FERMILAB-**TM-2722-DI**
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Accelerator/Experiment Operations - FY 2019

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Introduction

This Technical Memorandum summarizes the Fermilab accelerator and experiment operations for FY 2019. It is one of a series of annual publications intended to gather information in one place. In this case, the information concerns the FY 2019 NOvA and MINERvA experiments using the Main Injector Neutrino Beam (NuMI), the MicroBooNE experiment, LArIAT experiment, and Meson Test Beam activities in the 120 GeV external switchyard beam (SY120).

Each section was prepared by the relevant authors and was then edited for inclusion in this summary.

Accelerator Operations (M. Convery, C. Gattuso)

The low-energy and high-energy neutrino beams, muon beam to g-2, and the test beams in the Meson area were brought into operation after the summer 2018 accelerator shutdown. The Booster Neutrino Beam startup occurred in September, NuMI beam started up on October 16, and beam to MTest began on October 22. The g-2 experiment was ready for and started collecting physics data on March 15. Beam was delivered to users until the present shutdown which began July 8.

Prior to receiving the FY 2019 accelerator operations budget, the high-energy neutrino beam was scheduled for beam delivery for 41 weeks. Starting in May, run time was reduced to better match the operations funding available. The accelerator complex moved to a biweekly schedule of 5-days running / 9-days off. A total of four of these “off” periods occurred with the first starting May 11 and the last one ending July 1. There were 4911 hours of operation of beam to NuMI in FY 2019 with 5.6×10^{20} protons delivered. Integrated beam to NuMI met base expectations for the year.

The Booster Neutrino Beam exceeded the design goal for FY 2019 due to delays in g-2 readiness for physics. About 4967 hours of beam and 3.0×10^{20} protons were delivered to the MicroBooNE experiment.

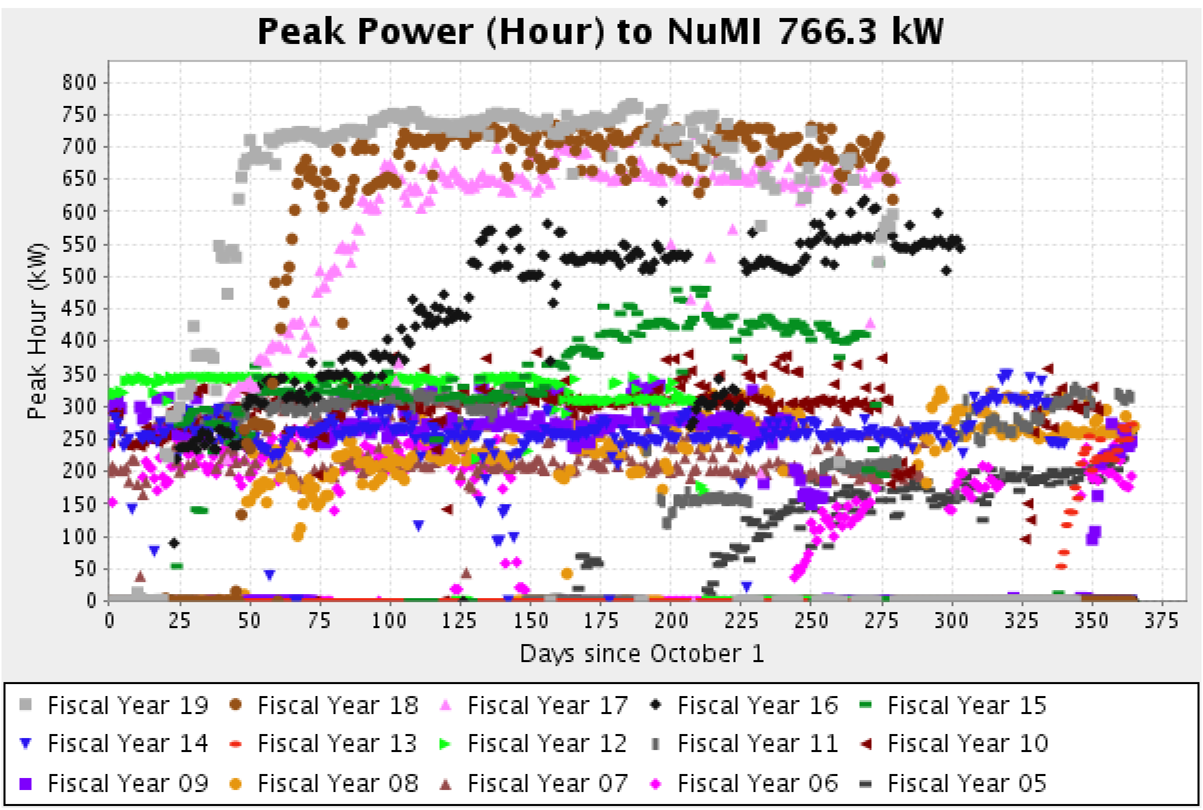
[1] Editor
[2] Administrative Support

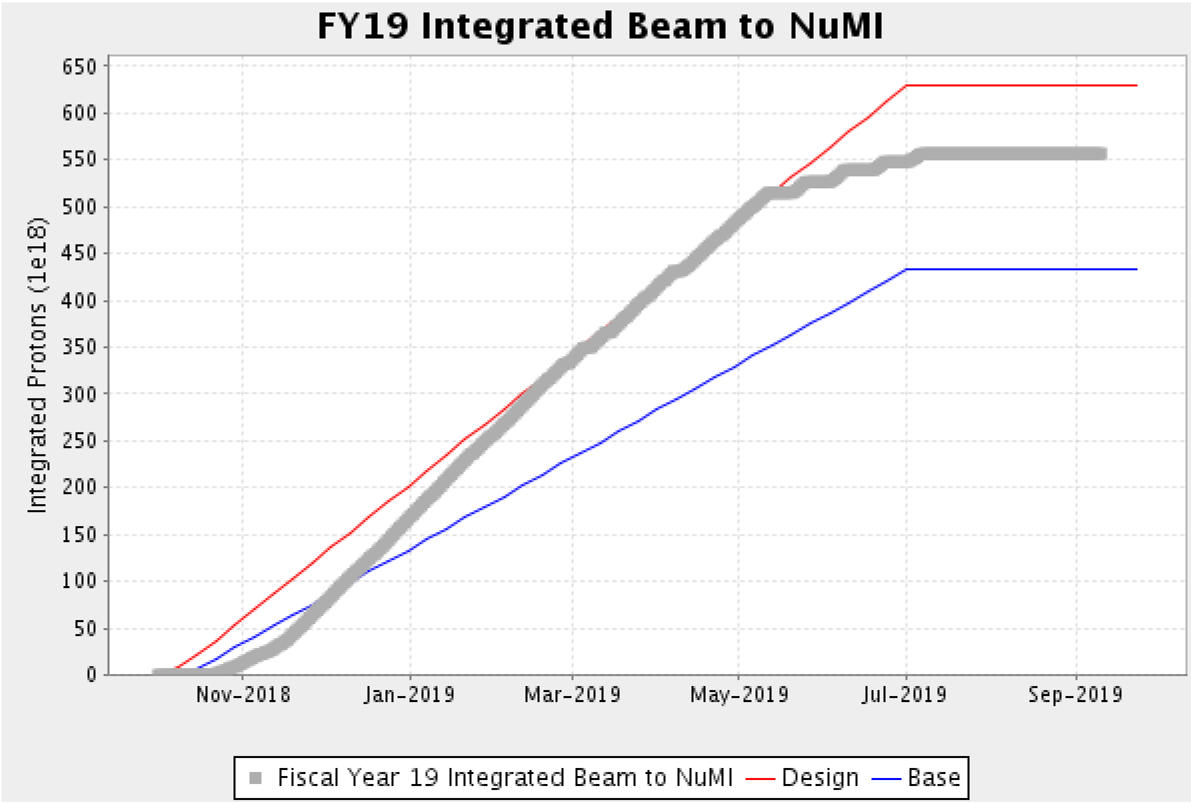
The Muon Campus was ready for operation well in advance of the time the g-2 experiment was ready for physics data in March. 1130 hours of beam and $1.2x10^{20}$ protons on target were delivered to the g-2 experiment.

