

localized energy densities to nucleate bubble formation. Acoustic sensors distinguish between alpha particle backgrounds and nuclear recoils. Currently, the collaboration is operating two G1 experiments at SNOLAB: PICO-2I and COUPP-60, now also renamed PICO after a newly formed, larger collaboration. They are both being used to study remaining backgrounds and understand how this technology might be used in the future to confirm and complement possible WIMP signals seen by other experiments. DOE and NSF chose not to proceed with a G2 experiment using this technology, but it may be a part of the G3 direct detection portfolio. Meanwhile, the G1 experiments may approach theoretical expectations for spin-dependent WIMP interactions. While the expanded PICO collaboration now includes many Canadian groups, Fermilab scientists will continue to participate in future operations and R&D at a low level.

#### **Two Phase Argon TPC for Direct Detection of Dark Matter (DarkSide)**

Bringing its expertise in liquid argon technology and data acquisition software (in particular, the artdaq system), Fermilab has played important roles in the development of the DarkSide-50 G1 experiment, which uses an argon time projection chamber to search for dark matter. This technology has demonstrated extremely good rejection of electromagnetic backgrounds, and control of the intrinsic radioactive background from  $^{39}\text{Ar}$  by exploiting and purifying underground sources of argon. A recent first physics result demonstrates the potential for liquid argon TPCs to play a role in confirming possible high-mass WIMP signals. While this technology was not selected in the G2 process in the US, the DarkSide collaboration, with leadership at Princeton and hosted by INFN/LNGS in Italy, intends to continue R&D towards larger experiments. Fermilab will participate at a low level of effort, bringing unique technical expertise closely aligned with its liquid-argon neutrino detector development.

#### **Dark Matter in CCDs (DAMIC)**

Thick CCDs of the type developed for the Dark Energy Survey can be read out with extremely low noise amplifiers, thus providing the lowest energy thresholds of any current technology. Fermilab, in collaboration with the University of Chicago, has led the effort to realize this potential with small (10 g) prototypes in an experiment at SNOLAB, and is currently upgrading to 100 g of target mass, funded mostly by a PECASE award to Juan Estrada. Despite the small mass, the prototype already yields the strongest limits on very low-mass ( $\sim 1$  GeV) WIMPs. The DAMIC collaboration has expanded to include NSF-funded university groups, and will continue this R&D program. Fermilab will support this effort at a low level.

#### **Fermilab Holometer**

The Fermilab Holometer uses a pair of correlated Michelson interferometers to explore the quantum coherence of space-time position with Planck spectral sensitivity for the first time. This experiment was enabled by an Early Career award to Fermilab scientist Aaron Chou, includes collaborators from three universities, and has involved nine undergraduate students. In the next two years, the experiment will discover or place bounds on exotic “holographic position noise” from new Planck scale physics.

### **Recent Technical and Scientific Accomplishments in the Cosmic program**

#### **Dark Energy**

The SDSS II Supernova Survey merged its large and well calibrated, medium-redshift sample with other surveys to create the best current measurements of cosmic acceleration.

In its first two seasons of data taking, the Dark Energy Survey (DES) created the widest, deepest digital image of the universe, mapping over 100 million galaxies and discovering over a thousand supernovae. Five papers based on early science data were submitted for publication in 2014, and 14 abstracts were submitted for the April 2015 APS meeting, with associated papers to be released at that time. Early science highlights include the discovery and properties of distant clusters of galaxies, discovery of superluminous supernovae, high-redshift quasars, and strong gravitational lens systems, measurement of cosmic shear weak lensing, of galaxy spatial clustering, and of the cross-correlation between DES galaxies and gravitational lensing of the cosmic microwave background as measured by the South Pole Telescope.

Fermilab theorist Scott Dodelson led a team from SCD, the Universities of Manchester and Chicago, rolling out the first version of CosmoSIS, a new framework for extracting scientific conclusions from varied cosmic data sets, already downloaded by dozens of university researchers.

