Fermilab Physics Advisory Committee Spring'2025 Report

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Executive Summary:

The PAC met between March 3 and 6, 2025, for an online meeting. At the very beginning, the PAC met with the interim director, Young-Kee Kim, in a close session with the purpose of better understanding the status of the laboratory after the change-over to Fermi Forward as DOE contractor. The PAC learned that the lab finds itself in times of uncertainty and is processing the implications of the recents changes on the functioning of the lab and on the execution of its program. Fermi Forward and the lab management are working to identify improvements so that Fermilab can continue to excel in scientific research through effective, efficient, safe, and secure operations. One of the major challenges identified for the near and far future is the aging infrastructure of the accelerator complex (50-year old). Otherwise, the PAC was pleased to hear that exploring the Quantum Universe remains the thrust of the research program. The PAC was also pleased to hear that the management is developing a program of regular meetings with lab staff and users. The PAC commended the progress in easing the Fermilab access to the public and congratulated the lab on the awards, financial and honorary, bestowed on its staff.

A report on the implementation plans for the science vision, as laid out in the Fermi Forward proposal and well aligned with the P5 recommendations, was presented by the CRO, Bonnie Fleming. Realizing the vision given the developing funding outlook will be a great challenge and may require a strategy for setting ranked priorities. Successful completion of LBNF/DUNE and PIP-II on time and on budget will remain the highest priority.

The chair of the LBNC, N. Saolidou, summarized for the PAC the progress made in advancing the LBNF/DUNE program. Progress was made on all fronts, securing international contributions, on the Far Site Building & Site Infrastructure project, on building the needed teams for the FD installations in South Dakota, on the LBNF beamline design, and on further advancing the ND technical design.

The PAC heard a report on the status of the Fermilab accelerator complex and on the FY2026 run plan for the Main Injector, that provides the 120 GeV energy beam to experiments as well as to the TestBeam area. Several damaging events occurred between August and September 2024, significantly impacting the infrastructure supporting accelerator operations, in particular the lab's electrical power infrastructure, and prevented the operation of the Main Injector in FY2025. Given the recent decline in

accelerator reliability, the PAC supports the campaign for upgrades, modernization, and investments in spare parts for the accelerator complex.

Two approved on-site experiments, Mu2e and Spinquest, reported on their readiness for data taking. In spite of progress made in 2024, the Mu2e completion is affected by significant delays in the vendor delivery of two solenoids. This may in turn affect its ability to collect data before the planned long shut-down in 2028, which will have adverse consequences for the present and future early career researchers. The experiment is expected to have a more reliable prediction for their readiness for data taking in about six months from now.

SpinQuest was approved in 2018 and collected its first data last year. The experiment plans to upgrade the detector with an electromagnetic calorimeter, which would allow it to set world-leading constraints (or potentially lead to a discovery) across a range of dark sector models, well ahead of competitors such as SHIP and FASER2 at CERN, provided it is ready to collect data before next year.

Lab management informed the PAC that the accelerator schedule is currently under revision for a possible update, taking into account all constraints. Under the circumstances, the PAC endorsed the initiative to reevaluate the long-term accelerator operations plan, including the 2028 shutdown.

The PAC heard a report on the activities within the Collider Physics Division, pertaining to CMS and detector R&D for future colliders. Accelerator R&D status and plans for a future Higgs factory and muon collider were also reported.

Fermilab is the second largest institute in CMS and the US host-lab with many responsibilities in running the experiment and with many deliverables for the HL-LHC detector upgrades. The team lost a significant number of scientific personnel since the last PAC meeting. While the PAC commended the group on its leadership role in the experiment, it expressed worries about its ability to deliver on the commitments for the HL-LHC detector upgrades, given the reduced level of scientific staff.