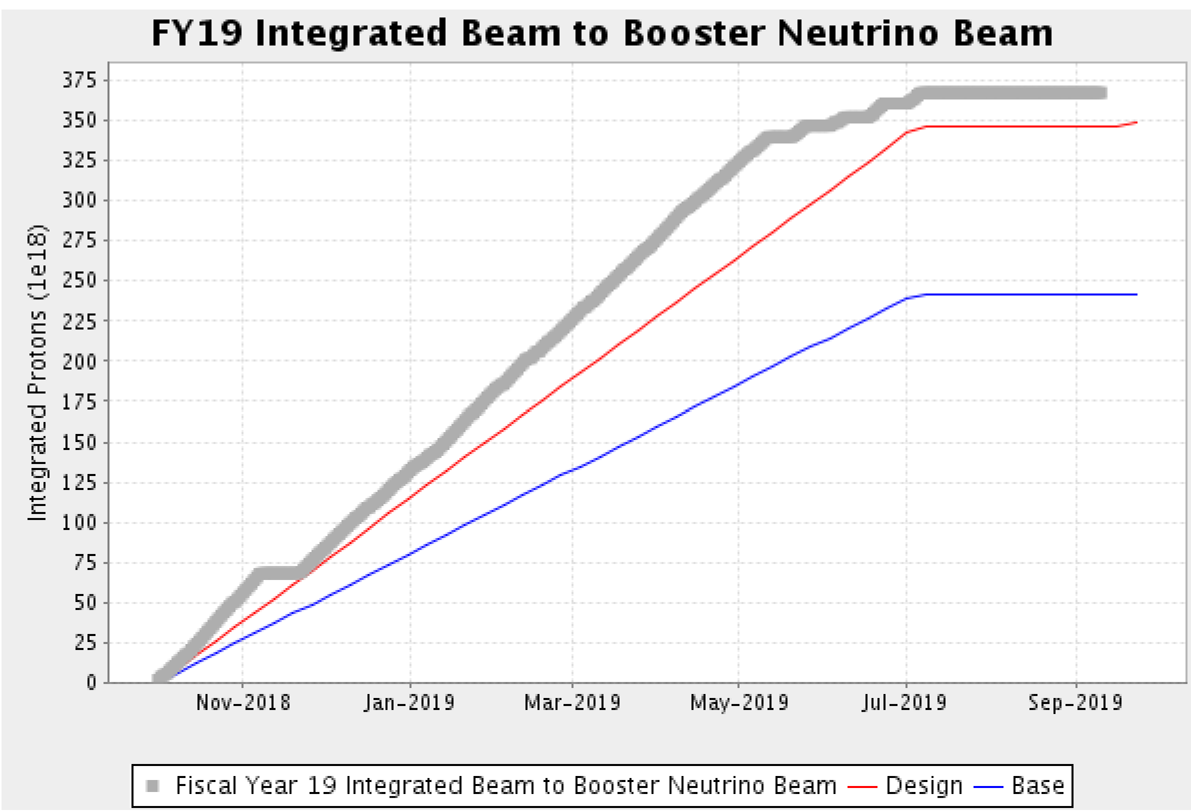
In Switchyard 120, beam to MTest for the Fermilab Test Beam Facility operated for 1476 hours driven by user requests. In MCenter, beam was delivered as requested to a NOvA experiment.

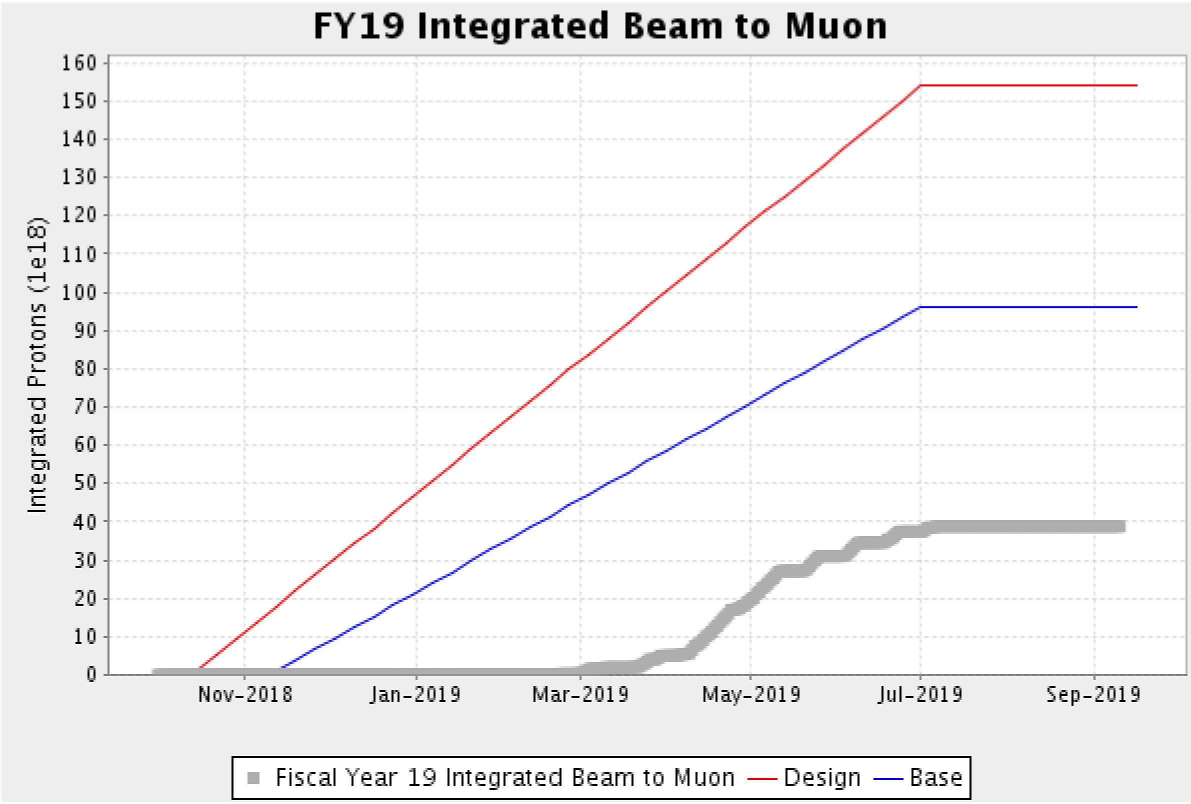
The length of the 2019 summer shutdown was driven by maintenance throughout the complex and replacement of cables due to radiation damage in collimator regions of the Main Injector (MI) and the MI8 transfer line from the Booster to the MI. Other important work included completion of the M4 beamline installation for Mu2e beam to the diagnostic absorber, and the installation of a total loss monitor system in the Switchyard 120 beamlines to allow construction of the IERC building while running beam.

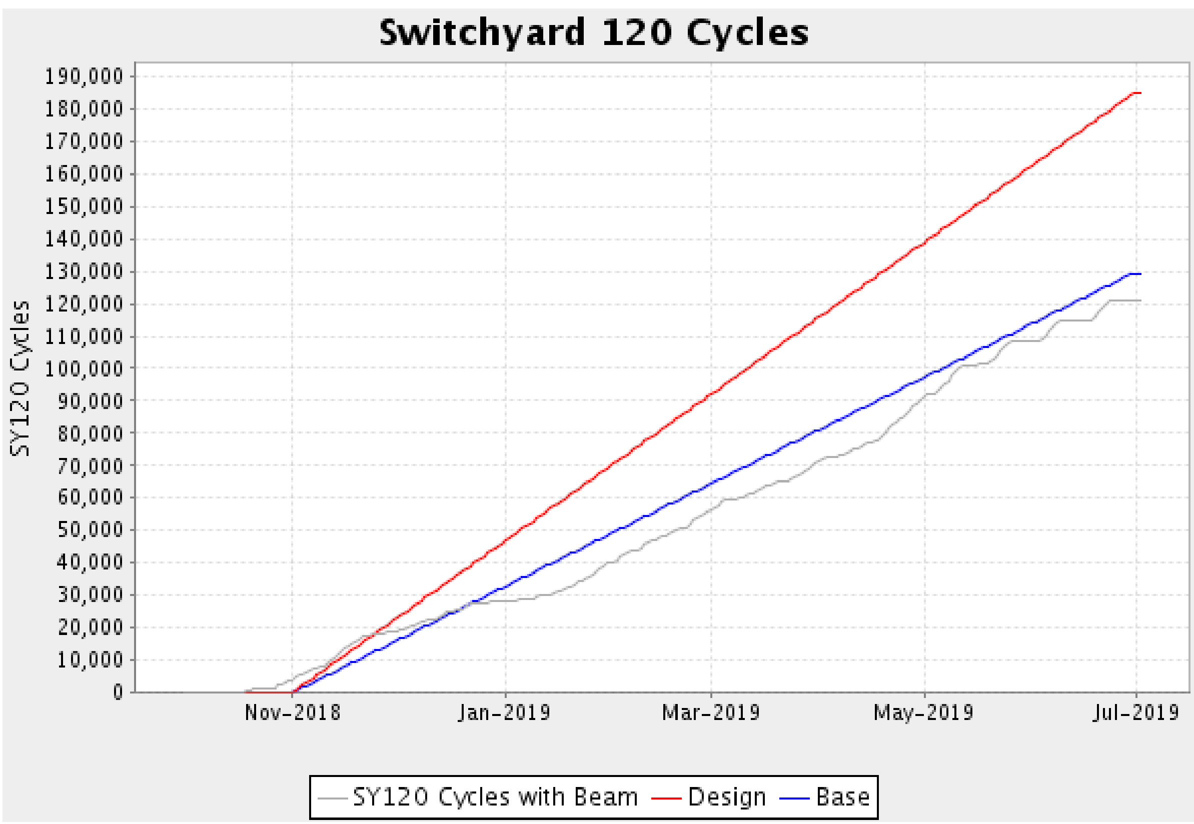
The following plots summarize the beam delivery in FY 2019.