#### **Dark Matter**

Separately, the DAMIC and CDMS collaborations published new limits on low mass WIMP dark matter, representing the world's best constraints over their respective mass ranges. The PICO collaboration published a new, world-leading direct limit on WIMPs with spin-dependent nuclear interactions. The Fermi Gamma-ray Space Telescope collaboration confirmed studies of Fermilab theorist Dan Hooper and collaborators that show a possible signal of dark matter annihilation near the Galactic center.

#### **Cosmic Microwave Background**

Fermilab established a new group that is designing and building a new camera for the South Pole Telescope, including detectors from Argonne. The initial work of this group is being funded partly through a Fermilab LDRD grant. The BICEP II collaboration published a detection of "B mode" polarization, a possible signature of cosmic origins based on a concept developed by Fermilab theorist Albert Stebbins and collaborators.

#### **Structure of Space and Time**

The Fermilab Holometer achieved its design sensitivity, and started the world's first studies of quantum geometrical coherence with Planck precision.

#### **High Energy Cosmic Rays**

Fermilab scientists led a study by the Pierre Auger Observatory on the nuclear composition of cosmic rays at the highest energies, and showed for the first time that the composition varies systematically with energy. This important result caps Fermilab's long leadership in the Auger collaboration, which is now shifting to the Karlsruhe Institute of Technology.

### **Near Term Plans: Cosmic Experiments under Development**

#### **Dark Energy Spectroscopic Instrument (DESI)**

DESI is the successor to the massive SDSS/BOSS spectroscopic survey, extending its reach by an order of magnitude, particularly for precision measurement of cosmic parameters using baryon acoustic oscillation (BAO) structure. Fermilab is a major partner in the DESI project (led by LBNL), with both science leadership and technical construction tasks. Fermilab contributions build on the scientific and technical expertise developed from leading design, construction, operations and science from SDSS and DES surveys. As in DES, Fermilab will lead the development of key structural elements of the massive image corrector system, and the packaging and testing of the detectors. Fermilab technical effort on DESI will grow with construction of the instrument over the next few years. DESI will be the largest Fermilab dark energy technical effort after the conclusion of DES. It should start its multi-year spectroscopic survey around 2019. The Project Scientist for DESI is Fermilab's Brenna Flaugher.

#### **Liquid Xenon Dark Matter Search (LZ)**

The successor to the LUX two-phase liquid Xenon experiment, which currently places the tightest constraints on massive WIMPs, LZ has been chosen by DOE as a G2 experiment. This technology has potentially the deepest reach to find weakly interacting dark matter over a wide range of WIMP masses. The project is led by LBNL, with important collaboration leadership also at SLAC and UCSB, and participation by many university groups. Fermilab scientists Hugh Lippincott (Wilson Fellow) and Eric Dahl (joint appointment with Northwestern University) have extensive experience with noble liquid TPC technology, including LUX and other prototype detectors of this type, and have joined the LZ collaboration. Fermilab plans to play a key technical role in designing and fabricating the cryogenic process control system for LZ. Fermilab effort on LZ will be significant for the duration of the experiment, in a time frame similar to SuperCDMS.

#### **Axion Dark Matter Experiment (ADMX)**

Axions have long been a leading candidate to constitute particle dark matter, motivated not by the "WIMP miracle" but by an elegant solution to the strong CP problem. The G2 ADMX direct detection search

employs a resonant RF cavity variably tuned to search for a tiny coherent excitation at the (unknown) axion mass, caused by Galactic dark matter. In a strong magnetic field, dark matter axions excite cavity modes that are measured with ultra-low-noise superconducting detectors. ADMX collaborators have developed the detector, RF cavity and magnet technology over many years. Recent advances in detectors now enable sufficient sensitivity to start searching efficiently over a range of axion masses, upwards of a few micro-eV, that could plausibly explain the dark matter abundance.