The Higgs Factory and Muon Collider Detector groups are strongly and visibly engaged in the US and also in international collaborations on detector R&D. The PAC was impressed by the progress achieved on multiple fronts in the development of novel technologies for future collider detectors. However, presently the progress on detector R&D is hindered by the limited availability of the test beam facility at Fermilab.

The European Strategy for Particle Physics update process is expected to yield a concrete plan for the next collider facility at CERN, which is expected to be an e+e- Higgs Factory. Fermilab possesses expertise in several areas relevant to future Higgs Factories such as superconducting RF cavities and high-field superconducting magnets. The PAC found that Fermilab's ongoing and planned accelerator R&D for the future Higgs Factory aligns closely with its accelerator expertise and that additional funding will be needed to ensure the sustainability of the R&D program.

As for the muon collider program, there is a renewed global effort with the formation of the international muon collider collaboration (IMCC) in 2021 and the 2023 P5 recommendation that the U.S. develops a collider with 10 TeV parton-parton collision energies. Two targeted panels, one focused on test facilities and one targeted to the evolution of the Fermilab accelerator complex, are expected to be established by DOE

in response to P5. Fermilab task forces identified the main challenges for the Muon Collider accelerator and detectors and outlined near term R&D priorities for the laboratory. The requirements of the muon collider are synergistic with ongoing laboratory developments in accelerator technologies.

The Fermilab microelectronics (ME) group is a great asset to the program of the lab. It has expertise in ASIC design and testing for extreme environments, with the largest ASIC design team across DOE labs. The group is currently supporting DUNE and CMS on a long term basis, but no new large projects are on the horizon. The group has identified synergies with HEP and Quantum capabilities and have current projects on developing ASICs for sensors that have application for both areas. At the same time, the group seeks to develop design competency in newer nodes and is proactive in leveraging on other projects (also interagency) in order to compensate for the lack of base funding.

All in all, the PAC was pleased to see an optimistic outlook for the laboratory in these challenging times. The PAC wishes the management a lot of success in its endeavor to mitigate the impact of the present situation and hopes that the end result will preserve the ambitious and impactful scientific program.

Status and plans for the Fermilab's accelerator complex

Charge: We ask the committee to review the status of Fermilab's accelerator complex. In particular, given the importance of delivering 120 GeV beam to NOvA, 2x2, SpinQuest and TestBeam before the Long Shutdown, as well as preparing the complex for Mu2e and later for LBNF/DUNE, we ask the committee to review the Main Injector run plan for FY26 and the associated risks.

Findings:

1) During the 2024 summer maintenance shutdown, 83% of over 650 jobs/tasks were completed.
2) Several damaging events occurred between August and September 2024, significantly impacting the infrastructure supporting accelerator operations. Notably, a fire destroyed the transformer T88.
3) Following a detailed inspection of the lab's electrical power infrastructure, five out of eight 13.8kV transformers were removed from the power grid.
4) Severe corrosion in the heat exchanger units led to the shutdown of nine out of fifteen units.
5) Main injector operations are excluded for FY25, meaning there will be no beam to NuMI and SY120.
6) Accelerator team succeeded in increasing the NuMI peak beam power by three since 2014. However, the recent decrease in reliability is concerning.

Comments:

1) The PAC commends the accelerator team for successfully completing most of the maintenance work during the summer of 2024 along with various on-going upgrade projects.
2) The suspension of main injector operations in FY25, due to several severe damaging events, is a significant concern. An accelerator reliability performance plan is urgently required.
3) The PAC supports the campaign for upgrades, modernization, and investments in spare parts for the accelerator complex.
4) The Main Injector run plan for FY26 appears reasonable; however, there is a high risk of potential delays in operations due to the recent severe damaging events and the possibility of a delay in the delivery of required repair parts. Given the impact to the DUNE 2x2 and other parts of the program, we encourage the laboratory to continue to seek ways to expedite the delivery of these parts with the aid of Fermi Forward and DOE.
5) We endorse management's initiative to re-evaluate the long-term accelerator operations plan, including the 2028 shutdown.