FY19 Integrated Beam to NuMI
Integrated Protons (1e18)
0
50
100
150
200
250
300
350
400
450
500
550
600
650
Nov-2018
Jan-2019
Mar-2019
May-2019
Jul-2019
Sep-2019
Fiscal Year 19 Integrated Beam to NuMI
Design
Base


FY19 Integrated Beam to Booster Neutrino Beam
Integrated Protons (1e18)
0
25
50
75
100
125
150
175
200
225
250
275
300
325
350
375
Nov-2018
Jan-2019
Mar-2019
May-2019
Jul-2019
Sep-2019
Fiscal Year 19 Integrated Beam to Booster Neutrino Beam
Design
Base


FY19 Integrated Beam to Muon
Integrated Protons (1e18)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Nov-2018
Jan-2019
Mar-2019
May-2019
Jul-2019
Sep-2019
Fiscal Year 19 Integrated Beam to Muon
Design
Base


Switchyard 120 Cycles
SY120 Cycles
190,000
180,000
170,000
160,000
150,000
140,000
130,000
120,000
110,000
100,000
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
Nov-2018
Jan-2019
Mar-2019
May-2019
Jul-2019
SY120 Cycles with Beam
Design
Base

<u>NOvA Report</u> (P. Vahle and P. Shanahan)

NOvA completed its fifth year of operations in FY 2019. The experiment recorded 5.5×10^{20} protons-on-target (POT) delivered to the NuMI beam in FY19, split between 2.2×10^{20} in neutrino mode and 3.3×10^{20} in antineutrino mode. The integrated exposure versus calendar month is shown in Figure N-1. To date, NOvA has accumulated an exposure in its Far Detector of 11.1×10^{20} protons-on-target (POT) (full-detector-equivalent, accounting for beam delivered when the detector was under construction) in neutrino mode, and 12.7×10^{20} POT with NuMI operating in antineutrino mode.

The NOvA collaboration presented updated long-baseline oscillation results at the Users' Meeting. The results featured 80% more antineutrino data than the 2018 results. In addition to analysis activity and operations of its near and far detectors, the experiment took commissioning data with its testbeam detector in the Fermilab Test Beam Facility.

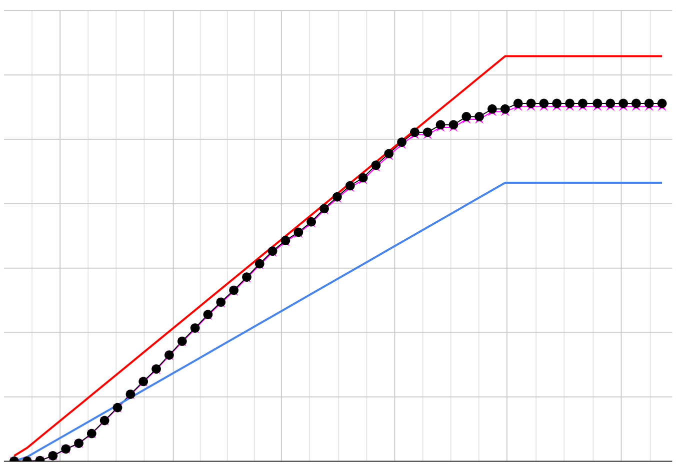


Figure N-1: The total protons on target delivered and recorded by the NOvA far detector in FY19 vs week. The far detector recorded data for 99.1% of the 5.56E20 protons delivered to the NuMI target. The NuMI beam was operated in both neutrino and anti-neutrino modes this fiscal year.

NOvA research resulted in 7 Ph.D.'s being awarded in FY 2019, bringing the total to-date to 32 (this is 9 more than reported last year, including 2 awarded in late FY18). Two institutions – University of Mississippi and Universidad del Magdalena, Santa Marta, Columbia – joined NOvA in FY19. University of Tennessee left the collaboration, bringing the total number of collaborating institutions to 50. The funding situation of the 9 Indian institutions on NOvA has been resolved and they are becoming active members of the collaboration again. NOvA has authored and approved a collaboration Code of Conduct to outline the culture of respect and inclusion expected of collaborators. That document is available publicly at http://nova-docdb.fnal.gov/cgibin/RetrieveFile?docid=32404&filename=Code_of_Conduct_for_the_NOvA_Collaboration.pdf

The experiment continued to staff data-taking shifts 24x7, with experts in data acquisition, detector controls, power supplies, and avalanche photo diode (APD) operations on-call 24×7.

Shifts took place at 25 Remote Operations Centers (ROC) including the ROC-West at Fermilab. New ROCs in Prague, South Dakota, Dallas, Wisconsin, and Austin were commissioned. A team of 2 Run Coordinators serving in a rotation oversaw daily operations and coordinated activities of the shifters, experts, and support staff. The maintenance and operation of the far detector, and of the Ash River Laboratory, were performed by a crew employed by the University of Minnesota under budget and safety oversight from Fermilab, and in coordination with the collaboration operations team.

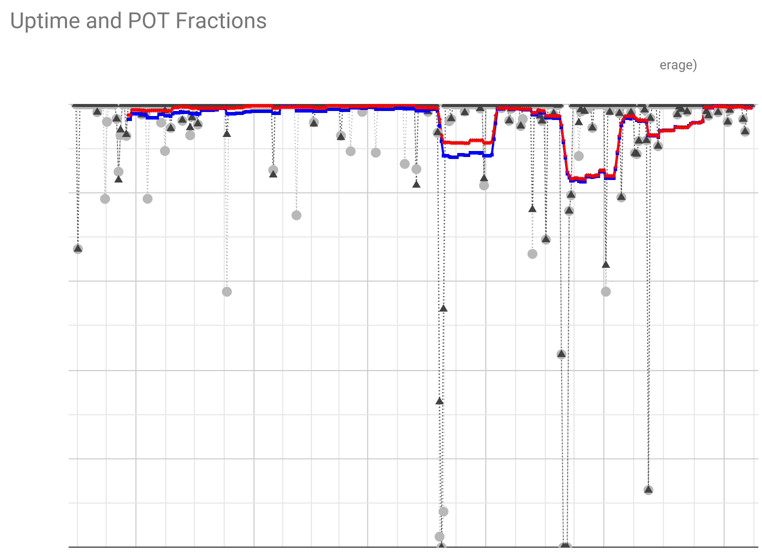


Figure N-2: The NOvA far detector uptime in FY19. This shows the daily (points) and 28-day (line) average uptime (with and without beam weighting) of the NOvA detector systems including planned downtimes for maintenance during beam-off times. Overall the detector operated 96% of the time during FY19, with beam-weighted uptime of 99.11%.

The Far Detector recorded 99.1% of protons delivered to the NuMI target during FY19 (Fig. N-2) with all but 0.04% of the FEB/TECC/APD units were typically active during data-taking. The near detector had 98.5% beam-weighted uptime for FY19.

Hardware spares usage continue to be light. In FY19, 39 (7) out of 10752 (631) Front-End Board/APD Cooling units were swapped on the Far (Near) Detector, as were 17 (13) Avalance Photo-Diodes. 900 spare FEB/TECC boards and 700 spare Avalanche Photo-diodes, in varying states of readiness, remain. Two low voltage supplies and 1 Power Distribution Unit out of 68 total of each were swapped between the two detectors.

NOvA presented an update of its signature three-flavor oscillation analysis in FY19, using 80% more antineutrino data over the 2018 NOvA result. The analysis measures the muon neutrino disappearance and electron neutrino appearance probabilities, comparing the oscillation probabilities in neutrinos and antineutrinos to extract information on the mass hierarchy, octant of the mixing angle θ_{23}, and the CP violating phase. NOvA sees electron antineutrino appearance in a muon antineutrino beam over a long baseline at 4.4 sigma significance. When combined with the constraint on the angle θ_{13} from reactor experiments, the NOvA data prefer the normal mass hierarchy at 1.9sigma, and the upper octant by 1.6sigma. The best fit implies

CP conservation, but all values of δ_{CP} are allowed at about the 1sigma level. A paper on these results – the first NOvA paper using antineutrino data - has been accepted by PRL and is the proofs stage. Currently, the results are available in arXiv:1906.04907. Figure N-3 shows the allowed region in θ_{23} - δ_{CP} parameter space coming from the combined fit of appearance and disappearance data in both neutrino and antineutrino mode.

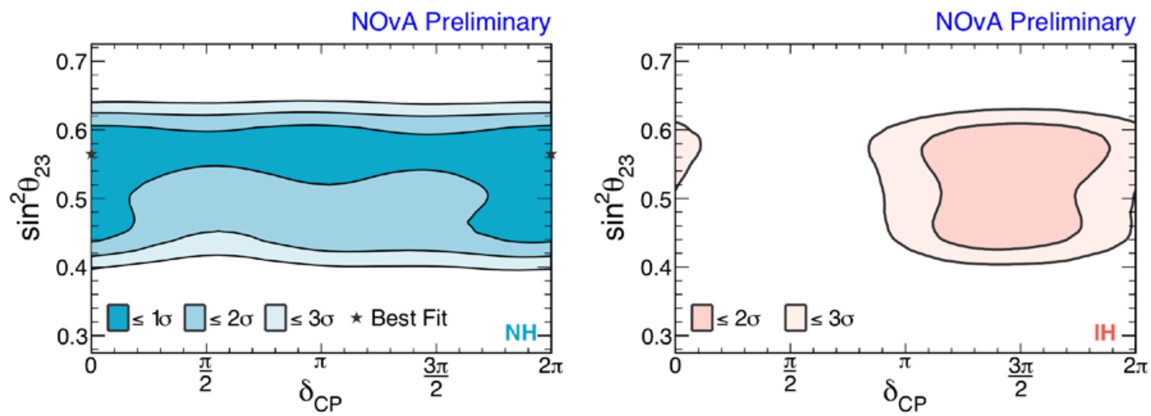


Figure N-3: The significance contours in $\sin^2(\theta_{23})$, δ_{CP}, and the Mass Hierarchy (Left: Normal, Right: Inverted) for the combined NOvA muon neutrino disappearance and electron neutrino appearance fit using θ_{13} from reactor neutrino disappearance. Unshaded regions are excluded at more than 3 sigma.