Over the next several years, ADMX will extend the search to even higher axion masses, which requires significant additional R&D on development of high frequency cavities. As the experiment grows, it also needs more help with project management and national lab support. A group of Fermilab scientists (led by Aaron Chou) with experience in axion searches plans to move their effort from other operating experiments to join the ADMX collaboration. Fermilab aims to contribute technical expertise on RF cavity design and development for the higher mass part of the axion search.

#### **Large Synoptic Survey Telescope (LSST)**

LSST, led by SLAC, has started construction of a dedicated imaging facility with an order of magnitude greater survey speed than DES, dedicated to a full time, ten-year survey that will produce a database of unprecedented precision, depth and coverage, to begin in the early 2020's. Fermilab is working to apply scientific and technical lessons of SDSS and DES to LSST, and plans active participation in survey operations. Fermilab astrophysicists and computer engineers in SCD are working with university researchers to build software frameworks that will encompass project tools and enable the hundreds of scientists in the LSST Dark Energy Science Collaboration to share code and work together efficiently.

#### **Cosmic Microwave Background: South Pole Telescope (SPT-3G) and CMB Stage 4**

Since the 1992 discovery of primordial fluctuations in cosmic background radiation by the COBE satellite, the quality of maps, made by satellites, balloons and ground based telescopes, has rapidly improved, largely as a result of advances in detector technology. They now provide astonishingly precise cosmological measurements, enabling many unique measurements of fundamental physics.

The highest resolution maps must be made from the ground, simply because of the required size of antennas. Although individual detectors are now almost at the quantum limit, further significant advances are possible with larger cameras that can survey much faster. As was for digital optical surveys at the advent of SDSS, the next generation of CMB camera systems are too large and complex to be developed mainly by university groups, and will require the capabilities of national labs. The P5 report enthusiastically endorsed a new venture by DOE, leading to deployment of a "stage 4" CMB experiment in the 2020's.

Fermilab is partnering with the University of Chicago, Argonne National Lab and others to develop the camera system for a new "stage 3" experiment at the South Pole Telescope (SPT). Fermilab will integrate and test detectors, and design, assemble and test the SPT-3G cryostat. These tasks build on Fermilab's experience with similar engineering, integration and testing of the Dark Energy Camera, and adds new lower-temperature cryogenic capabilities at the lab that synergize with our efforts in dark matter experiments and detector R&D. Through an LDRD grant to Bradford Benson, our team at Fermilab is currently developing the facilities and methods that would be needed to package, test and integrate such a large array of TES-based detectors.

The initial SPT-3G camera will be deployed at the South Pole in early 2016, with upgrades in following years. Fermilab will gradually expand its effort in this area, and work with a large network of partners to develop and align our efforts with the next generation S4 project. It will likely be our largest technical construction effort on the cosmic frontier in the 2020's.

#### **Cosmic Detector Research and Development**

Fermilab has an active Detector R&D program, from which many ideas have been developed into particle astrophysics experiments. One example is the Holometer, which developed experimental techniques to cross-correlate laser interferometers in the MHz range, well above the region covered in most gravitational wave detectors. Such synergy continues with efforts by several young particle astrophysicists at Fermilab to develop new detectors for cosmic surveys. R&D programs take advantage of unique technical infrastructure

and support available at Fermilab. They also help incubate new capabilities at the lab; for example, new, sub-Kelvin cryogenic capabilities at Fermilab are being developed and shared for MKIDs, CMB, ADMX, and CDMS detector development. Magnetic Kinetic Inductance Detectors (MKIDs) have the potential to provide a unique combination of spectral and timing information for each photon received with large telescopes. This technology could enable unique precision “chronospectrophotometric” studies of supernovae or other transient sources, as well as follow up of specific targets from DES or LSST, and possibly a wide field spectral survey. Thick CCD detectors have become the workhorse for optical surveys such as DES, DESI and LSST, and have shown promise as low threshold dark matter detectors (DAMIC). Development work continues towards reducing readout noise especially for the latter application, but also for low noise spectroscopy.