Recommendations:

1) Sufficient beam time must be allocated to the Test Beam Facility in the future, as its accessibility is crucial for several experiments.
2) Given the recent decline in accelerator reliability, there is an urgent need to modernize the aging systems, particularly in light of the upcoming DUNE project.

Status of the SpinQuest experiment

Charge: We ask the PAC to review the status of the SpinQuest experiment as well as the potential physics opportunities and plans for the dark sector and additional upgrades, taking into account the updated schedule for the MI beam. The committee is also asked to review the status of the recommendation made at previous reviews:

1. The PAC encourages SpinQuest to collaborate closely with the accelerator group to understand how beam delivery scenarios, together with improvements in data-taking efficiency, can allow them to accomplish physics goals

Findings:

1) SpinQuest was approved in 2018 and collected its first data last year. The collaboration is currently analyzing this commissioning data to validate the full experimental setup and optimize future runs.

2) The proposed SpinQuest upgrade for the dark sector and transversity program has received Stage 1 conditional approval from the PAC. The upgrade includes repurposing the PHENIX electromagnetic calorimeter with new readout electronics. An EMCal test module was tested at the Fermilab test beam facility last year, confirming the suitability of the EMCal and its newly developed readout electronics for the SpinQuest experiment. This was documented in a recent preprint. The whole EMCal + DAQ upgrade is supported by an NSF MRI grant.
3) SpinQuest is requesting 3*10^17 live POT from the SY120 for next-year run. The collaboration plans to prioritize the polarized proton run for best Sivers measurement of J/psi and Drell-Yan.
4) The installation of the EMCal+DAQ dark sector upgrade is tentatively scheduled to be completed by the end of the summer of 2025, to enable the upgraded experiment to collect data the whole coming year.
5) The collaboration formed a committee to review the technical aspects, resources, and risks involved with the installation of the EMCal.

Comments:

1) The dark sector upgrades yield access to a range of dark matter (DM) and dark sector searches for relatively small effort compared to other experiments, such as SHiP and FASER 2 at CERN. The physics program aligns well with P5 recommendations. Next year's run with 3*10^17 live POT would set world-leading constraints (or potentially lead to a discovery) across a range of dark sector models. These include models with a dark photon, muon-philic scalars, strongly interacting DM, inelastic DM, among others. Without the dark sector upgrade, many of these models will remain unexplored for many years to come
2) The internal upgrade review might take up to two months, which leaves very little time before the scheduled beam-time for the next step of the approval process, which is a technical and resource review organized by the office of Fermilab CRO.
3) Extending SpinQuest operations beyond the long shutdown would greatly benefit both the spin and dark sector physics programs.

Recommendations:

1) The PAC recommends continued close collaboration with the accelerator group to improve slow extraction, to tune beam uniformity for optimal data, and to establish well-defined, achievable luminosity goals for the coming year. In particular, the results of a physics program compatible with the running plans of the Main Injector should be developed.

2) The PAC encourages the collaboration to complete in a timely fashion its internal review of the EMCal+DAQ upgrade (see finding n.5) to ensure that it can be fully implemented before the start of the MI beam. If the review yields a positive outcome, the PAC endorses the plan for the EMCal + DAQ upgrade in time for the MI beam restart. Because of the tight schedule, the PAC also recommends to concurrently proceed with the final approval stage by the office of Fermilab CRO.

Report from Microelectronics

Charge: We ask the PAC to review the status of the MicroElectronics (ME) activities at the laboratory and of the recommendations made at past meetings:

1. The lab should help the ME group develop strong bids by providing adequate personnel support and resources for the needed capture team.
2. We recommend that the ME group continue to strive to develop capabilities in service of future HEP needs.