In addition to oscillation measurements, NOvA also published a paper on the rate of multiple cosmic-ray muon events in the Near Detector (Phys.Rev. D99 (2019) no.12, 122004), and has a paper on the measurement of neutrino-induced neutral current coherent π^0 production in peer review (arXiv:1902.00558). Two other publications are in advanced stages of internal collaboration review, one on π^0 production in charged current interactions and another on the tuning of the cross section model that NOvA employs to better match simulation to the data in the Near Detector.

In FY2019, the NOvA collaboration filled, instrumented and commissioned with beam data the first of two 32-plane blocks of its testbeam detector in the Fermilab Test Beam Facility. Filling of the second block was delayed due to water contamination of the scintillator to be used at the level of 30 ppm. Left-over scintillator stored at Ash River has been brought to Fermilab to fill the second block. During commissioning, it was found that the rate from beam halo swamps that from beam in the beam channel and overloads the NOvA electronics. Solutions from FTBF and NOvA electronics experts are being sought. Mitigating the beam halo rate will be the highest priority when data-taking resumes in FY20. Once operating stably, the detector will collect data from tagged electron, muon, pion, and proton beams which will enable a detailed understanding of the detector’s muon energy scale, electromagnetic and hadronic response in addition to providing real data for the detailed study of particle identification techniques.

The NOvA collaboration has identified several potential improvements in analysis and beam operations to enhance the physics reach of the experiment. A high power target was constructed in FY19 and installed during the shutdown. Other improvements to the target area and measures to reduce losses in the Booster promise to enable up to 900 kW beam power to be delived to

NOvA in the experiment's final years. The final impact of these intensity improvements remains uncertain as pressure on annual run length mounts.

E-938 / MINERνA Report (L. Fields, D. Harris)

The MINERνA experiment took physics quality data in in the NuMI Low Energy beam from November 2009 until summer 2013. In FY 2014 through FY 2018, the MINERvA experiment took data in the NuMI Medium Energy beam, and continued this data taking in FY 2019.

FY 2019 Operations

The data taken in FY 2019 was all Medium Energy antineutrino data (6 GeV peak antineutrino energy). Between October 1, 2018 and February 26, 2019 when the physics run was completed, the experiment received $3.18{\times}10^{20}$ POT in antineutrino mode. Since 2013 the experiment has received over $30{\times}10^{20}$ POT in medium energy running, taken with a MINERvA Detector integrated livetime of 97%.

During the FY 2019 running period, the collaboration continued to calibrate the detector, monitor the detector light levels, and check the reconstruction performance of both the MINERvA and MINOS detectors continuously. The experiment operates 40% of its shifts remotely, and in FY 2019 continued its checklist-based shifts. Figure MV-1 shows the FY 2019 protons delivered and recorded versus time, including the POT recorded when the MINERvA detector was live and, noting that some MINERvA analyses use the MINOS near detector, the POT recorded when both MINERvA and the MINOS Near Detector were live. In FY 2019, MINERvA took data without helium in the cryostat to continue its empty target measurement. The MINERvA collaboration took responsibility for the MINOS Near Detector in Spring 2016, including data processing, data quality monitoring, and routine swaps of MINOS electronics boards in case of failures.

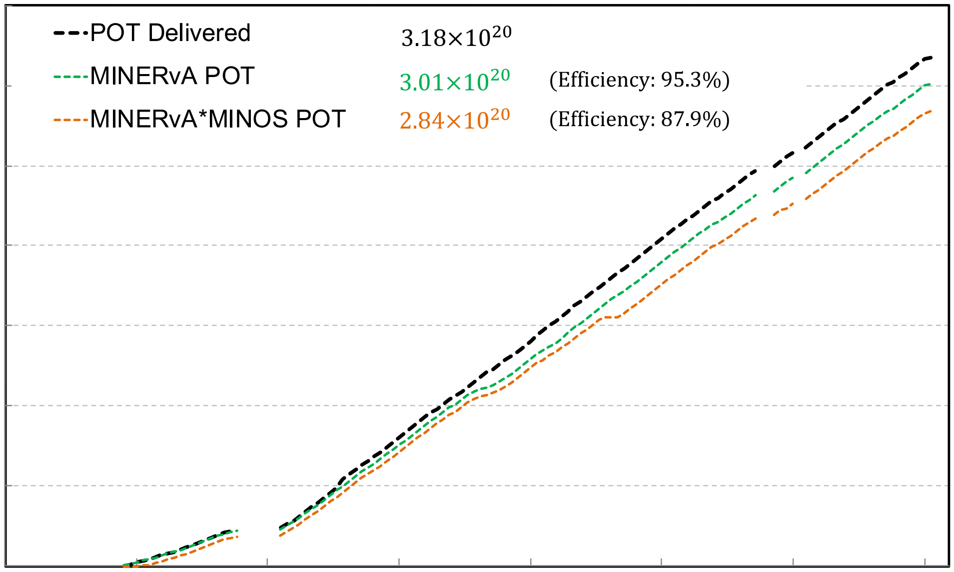


Figure MV-1: Shows the protons on target versus time, as well as the integrated livetimes of the MINERvA detector alone and the MINERvA and MINOS Near detector combined for FY19.

MINERνA Construction and Installation Activities in FY 2019

During FY19 MINERvA did not change anything associated with its DAQ or electronics. MINERvA took data with water in the water target for most of the year, but there was a short period and the end where the water target was emptied, so we could take empty water target data for the purposes of background subtraction.

MINERνA Results through FY 2019

The low-energy neutrino data, which is still being analyzed, was taken to provide exclusive cross-section measurements. Low energy events tend to have few final state particles, which allows the identification of single particles in the MINERνA detector and the measurement of exclusive channels important for current and future oscillation experiments. The MINERνA detector has a granularity that is about a factor of 10 more than the NOνA detector, and can be used to identify processes that will contribute backgrounds and signal processes in NOνA, DUNE, T2K and the SBN experiments.

By the start of 2019, the MINERvA Collaboration had published a total of 26 papers covering a broad range of neutrino and antineutrino interaction channels. By FY16 the channels included different ways of analyzing the charged current quasi-elastic interaction, a measurement of the inclusive charged current cross section ratios lead/scintillator, iron/scintillator, and carbon/scintillator, neutrino and antineutrino production of charged and neutral pions, coherent production of charged pions by both neutrinos and antineutrinos, and a first electron neutrino charged current quasi-elastic cross section measurement. The FY17 publications include measurements of both charged current inclusive and charged current coherent kaon production, diffractive neutral pion production, and deep inelastic scattering cross section ratios on carbon, iron and lead to scintillator. The FY18 publications include measurements of antineutrino events at low recoil which showed evidence for multi-nucleon correlations, as well as measurements of double differential antineutrino cross sections for quasielastic-like events.

In FY19 MINERvA released four additional cross section results, including one now from the medium energy data set in neutrino mode. Those results include a new measurement of charged current charged pion production by antineutrinos, the neutrino double differential cross section for quasielastic-like scattering as a function of muon kinematics, and a first measurement of neutron multiplicity and kinematics in antineutrino low recoil scattering, which is paving the way for DUNE near detector designs given the importance of neutron production when trying to reconstruct antineutrino energy.

MINERvA has also made significant progress with analysis and simulation of the medium energy neutrino and antineutrino data sets. In FY17 we completely overhauled the way we simulated accidental activity in the detector as a function of booster batch intensity, and in FY18 we carried out a successful processing campaign where we simulated 2 times our neutrino data statistics in the scintillator tracker and 10 times our neutrino data statistics in the nuclear target region where our analyses are more likely to be statistics limited. By the end of FY19 we finished the calibrations of all of our antineutrino data. In addition, we have simulated two times the data statistics for a run period that corresponds to the first third of our total antineutrino data set. We have continued our program for a data preservation campaign that will enable future analyses of our data, and/or enable future models to be tested against our data.