## Theory

Astrophysics at Fermilab began in the Fermilab theory program, which seeded the current cosmic frontier experimental program. While the major focus is theoretical research, theorists also play a major role in developing and supporting experiments. Theorist Frieman is director of DES while Dodelson directs a team of scientists and computer professionals in developing a suite of software tools (called COSMOSIS) for surveys such as DES and LSST. These large surveys will reach unprecedented levels of statistical precision and require detailed understanding of cosmological hydrodynamics and galaxy formation to disentangle normal astrophysics from the fundamental physics. Gnedin has developed state of the art techniques for computational hydrodynamics that are important for interpreting the results of cosmological surveys.

Cosmic microwave background (CMB) observations offer unique probes of the neutrino mass spectrum, the number of light weakly interacting species, dark matter annihilation and primordial magnetic fields, in addition to providing the best window into the very early universe. Fermilab theorists have a strong background in CMB theory (as evidenced by the award of the 2014 Medal of the Institute of Astrophysics of Paris to Stebbins) and work to develop this nascent experimental CMB program at Fermilab.

Fermilab’s theoretical support of the cosmic frontier extends beyond projects in which Fermilab is directly involved. Hooper’s work on evidence for indirect detection of dark matter annihilation toward the Galactic center is an important aspect of the science output of from the Fermi satellite. Stebbins is developing techniques for neutral hydrogen intensity mapping for future cosmological surveys. Fermilab’s theory program strives to make the most of the cosmic window on fundamental physics.

## Long Range Vision

The future of the field will be shaped by data. In the next ten years, the unexplained phenomena of dark matter and cosmic acceleration will be studied in quantitative detail orders of magnitude beyond that of today’s experiments. Fermilab’s experimental program will follow these investigations to their natural limits, aimed at discoveries that will lead to profound extensions of our current knowledge.

Over the next decade, Fermilab-supported experiments will pursue direct detection of WIMP dark matter, across a broad range of mass, to the natural limits set by neutrino backgrounds, and QCD axion dark matter across the entire mass range suggested by theory. The new cosmic surveys DESI and LSST will build on pioneering Fermilab experiments SDSS and DES to extend the precision of cosmological probes of dark energy and global gravity by orders of magnitude. A new joint effort of Fermilab, other labs and the community will study the cosmic background radiation with unprecedented detail and precision, to fundamental limits set by cosmic variance, probing dark matter, new species of invisible relativistic matter, primordial and present-day cosmic acceleration, and the masses of neutrinos. These experiments will collect their data at sites all over the world, but will have common roots in scientific programs and technologies developed with unique contributions from Fermilab.

## Cosmic Frontier Summary

Cosmic acceleration and dark matter remain central themes in the national particle-astrophysics program, as well as at Fermilab. The lab’s experimental program supports the diversified approach to dark matter



direct detection recommended by P5, with leading roles on some projects and technologies. The laboratory is the current world leader in cosmic surveys with DES, plans a strong project role in DESI, and an important intellectual footprint in LSST. Fermilab's new involvement with the South Pole Telescope will foster a growing collaboration of labs and universities that will ensure U.S. leadership in CMB science. The theoretical astrophysics group actively engages with the experimental program on many fronts including phenomenological studies, concept development, science analysis, and collaboration leadership. The computing division collaborates to develop new tools for simulation, analysis, and data management demanded by precision cosmology and low-background experiments. The next wave of technological development is now adding new sub-Kelvin capabilities, a new generation of detectors, and new instruments to study the cosmic microwave background. The strength of the Fermilab particle-astrophysics program lies in our ability to merge the talents of our scientists with the lab's technical expertise, and partner these with the rest of the community, to lead cutting-edge experiments to scientific results.