Findings:

1) The microelectronics (ME) group has expertise in ASIC design and testing for extreme environments, with the largest ASIC design team across DOE labs, comprising 24 people. This includes designers and testers, augmented by an associate program which rotates 5 PhD/Masters students per year.
2) The group seeks to develop design competency in newer nodes, chiplets / advanced packaging, and heterogeneous integration.
3) The group is currently supporting DUNE and CMS on a long term basis, but no new large projects are on the horizon.
4) The ME group has been successful in developing AI on chips, including the ECON chip for CMS.
5) The group has identified synergies with HEP and Quantum capabilities and has current projects on developing ASICs for sensors. These have applications in both HEP and Quantum areas, including SNSPD, skipper-CCD, dSiPM, and LGADs, as well as cryoelectronics for Si spin qubits, ion traps / atomic clocks.
6) The ME group is proactive in leveraging on other projects (also interagency) in order to compensate for the lack of base funding.

Comments:

1) The ME group is aware that US leadership in custom ASIC design has slipped or lapsed compared to Europe, and that cost-effective access to licenses, tools, and foundries would benefit ASIC development also beyond HEP projects.

2) The ME group has the opportunity to enhance competences in AI for HEP and HEP for AI.
3) The PAC takes note that there is no funded long-term project at the moment beyond CMS and DUNE, and that the ME group has to find a way to preserve and expand expertise, exploiting collaborations beyond HEP.
4) The ME group is successful in competing for funding beyond HEP, however this comes with some administrative hurdles.

Recommendations:

1) The lab should support the ME group in getting access to appropriate tools for ASIC development.
2) The PAC would like to see a prioritized technical portfolio inside the reduced funding scenario.

Report from the Collider Physics Division

Charge: We ask the committee to review the status of the recommendations made at previous reviews:

1. The PAC notes that the budget challenges faced by CMS are similar to those reported labwide and nationwide. Still, given the time-critical nature of the group's contributions to the upgrades, we encourage the group and the lab leadership to work together with the DOE HEP to ensure that the group has sufficient scientific resources, including postdoctoral researchers, to deliver on US commitments to the CMS upgrade, despite the challenging budget.
2. We recommend the lab continue to explore more efficient methods for the distribution of funds to university and lab partners.

Findings:

1) Fermilab is the second largest institute in CMS, with vital contributions to physics production, operation and upgrades. Scientists from Fermilab regularly hold important positions in the CMS experiment management, including two spokespersons and two deputy spokespersons in the last 9 years.
2) Fermilab is the US host-lab for CMS, with responsibilities for the Remote Operation Center, the Tier-1, and the LPC.
3) Fermilab scientists are strong leaders on CMS physics analyses, in particular in Exotica and Higgs.
4) Fermilab is the CMS institute responsible for the most deliverables for the HL-LHC detector upgrades, including HGCal cassettes, tracker modules, ETL modules, tracker mechanics, cooling plates, scintillators, etc.
5) A new procedure for distribution of funds to university partners was approved on 10/29/2024, but has not been implemented yet.

6) The Fermilab CMS group has lost a significant number of scientific personnel since the last PAC meeting.

Comments:

1) The PAC congratulates the CMS group on the successful postdoc mentoring program and the promotion of 6 RAs to faculty positions in academia and one in public service.
2) Maintaining the strength of the scientific staff is critical to allow Fermilab to deliver on its commitments for the HL-LHC detector upgrades.

Recommendations:

1) The lab should maintain the necessary level of scientific staff for a successful CMS program in the areas of HL-LHC deliverables and physics analysis.
2) The lab should expedite the implementation of the new procedure to distribute funds to the university partners.

Detector R&D for Future Colliders

Charge: We ask the PAC to comment on Fermilab's ongoing and planned detector R&D for the future Higgs Factory and Muon Collider.

Findings:

1) Fermilab collider physics division made tremendous progress on multiple fronts in the development of novel technologies for future collider detectors.
2) The Higgs Factory and Muon Collider Detector groups are strongly and visibly engaged in the US and also in international collaborations on detector R&D.
3) The limited availability of the test beam facility at Fermilab hinders the progress of the detector R&D work.