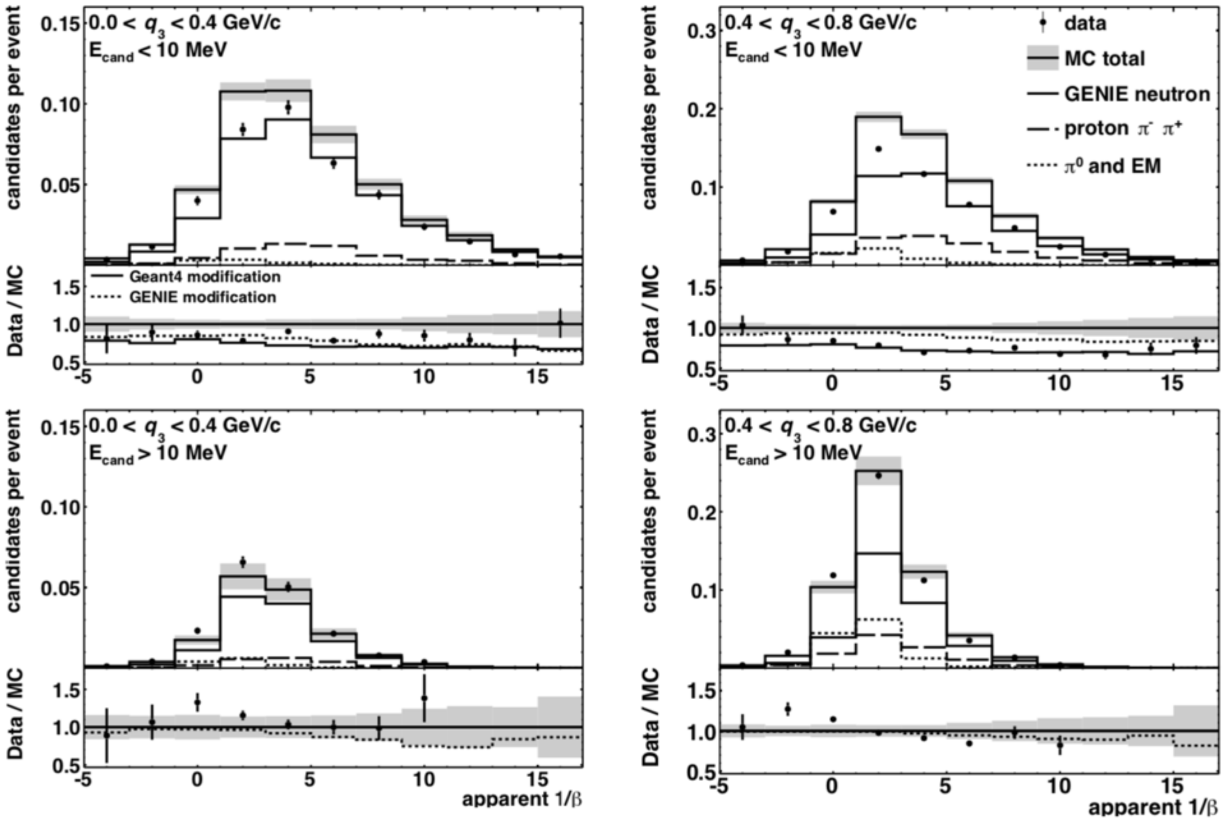


Figure 2 shows the apparent 1/β distributions for antineutrino charged current events with 3-momentum transfer below 0.4GeV on the left, and between 0.4 and 0.8GeV on the right, and for neutron candidates with visible energy below (top) and above (bottom) 10MeV. Data are shown with statistical uncertainties only; the simulation is shown with systematic uncertainties. Bins with very large data statistical uncertainties are not shown.

MINERvA's measurement of neutrons is making an impact in the oscillation community because it was the first time that neutron kinematics (time of flight, spatial, and speed (1/β) distributions) have been measured, and compared with the reference simulation being used by many oscillation experiments. One example of these results are shown in the figure above. The predictions from the generators do not match well which signals a problem with either the final state interaction modeling, or the neutron propagation model in the detector. [Phys. Rev. D 100, 052002 (2019)].
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MINERvA's first Medium Energy result was submitted for publication this year, and showcases the impressive statistics accumulated in this new mode. The analysis uses neutrino-electron scattering, a process whose cross section can be calculated to better than a per cent, to limit flux uncertainties in the NuMI beamline to an unprecedented level [arXiv:1906.00111 [hep-ex]]. MINERvA sees 810 neutino-electron scatters after background subtraction, which results in a measurement that reduces the normalization uncertainty on the ν_μ NuMI flux between 2 and 20 GeV from 7.5% to 3.9%. This is the most precise measurement of neutrino-electron scattering to date, will reduce uncertainties on MINERvA's absolute cross section measurements, and demonstrates a technique that can be used in future neutrino beams such as LBNF.

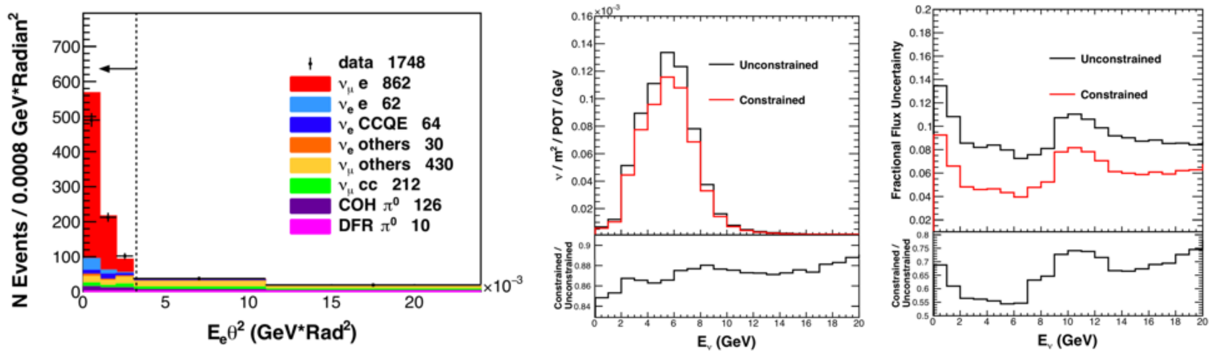

Figure 3 (left) shows distribution of the electron energy times the square of the angle of the electron with the beam birection, which is the most powerful way to select neutrino electron scattering events. The middle (right) plot shows the muon neutrino flux prediction (flux uncertainty) before and after the constraint from these events.

<u>Fixed Target Switchyard 120 GeV (SY120) and MTest</u> Reports (T. Kobilarcik, M. Rominsky, J.J. Schmidt)

The general operation of SY120 was relatively smooth. The MTest beamline was operated for the FTBF program as requested by the test beam experiments. The MCenter beamline, with tertiary beam capability, was commissioned for the NoVA test beam run Modifications were made to the downstream section of the NM beamline in anticipation of running for E1039 in FY2020. Planned improvements, such as an upgrade to the vacuum instrumentation, were deferred due to budgetary constraints.

During the FY2019 shutdown, radiation interlocks in Switchyard were improved. An interlocked total-loss monitor system was installed between A0 and the Switchyard dump. The new system will be commissioned when beam resumes. This system is necessary for the concurrent construction and occupation of the Integrated Engineering Research Center (IERC), and operation of the SY120 program.

<u>The Fermilab Test Beam Facility</u> (M. Rominsky, J.J. Schmidt, E. Niner)

The Fermilab Test Beam Facility (FTBF) provides users from around the world an opportunity to test detectors in a variety of charged particle beams. The facility offers two beamlines (MTest and MCenter) to accomplish this goal. A plan view of the facility is shown in Fig. TB-1. The facility offers instrumentation to understand the beamline and infrastructure such as gas lines, high voltage lines, and signal cables.

In FY19 a tertiary target and beamline instrumentation was installed in MC7B and commissioned for the NOvA test beam run. There are now two experimental areas with tertiary targets capable of delivering beam down to a few hundred MeV in MCenter with the station used for LArIAT upstream. Work was done in the facility to continue integrating otsDAQ into the beamline instrumentation.

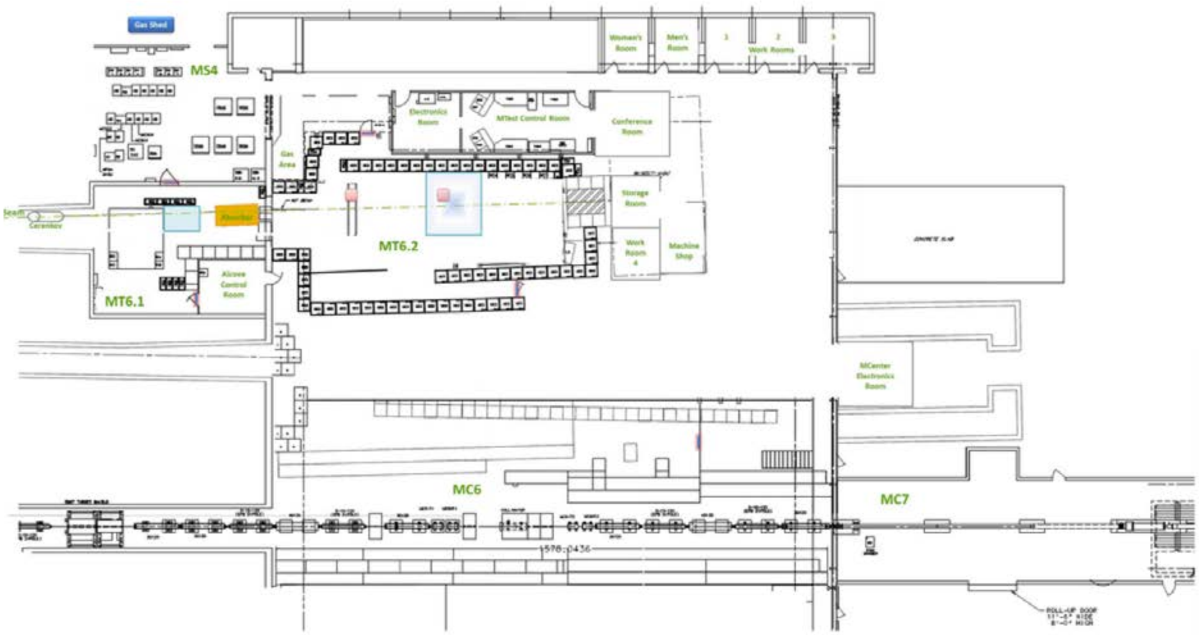

Figure TB-1: View of the Fermilab Test Beam Facility. The beamline at the top of the picture is MTest and the beamline at the bottom of the picture is MCenter.