## Technology R&D

### SRF Current Program

Inspired by the ILC, XFEL and the worldwide SRF collaboration, Fermilab mastered SRF technology over the last decade to install a full-scale SRF facility and its associated infrastructure. We participated strongly in the ILC high gradient push. Fermilab is now in an excellent position to launch and realize large-scale SRF projects. Several SRF experts joined our team. The opportunity to build 17 cryomodules for LCLS-II puts Fermilab in an excellent position to co-ordinate the production of full-scale cryomodules for PIP-II, and to make a significant contribution to the ILC if this goes forward. The fabrication of the first LCLS-II prototype cryomodule is well underway. LCLS-II is the highest priority project for the Office of Science, and Fermilab's contribution to LCLS-II has corresponding priority at the lab.

The P5 roadmap makes PIP-II a high priority for Fermilab. As a major step in the neutrino program it will be the platform upon which we build our future. PIP-II will increase the proton beam power for generating neutrinos from 700 kW to 1.2 MW. It will be a powerful, flexible machine with state of the art technology to serve the lab for many decades, fully utilizing our investment in SRF technology. Development of a suite of SRF structure prototypes (with  $\beta = v/c = 0.11, 0.22, 0.51, 0.61$  and  $0.9$ ) has been underway for the last several years. The lowest  $\beta$  structure is a collaborative effort with ANL. Major Indian Laboratories collaborate with us to promote high intensity proton accelerators in India.

The on-going effort to build the prototype LCLS-II cryomodule is planned for completion by the end of CY 15. It will be followed by the full-scale LCLS-II production and testing over 4-5 years. The PIP-II prototyping effort will continue through LCLS-II production but with lower priority. Construction for PIP-II will roll in after LCLS-II completion and will benefit from the extensive cryomodule production experience.

### SRF Recent Accomplishments

Having successfully completed and tested a record performing ILC cryomodule to demonstrate the ILC specification of 31.5 MV/m with Q value near  $10^{10}$ , Fermilab's SRF R&D program shifted emphasis from high gradients to high Q values at medium gradient to benefit future long pulse and CW accelerators, in particular LCLS-II at SLAC and PIP-II at Fermilab. Two spectacular breakthroughs on the high-Q frontier allow Q values to more than double the expected value at 2K. In the first discovery, doping the RF layer with approximately 100 ppm nitrogen inhibits basic RF loss mechanisms. In the second, closely following on the heels of the first, rapid cool-down through the transition temperature (9.2K) expels the ambient DC magnetic flux to further reduce RF losses. Reproducibility has been demonstrated with several 9-cell structures. Cornell and Jlab have verified the high Q potential of the doping and fast cool down techniques. As a combined result of the two techniques the capital cost of LCLS-II could decrease by more than 50 million dollars due to refrigerator cost reduction. Operating costs will see a roughly 4 MW reduction.

### SRF Near-term Plans (1-3 three years)

In the near- and medium-term, we plan R&D to understand the basic physics mechanisms of the transformational discoveries that lead to the high Q, so that the limits of the Q improvement can be established to expose the full potential. Such advances will allow us to extend high Q's to a wide range of frequencies for potential future accelerator applications. Practices to maintain the high Q will be enhanced.

SRF R&D in the last decades was strongly focused on gradient improvement to obtain factors of 4 - 5 gains. Substantial gains are still possible with new cavity shapes (to 50 MV/m) or with new materials (e.g Nb3Sn to 90 MV/m). Proof of principle for such gains has been demonstrated with single cell cavities and in special pulsed rf tests. Our plan is to extend these gains with Niobium cavities to full-scale structures along with Q improvements of factors of 4 by pushing the limits of the new doping and cooling discoveries. Exploration of Nb3Sn ( $T_c = 18$  K) will also continue to determine how to improve the coatings by mapping the low performing areas and analyzing those for directions to improvement.

### SRF Long-term Plans

To translate gradient gains into affordable accelerator facilities there is now a critical need for major cost reduction. Gains in this arena will benefit all accelerators for Office of Science, near-term, mid-term and long-term (e.g CW light sources, high intensity proton accelerators, neutrino factory, Higgs factory start to FCC or ILC). We plan to pursue two main thrusts in cost reduction: (i) Lower the Capital and Operating costs of refrigerators for CW (or long-pulse) accelerators via continuation of high Q R&D. Operating costs will also be strongly reduced. (ii) Lower the cost of cavities by a factor of more than two by reducing the cost of Nb material and developing alternatives to standard fabrication methods.