Comments:

1) A table summarizing the goals, timelines and milestones for each initiative would be helpful for the PAC to evaluate the progress and the availability of resources that might be shared among different projects.
2) More targeted funding will be needed to scale up from R&D to full prototyping.
3) The core capabilities of the Helen Edwards Engineering Research Center need to be improved with respect to detector design, construction, and electronic development.

Recommendations:

1) Sufficient beamtime at the Fermilab test beam facility should be provided by the laboratory.
2) The PAC would like to see the facilities plan for the Helen Edwards Engineering Research Center

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Higgs Factory Accelerator R&D status and plans

Charge: We ask the PAC to comment on Fermilab's ongoing and planned accelerator R&D for the future Higgs Factory.

Findings:

1) A US Higgs Factory Consortium Committee (HFCC) has been established by the DOE and NSF to provide strategic direction and leadership for the U.S. community.
2) The primary goal of the HFCC is to identify key R&D topics that will contribute to Higgs Factory designs, enhance core capabilities in the U.S., and ideally position the U.S. for a significant role in a future construction project.
3) Fermilab possesses expertise in several areas relevant to e+e- Higgs Factories, such as superconducting RF cavities and high-field superconducting magnets.
4) Very little funding is expected to be available in FY25 for Higgs Factory Accelerator R&D work.

Comments:

1) Fermilab's ongoing and planned accelerator R&D for the future Higgs Factory aligns closely with its accelerator expertise.
2) The European Strategy for Particle Physics update process is expected to yield a concrete plan for the next collider facility at CERN.
3) Additional funding will be needed to ensure the sustainability of R&D work at Fermilab in support of a future Higgs factory.

Recommendations:

None

Muon Collider Accelerator R&D status and plans

Charge: We ask the PAC to comment on Fermilab's ongoing and planned accelerator R&D for the future high energy Muon Collider.

Findings:

1) There is a renewed global effort on a Muon collider program with the formation of the international muon collider collaboration (IMCC) in 2021 and the 2023 P5 recommendation that the U.S. develops a collider with 10 TeV parton collision energies. Small footprint of the Muon Collider and its luminosity over power scaling with energy make it a highly attractive possibility.
2) Two targeted panels, one focused on test facilities and one targeted to the evolution of the Fermilab accelerator complex, are expected to be established by DOE in response to P5.
3) Fermilab task forces identified main challenges for the Muon Collider accelerator and detectors, and outlined near term R&D priorities for the laboratory.
4) Ongoing Fermilab efforts, such as IOTA, provide good synergies with the requirements of the Muon Collider. Other examples are the development of targetry, high-field magnets, and the development of RF cavities of the type also needed for a future Higgs Factory.
5) Many activities have been carried out with short-term targeted funds and contributions from university collaborators.

Comments:

1) The Muon Collider group has identified key areas of needed R&D and the areas where Fermilab could make major contributions. Substantial engineering challenges exist that can only be addressed with dedicated R&D.
2) The Fermilab's ACE program could become the platform for developing a proton driver and targetry for a muon collider.
3) R&D investment is required to plan for a Booster replacement compatible with the Muon Collider program.
4) Many of the muon collider R&D activities are synergistic with activities related to HL-LHC and other future colliders.
5) The significant ramp up in scientific accelerator labo that will be necessary to develop proposals for the Muon Collider and its needed test facilities cannot be replaced by particle physicists' short term contributions and needs to be addressed at the global level.
6) The PAC commends Fermilab for awarding an LDRD to evaluate the possibility of hosting an ionization cooling demonstrator.
7) R&D funding at an appropriate level is necessary to deliver a proposal for a muon collider demonstrator program in time for the intermediate panels recommended by P5 and planned by the DOE.

Recommendations:

None