Research Performed at the FTBF in FY 2019

Each test beam experiment is required to prepare a Technical Scope of Work (TSW) with the laboratory in which the beam, infrastructure, and safety requirements are spelled out in detail. In FY19, 21 experiments ran, often multiple times, comprising 242 individuals from institutions around the world. These experiments are listed in Table TB-1. There were four new experimental efforts in FY19. Figure TB-2 shows how the experiments broken down by research focus and Figure TB-3 shows users by job title. We supported groups from both ATLAS and CMS, as well as groups from Brookhaven and the Relativistic Heavy Ion Collider (RHIC). We saw new users this year from the LHC shutdown and expect that trend to continue in FY20. We supported the neutrino and muon experiments NOvA and Mu2e. We also had several groups come in to test general detector research and development. Full information from these groups will be included in the annual test beam report (in preparation).

In FY19 there were 30 beam weeks available which experiments fully utilized besides the holiday period. Counting each user per week yields 46 weeks of experiment time during FY 2019, with multiple users in the beam line at the same time. In May/June 36 additional days of beam running were lost due to the reduced accelerator schedule. The groups work cooperatively and efficiently to run as many as five groups simultaneously and take data when available. The MCenter beamline was used for NOvA installation and took commissioning beam the last four weeks. NOvA will remain installed for a physics run in FY20.

Experiment Number	**Description**
T0992	US CMS pixels phase II sensors
T0992	INFN CMS pixels phase II sensors
T0992	CMS outer tracker phase 2
T0992	CMS RD53a chip
T1018	Tungsten powder calorimter
T1043	Mu2e CRV scintillation counters
T1068	SVX4 telescope
T1224	ATLAS pixel telescope tests
T1409	CMS timing barrel
T1409	CMS timing endcap
T1429	PerformancesStudy of MPGD based detectors with zigzag pad readout
T1439	sPHENIX silicon strip tracker (INTT) tests
T1441	sPHENIX MAPS vertex detector (MVTX)
T1450	EIC PID R&D: ANL pixelated MCP-PMT test
T1473	FLYSUB-Consortium tracking and RICH performance evaluation

T1512	NOvA Test Beam
T1516	CMS HGG-BH Tests
T1557	Seed germination for ACT-SO student
T1564	LHCb upstream tracker
T1575	Joint Zero Degree Calorimeter Project
ORC-1553	LAPPD-TOF phase 0

Table TB-1: Test Beam experiments performed in FY 2019.

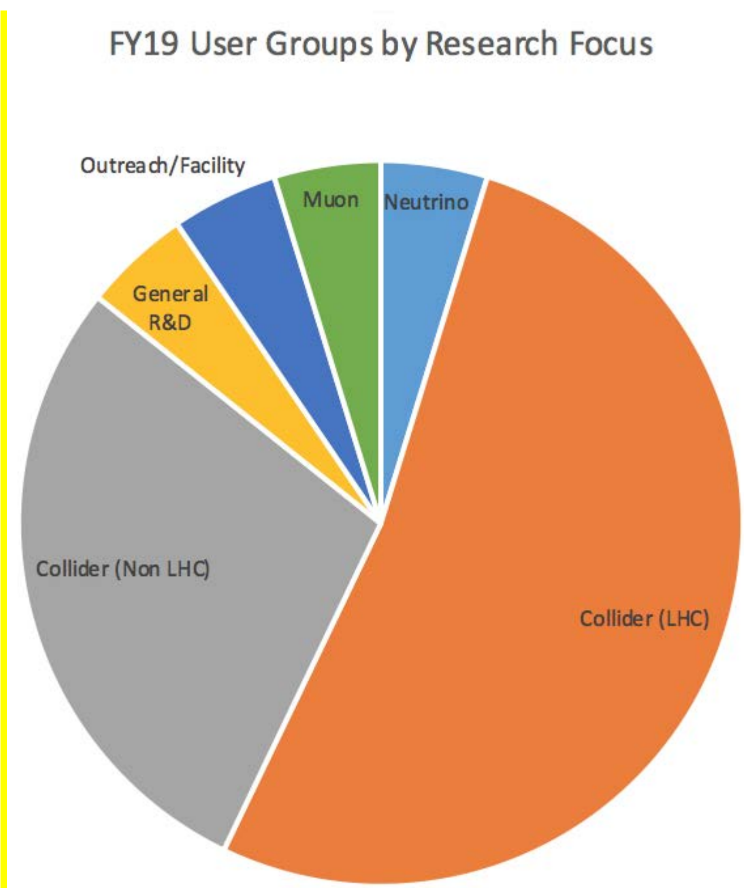

Figure TB-2: The research focus of the different groups that came to the test beam in FY2019.

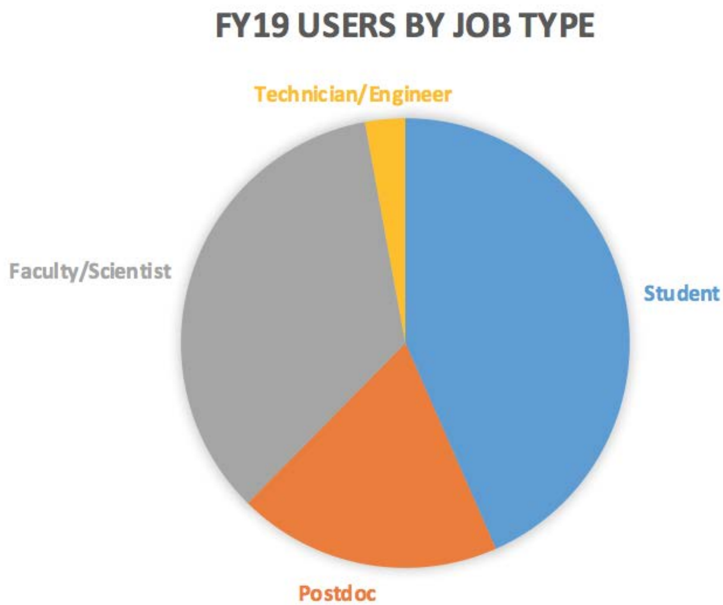

Figure TB-3: The distribution of FTBF users by job type in FY2019.

MicroBooNE report (B.T. Fleming and G.P. Zeller)

MicroBooNE completed its fourth year of operations in FY 2019 and to date has collected a total of 13.4x10^{20} POT (12.8x10^{20} POT recorded) of Booster Neutrino beam (BNB) with the detector fully operational (Figure M-1). Combined detector and DAQ uptime for the year has been >95% and the experiment has been averaging ~3x10^{20} POT/year from the BNB due to the excellent performance of the Fermilab accelerator complex. In FY 2019, MicroBooNE operations were handled by series of 5 Run Coordinators from the University of Manchester, Columbia University, Kansas State University, and Fermilab. Shifts were performed across multiple shift-taking sites including ROC-W at Fermilab and 21 remote shift centers in the U.S., U.K, and Switzerland.

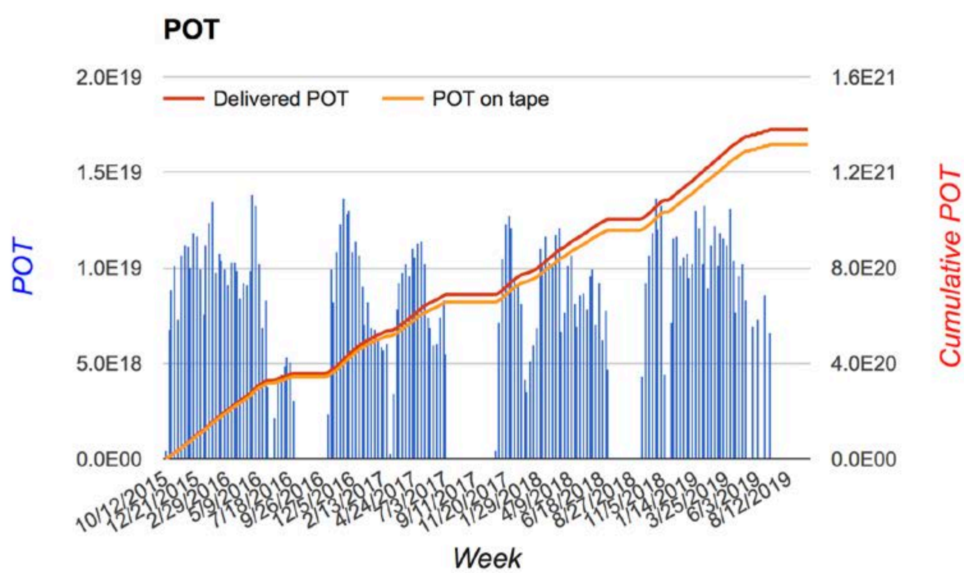

Figure M-1: Total protons on target delivered (red) and recorded (orange) by MicroBooNE since the start of operations in October 2015 to the present.