The cost of Nb is a large fraction (e.g. 60% for 650 MHz cavities). Our strategy is to replace bulk Nb with Nb-Cu composite (e.g. 1 mm Nb-5mm Cu) formed by explosion bonding (already proven). In addition we plan to reduce fabrication cost by eliminating most of the expensive steps of welding and machining by using monolithic fabrication through hydroforming and spinning. Proof of principle for hydroforming and spinning has already been demonstrated for such cavities. Single cell 1.3 Ghz Nb-Cu cavities fabricated by hydroforming and spinning prepared by standard techniques for bulk Nb reach 40 MV/m with Q values of  $10^{10}$ . A 3-cell Nb cavity spun by INFN in Italy was recently tested at Fermilab to give 34 MV/m gradient at Q value near  $10^{10}$ . N-doping and flux expulsion methods will be applied to raise the Q values.

### Superconducting Magnets

The overall Fermilab magnet program supports a wide variety of projects at Fermilab and CERN, as well as preparation for future accelerators. Current projects include 11-Tesla dipole magnets for the LHC, and new intersection region quadrupoles for the LHC High Luminosity Upgrade Project. Three large solenoid magnets will be built for the Mu2e experiment, high frequency magnets for the Mu2e beam extinction system, as well as an inflector magnet for injection in the Muon g-2 ring (the last two are not described for length limitations). At the same time, R&D continues to lay the groundwork for future magnets, just as past R&D prepared Fermilab for its leadership in the current projects.

### LARP and the High Luminosity LHC Upgrade

Fermilab has been collaborating with other U.S. laboratories on the LHC Accelerator R&D Program since its inception. A major goal of the program has been to design the next generation intersection region quadrupoles for the LHC. The original IR quads, which Fermilab built, will reach their end of life due to radiation damage in perhaps ten years, and increased luminosity demands will require large aperture quadrupoles at comparable gradients, leading to much higher magnetic fields at the coils. The NbTi conductor that has been used in all superconducting accelerator magnets to date will not meet the needs. Building on the development of the Nb3Sn strand and cable technology from the HFM program, a major focus of LARP has been design of the IR quadrupole magnets.

Over the last five years a series of smaller aperture Nb3Sn model quadrupole magnets have been constructed. The next two years will see full aperture model quadrupoles constructed and tested, followed by long quadrupole models. The necessary tooling will also be designed and fabricated. We expect the Hi Luminosity LHC Upgrade Project to start in 2018, with Fermilab actively participating in the construction and testing of cold masses for IR quads.

### High Fields Magnet Program (HFM)

The FNAL HFM Program is developing advanced high-field SC magnets, materials and technologies for present and future particle accelerators. Since the end of 1990s the program focused on the 10-15 T high-field accelerator magnets based on Nb3Sn superconductor demonstrating the first in the world series of 10-12 T accelerator-quality dipoles and quadrupoles, and forming a strong foundation for the success of LARP. Fermilab, in collaboration with CERN, is working on the 11 T Nb3Sn dipole to provide additional space in the LHC lattice for various insertion devices such as collimators, correctors, etc. Three short single-aperture dipole models have been fabricated and tested to 11.7 T. The first twin-aperture dipole model has been fabricated and being prepared for testing. In the future, these magnets or their modifications could be also used for a new high energy hadron collider. This year the program started development of a 15 T Nb3Sn dipole demonstrator for the Future Circular Collider with the goal of testing the first model by mid 2016. In the longer term, the program will thrust the development of accelerator magnets beyond the limits of Nb3Sn technology with fields 20-25 T based on LTS (Nb3Sn) and HTS (Bi-2212 or YBCO). The present results and progress towards the new goals rest on the successful development by the FNAL HFM program in collaboration with industry Nb3Sn and new SC materials suitable for use in high-field accelerator magnets. This program supports also the development of magnet design and analysis methods and tools, fabrication and test infrastructure, instrumentation, and training of young magnet scientists and engineers.