The MicroBooNE detector ran extremely well in FY 2019 and became the longest running liquid argon TPC to date. Throughout the year, MicroBooNE was in steady operations with the exception of a week-long period during the “polar vortex” in the Chicagoland area in January 2019 during which the experiment observed drift high voltage instabilities reminiscent of a similar period two years prior. The MicroBooNE team is becoming very experienced in diagnosing and addressing drift high voltage connectivity problems. The procedure for diagnosing and fixing an intermittent high-voltage-to-cathode connection is being documented both for MicroBooNE and other liquid argon TPCs which share similar drift high voltage feedthrough designs. During the summer 2019 accelerator shutdown, MicroBooNE activities including regeneration of the argon filters in the experiment for the first time in 4 years, replacement of the nitrogen analyzer which reached end of life, upgrade of cryogenic control computers, replacement of the argon recirculation pump as part of annual maintenance, and completion of an annual UV laser calibration run to map out the electric field in the detector. For entirety of the year, MicroBooNE staffed 24/7 shifts either in ROC-W or remotely.

MicroBooNE presented a total of 62 talks at conferences and workshops in FY 2019, in addition to several prize-winning posters. Four MicroBooNE students won awards at poster contests during the summer of 2019 and were featured in a Fermilab News article: https://news.fnal.gov/2019/08/four-microboone-researchers-place-in-poster-contests/?utm_source=newsletter&utm_medium=email&utm_campaign=ft-190826.
MicroBooNE also released 4 new neutrino cross section results at the NuInt conference in Gran Sasso in October 2018, including a measurement of kinematic distributions for electron neutrinos from the NuMI beam as detected in the MicroBooNE detector (https://microboone.fnal.gov/wp-content/uploads/MICROBOONE-NOTE-1054-PUB.pdf). The analysis of NuMI data in MicroBooNE is particularly important as these events are in an energy range of interest for DUNE and are the first measurement of electron neutrino interactions in argon at these energies.

In FY 2019, the MicroBooNE collaboration produced 6 new public notes (http://microboone.fnal.gov/public-notes/) and 5 papers. Among these papers, MicroBooNE published its first PRL (https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.131801). This publication includes several firsts: the results are the first double differential neutrino cross sections on argon, the first charged current inclusive cross sections on argon at low (~1 GeV) neutrino energies, and the first differential cross section results from MicroBooNE. This work was the subject of a Fermilab Wine & Cheese seminar presented in May 2019 and is the first test of neutrino event generators against double differential neutrino scattering data on argon (see Figure M-2). This year, MicroBooNE also published the first measurement of the muon neutrino charged current neutral pion cross section in argon that appeared in PRD in May 2019 (https://journals.aps.org/prd/abstract/10.1103/PhysRevD.99.091102). Together, this is the first time such neutrino cross sections have been quantified in argon at these energies - they are important for DUNE because these measurements are on argon and in the region of DUNE’s second oscillation maximum.

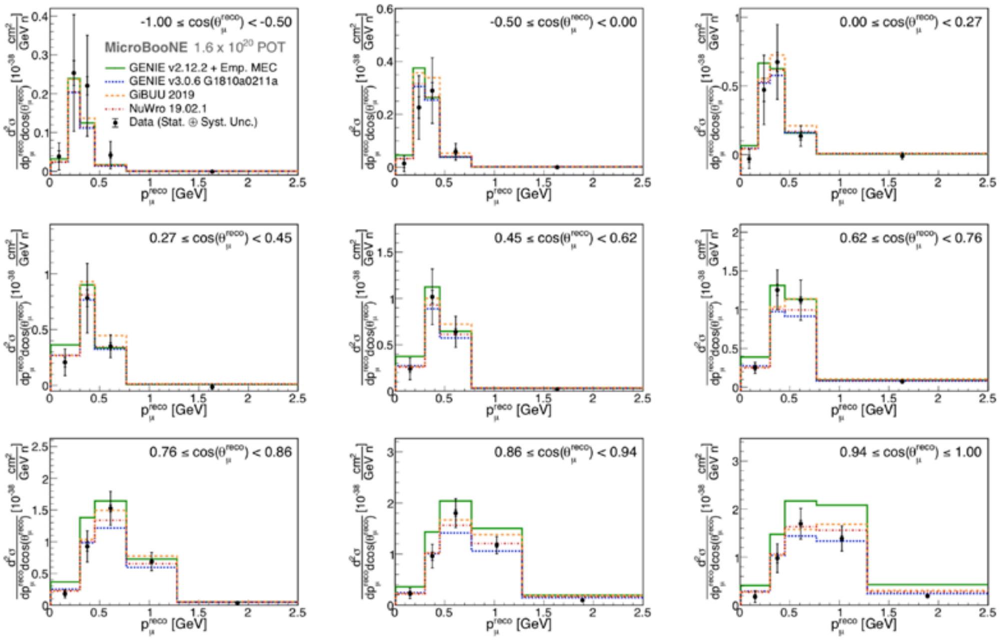

Figure M-2: Measurement of the double differential cross section for muon neutrino charged current inclusive scattering on argon in MicroBooNE as a function of muon momentum in bins of muon scattering angle from the most backwards scattered muons (upper left corner) to the most forward scattered muons (lower right corner). The results are compared to the predictions from three neutrino event generators: GENIE, GiBUU, and NuWro. The MicroBooNE data already is observed to have some discriminating power between models, preferring the use of the local Fermi Gas nuclear initial state and Random Phase Approximation (RPA) corrections.

In addition to these pioneering measurements of neutrino-argon scattering, MicroBooNE produced a new paper on calibrating the charge and energy response of a liquid argon TPC using muons and protons (https://arxiv.org/abs/1907.11736) and documented the design and construction of the cosmic ray tagger (CRT) (https://iopscience.iop.org/article/10.1088/1748-0221/14/04/P04004/meta). In January 2019, work from MicroBooNE was featured in a DOE HEP Office of Science highlight titled "*MicroBooNE, Machine Learning, and Liquid Argon*": (https://science.osti.gov/hep/highlights/2019/hep-2019-01-c/) and in May 2019, signal processing work from MicroBooNE was featured in a similar DOE highlight titled "*Extracting Signs of the Elusive Neutrino*" (https://science.osti.gov/hep/Highlights/2019/HEP-2019-05-a). Throughout the course of 2019, MicroBooNE also supplied documentation on our UV laser calibration system, noise measurements in cold front-end electronics, and performance of the continuous readout stream to DUNE for use in preparation of the DUNE Technical Design Report (TDR).

E989: Muon g-2 Report (C. Polly and M. Lancaster)

g-2 completed a one-month commissioning run (Run-0) in July 2017 and a first physics data taking period (Run-1) from March-July 2018. A second physics data taking period (Run-2) ran from March-July 2019. The two data taking periods have resulted in a raw data sample over four times that taken by the BNL E821 experiment (see Figure 1).

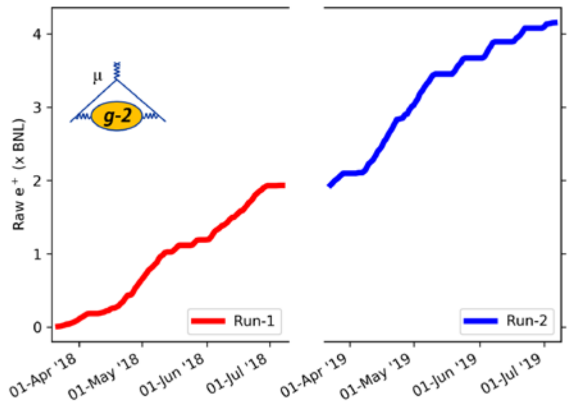

Fig. 1: The recorded raw number of e^+ *recorded by g-2 as fraction of that accumulated by BNL (for both* μ^- *and* μ^+*) in the two g-2 running periods to date.*

The analysis of the run-1 dataset is at an advanced stage and significant upgrades of the experiment were undertaken in the 2018/19 shutdown to improve the cryogenic, kicker and electrostatic quadrupole systems.

The work in the shutdown was to remediate issues that arose during the Run-1 data taking period. Towards the end of Run-1, there were several quenches arising from impurities in the cryogenic system and a significant amount of work was undertaken to identify and fix leaks and to reduce the introduction of impurities. The situation in Run-2 was much improved with only a couple of days a month required for warm ups to improve the purification. However, the experiment remains reliant on a very old mobile purifier requiring frequent interventions with a flow-rate significantly below the requirements and would certainly benefit from an improved purifier. In Run-1 there were several failures of the kicker system that became worse towards the end of the run: frequent sparks in the Blumlein, failing power supplies, resistor burnouts and leaks of the flourinert into the vaccum. This resulted in the re-design of several key parts of the system which were very successful with the exception of some residual sparking which was fixed after a week of running with the installation of a new corona shield. The kickers ran reliably at 47 kV, around 6 kV on average higher than in Run-1 bit still somewhat short of the design of 55 kV. This was primarily due to the HV cables failing for kicker voltages above 50 kV. Given the limited cable spares and the downtime to replace cables, it was decided to sacrifice a somewhat lower kick for stable running. Investigations of alternate cables and improved connectors that would speed up cable replacements have been undertaken during the current shutdown. In addition to the cryogenic and kicker system updates, resistors that had failed during Run-1 in the electrostatic quadrupole system were replaced and thermal blankets were introduced on the magnet to reduce diurnal temperature variations. A new HVAC system has since been installed ready for Run-3 to further stabilize the temperature in the experimental hall. Towards the end of the shutdown period, a quench of the magnet was induced when a magnetic shielding brick was inadvertently brought towards the magnet while it was energized. This resulted in a work-pause and a complete overhaul of procedures pertaining to work planning, training and the use of magnetic materials and the introduction of much better-defined operational roles and responsibilities including the addition of a PPD Operations Manager. These changes and the restructuring of the experimental areas to reduce clutter have resulted in a significantly improved environment which has been readily adopted by the collaboration.

Once Run-2 began, data was accumulated smoothly in just a single configuration in marked contrast to Run-1 where many different configurations were employed to mitigate failing components. 15% of the Run-2 data taking period was also devoted to dedicated systematic runs. The uptime of the pulsed systems in Run-2 was over 90%, with the kickers live for 99% of the time in the last two months of the run. The DAQ uptime was 92%. The overall uptime was 50% against a TDR expectation of 72%. The reduction with respect to the TDR is from a variety of sources: the live-time of the experiment is 85% of the expectation (predominantly from the quadrupoles) but beam availability has only been 80% of the expectation due to the MI cycle changing from 1.33 to 1.4 s, the unforeseen effect of the switchyard/testbeam, and the accelerator uptime. The accelerator uptime was lower than Run-1 due to the 5/14 running from May onwards and restrictions on overtime working prior to that. Despite this, in Run-2 50% more data was accumulated per day compared to Run-1 with the instantaneous rate being 30% higher (see Fig.2).

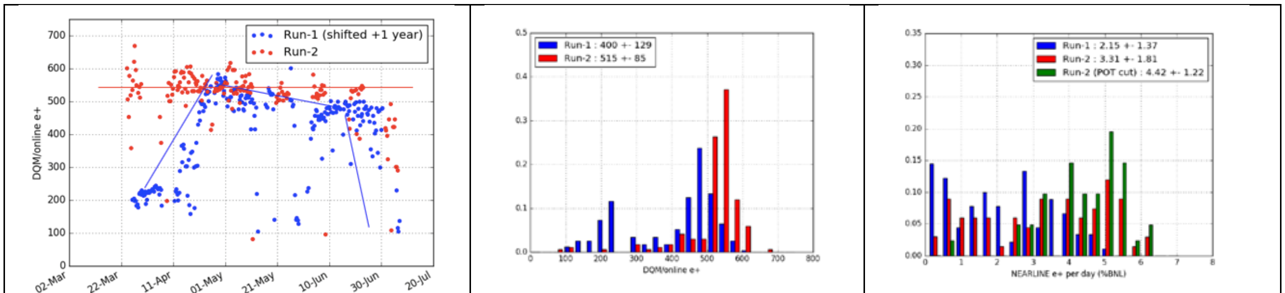

Fig.2 (a): Raw number of e^+/fill in Run-1 and Run-2	*(b): Raw number of e^+/fill in Run-1 and Run-2*	*(c): Number of e^+ recorded per day as function of the BNL(e^+/e^-) dataset.*

On average 3.3% of a BNL dataset was accumulated per day and this rose to 4.4% on days where protons were delivered for than 12 hours of the day. The instantaneous rate was lower than anticipated due to the failure of the Lithium lens. This is the second lens to fail and has resulted in the decision to mitigate the heating effect on the lens by reducing the current to the lens by 10% which has reduced the muon yield by 19%. The first lens failed in Run-1 after receiving only 29M pulses (plus 13M during its use in the Tevatron), the second lens failed after 52M pulses. This second lens survived 100M pulses at 12 Hz during testing, but the g-2 running, while at an average of 12 Hz, has an instantaneous rate of 100 Hz and this is believed to be causing the failures. There remains one spare lens and this is clearly a cause for concern since 500M more pulses need to be accumulated to reach the statistical goal of the experiment.

The analysis of the Run-1 data has been progressing well. Six independent analysis teams using three different reconstruction methods are analyzing the calorimeter and tracker data to determine ω_a while two independent teams are determining ω_p. The data remains hardwire-blinded but there has been a relative software unblinding across both the ω_a and ω_p teams. A comparison of the software unblinded ω_a analyses for a subset (approximately 10%) of the Run-1 data is shown in Fig. 3(b): excellent agreement across the analyses was obtained. The consistency (in ω_a) across the three main Run-1 data subsets is shown in Figure Fig. 3(a).

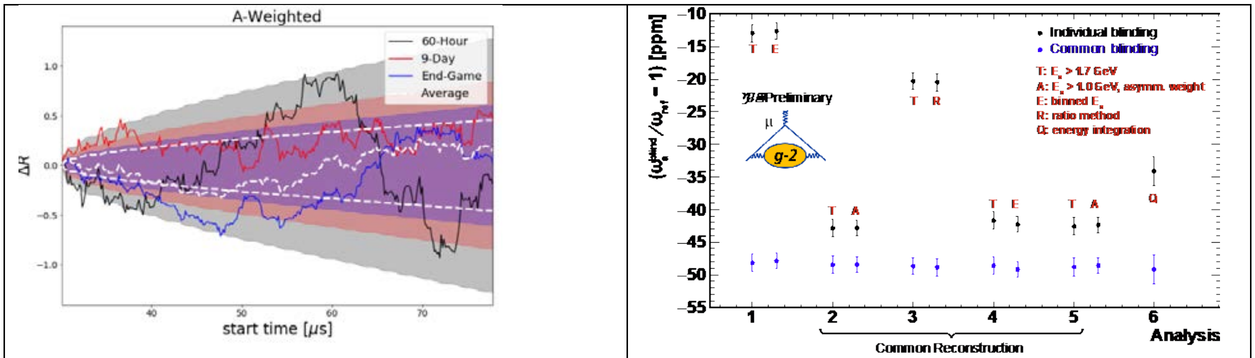

Fig. 3 (a): A comparison of the results obtained fitting ω_a as a function of time after the nominal fit start time across three datasets. All datasets fall within the expected statistical variance.

(b): A comparison of the software unblinded ω_a values (blue points) across the six independent analyses.

The distribution of the number of e^+ measured in the calorimeters as a function of time determining ω_a is shown in Fig. 4(a) for a Run-1 data subset. An excellent fit is achieved to the data when the harmonic beam motions are corrected for using parameters determined from an analysis of the data from the straw trackers as shown in Fig. 4(b).

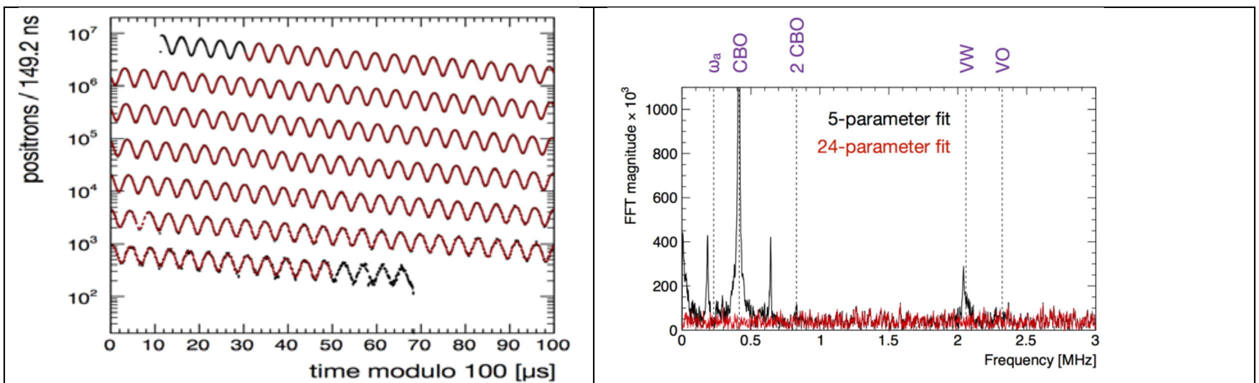

Fig.4: (a) Number of e^+ as a function of the time in the fill for 60hrs of data accumulated in April 2018. The frequency of the characteristic "wiggle" is used to determine g-2.

(b) The FFT residuals of the fit from (a). A 5-parameter fit not including the harmonic beam motions results in characteristic beam oscillation frequencies. (b) The fit when these are incorporated has a chisq/df of 1.

The Run-1 data has been reprocessed several times as the calibrations and reconstructions algorithms have evolved and to use the CPU efficiently significant effort has gone into speeding up the code, reducing the size of the processed data written out and in reducing the memory footprint of the code. The CPU efficiency of the "production" jobs is now 90%. Recently a significant effort has been invested in changing the offline calibration code to use a standard database interface and in structuring the code and jobs such that calibrations can be done shortly after the data is taken thereby allowing the production jobs to process data as it is accumulated. This has been tested on Run-2 data and will be used for Run-3. The continued analysis of Run-1 data, the processing of Run-2 data that has just begin and the imminent start of Run-3 will require significant CPU resources and we have requested an increase in our grid quota to accommodate this as well as exploiting offsite grid resources in the UK, Italy and NERSC for simulation.

In Run-3 and Run-4, we expect to continue accumulating data at the rate of approximately 1 BNL per month, which was achieved in Run-2 and to achieve our statistical goal this requires 17 months of data taking.

Acknowledgement

This report gives a brief summary of the performance and output of the accelerator complex and associated accelerator-based experiments during FY 2019. It therefore summarizes the work of many people from Fermilab and from the collaborating institutions. The credit for the successful outcome of the FY 2019 running is shared amongst many.