### Mu2e Solenoids

Fermilab is responsible for the solenoid system for the Mu2e Project. This accounts for about half the project by cost, and is on the critical path for most of the project time line. The solenoids consist of 3 magnet systems, Production (PS), Transport (TS), and Detector (DS) solenoids plus support infrastructure such as power system, quench protection and cryogenic distribution. PS and DS will be built in industry from detailed project-supplied reference designs. Fermilab is responsible for the TS final design, test and final assembly with components built in industry.

Fermilab has developed detailed reference designs for all three solenoids, interacting with the experimenters to refine the functional requirements and conducting extensive design studies. The field uniformity and longitudinal gradients have been tailored to optimize the performance while remaining in the realm of practicality for construction. The superconducting cable (four different cross sections) has been specified, prototype runs have been successful, and production quantities have started to be tested at Fermilab. The PS and DS magnets and TS coil modules will be ordered in the next year. Production lengths of DS and TS conductor will be completed in 2015, then shipped to Fermilab.

The remainder of the year will be focused on completing the final designs of all solenoid and muon beam line components, as well as shepherding the PS and DS final design in industry and starting the fabrication of the TS coil modules. TS coil modules will arrive in late CY2016 with testing throughout CY16 and CY17. PS conductor will be completed late in 2016. Magnet installation and commissioning is planned for 2019-2020, with first beam in late 2020.

For the longer term, Mu2e will be looking for ways to increase the experiment sensitivity. One handle will be to increase the beam intensity. The limiting factor will be beam dynamic heating which raises the temperature of the PS coil and damages the aluminum stabilizer. Replacing the heat and radiation shield with an all-Tungsten shield, and lowering the input temperature of the LHe are likely modifications.

## Conductor Development Program

### ***Engineering high-field superconducting materials for frontier accelerator facilities***

The goal of conductor development program at Fermilab is to transform high-field superconductors to practical magnet conductor that can be used to generate fields above 20 T for the next generation of accelerators, or to power accelerators at a fraction of energy use for current HEP machines.

To effectively generate magnetic fields, practical superconductors need to carry a high engineering current density  $J_E$  of 600 A/mm<sup>2</sup>. Works at Fermilab significantly improved the  $J_E$  of commercial powder-in-tube Ag-sheathed Bi-2212 round wire by several fold, with the highest values of 20 T (4.2 K)  $J_E$  exceeding 700 A/mm<sup>2</sup>. Such  $J_E$  improvement, demonstrated in commercial wires using both cold densification methods and an overpressure melt processing, was made possible by a close collaboration with university programs and U.S. wire industry and an intensive study of the micro- or nanostructures that produce high  $J_E$  in Bi<sub>2</sub>Sr<sub>2</sub>CaCu<sub>2</sub>O<sub>x</sub> (Bi-2212) multifilamentary round wires, through characterizing the phase transformation, microstructure development, and field dependence of critical current densities in wires and other conductor forms.

One of main goals of the next ten years is the development of conductor and magnet technology for constructing high-temperature superconducting magnets that have all characteristics to constitute the high field insert of a 20 T dipole magnet for a high-energy LHC and future circular colliders. Bi2212 coils made so far are small in scale in terms of stored energy and wound from strands that carry currents of less than kA, and therefore don't represent practical magnets used in accelerators, which are fabricated from 10-20 kA Rutherford cables and carries a stored energy up to several tens of MJ. Logically, the next step for the HTS accelerator magnets is an R&D program addressing how to bridge this gap. These are the basic points that have to be addressed and that will constitute the major progress in the next three years:

- Continue to push the materials science and wire technology to get the conductor  $J_E$  beyond 1000 A/mm<sup>2</sup> at 4.2 K and 20 T.
- An increase in cable current from 1-2 kA to 10-20 kA, a jump in an order of magnitude, in the Rutherford cables and the braided cables for canted cosine-theta magnets.
- The implementation of overpressure processing to a coil of meter in length wound from many km of strands, development of overpressure processing facilities, and improvement of processing reliability.
- A magnet design and fabrication approach capable of accommodating the high transverse stresses shown to significantly reduce the performance of Rutherford cables
- A quench detection and protection strategy capable of protecting HTS coils whose normal zones only propagate at several cm/s, two to three orders of magnitudes lower than that of Nb-Ti and Nb<sub>3</sub>Sn.

## Accelerator Science

Fermilab pursues accelerator science in its operating accelerators, purpose-built test accelerators, dedicated experiments, high-performance computing, and studies for future machines. Fermilab has recently started consolidating its efforts towards the accumulation, acceleration, and disposition of high-intensity proton beams. Major items of research include:

- Experimental and theoretical studies of instabilities with the Fermilab accelerator complex. Phenomena such as the electron cloud, head-tail, resistive wall, and other instabilities manifest themselves under certain conditions. Study of these effects improves operation for the present research program and opens possibilities for future accelerators.
- Manipulations of H<sup>+</sup> beams are some of the first steps in proton beam production. High-current, long-pulse, and low-emittance sources are under development. Neutralization and stripping via lasers allow beam notching, injection, and sensitive instrumentation.
- Longitudinal RF gymnastics are used to combine proton beams, to double the available intensity. The primary technique, slip-stacking, is used in operation presently. Further research will reduce beam loss and enable future higher intensity machines (PIP-II, etc.)

- Integrable optics use non-linear focusing techniques to allow beams of much larger tune shift (and thus intensity) to be stably stored within an accelerator. A test-accelerator, IOTA, will demonstrate this and other techniques.
- Space-charge compensation through wires, electron lenses, columns, and other techniques offer another potential path to much more intense beams. These are studied theoretically, and are to be studied experimentally in the IOTA ring and at other labs (BNL, CERN).
- High-power targetry: the materials used in these targets are stressed to their limits by the thermomechanical shock of the intense beams and the accumulated radiation damage. Fermilab is leading efforts to test these effects with traditional radiation and mechanical tests, as well as spearheading novel micromechanical and multiple-beam ion irradiation techniques.

Researchers from universities and other labs collaborate with Fermilab on these investigations. Fermilab hosts an accelerator PhD program that attracts students from universities across the globe, and trains a substantial fraction of U.S. accelerator physicists.

### Technology R&D Summary

Fermilab has developed the capability to launch and realize large-scale SRF projects, with a growing team of SRF experts. The opportunity to build 17 cryomodules for LCLS-II puts Fermilab in an excellent position to co-ordinate the production of full-scale cryomodules for PIP-II. Construction for PIP-II will roll in after LCLS-II completion and will benefit from the extensive cryomodule production experience. Fermilab will also be positioned to make a significant contribution to the ILC if this goes forward. Fermilab's recent SRF R&D program emphasized high Q values at medium gradient to benefit future accelerators, in particular LCLS-II and PIP-II. Two spectacular breakthroughs on the high-Q frontier allow Q values to more than double the expected value at 2K. As a combined result of the two techniques the capital cost of LCLS-II could decrease significantly due to refrigerator cost reduction. Future R&D will focus on understanding the basic physics mechanisms of the transformational discoveries that lead to the high Q. Other R&D will focus on gradient improvement, where substantial gains are still possible with new cavity shapes or materials, and on cost reduction of SRF cavities.

The Fermilab magnet program supports a wide variety of projects at Fermilab and CERN, as well as preparation for future accelerators. Current projects include 11-Tesla dipole magnets for the LHC, and new intersection region quadrupoles for HL-LHC. Three large solenoid magnets will be built for the Mu2e experiment, high frequency magnets for the Mu2e beam extinction system, as well as an inflector magnet for injection in the Muon g-2 ring. At the same time, R&D continues to lay the groundwork for future high field magnets, just as past R&D prepared Fermilab for its leadership in the current projects.