Fermilab Accelerator Advisory Committee Meeting
October 14-16, 2014

Final Report

AAC Committee:

Members present: Frederick Bordry (CERN), Wolfram Fischer (BNL), John Galambos (ORNL), Mark Hogan (SLAC), Jens Knobloch (HZB), Lia Merminga (TRIUMF) (chair), Peter Ostroumov (ANL), Yoshishige Yamazaki (MSU)
Excused: Roland Garoby (ESS), Wim Leemans (LBNL)

Tasks/Assignments:

PIP & 700kW plans**:** W. Fischer (lead), J. Galambos
LCLS-II: J. Knobloch (lead), M. Hogan
PIP-II**:** P. Ostroumov (lead), F. Bordry, Y. Yamazaki, L. Merminga
PIP-III: J. Galambos (lead), P. Ostroumov, L. Merminga

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Executive Summary

The AAC was convened from October 14-16, 2014 to assess and provide advice on the plans for PIP, PIP-II, LCLS-II deliverables and possible interferences, and PIP-III R&D.

The AAC commends the FNAL Accelerator and Technical Divisions for excellent progress on multiple fronts in the past year, and their many accomplishments, despite multiple changes and challenges. Most notable accomplishments include the high Q breakthrough, PXIE initial commissioning, ILC CM-2 completion and high performance, and LCLS-II project fast formation and excellent execution. FNAL is playing a critical role in enabling LCLS-II, a high priority project of the DOE Office of Science. AAC notes the rapid and complete alignment of both divisions with the laboratory's scientific priorities, and with the P5 plan, and commends the leadership of both divisions.

The Main Injector (MI) beam power goal of 460 kW in 2015 is achievable, however, 700 kW may require the understanding and cure of beam instabilities and losses in the Recycler Ring (RR). We strongly encourage the Accelerator Division (AD) to pursue a campaign of simulations and theoretical and experimental studies and solicit help from experts inside and outside Fermilab to understand and mitigate the instabilities in a timely manner.

The AAC finds the goals, deliverables and plans for PIP to be well understood and achievable, and endorses the plans to address the Linac and Booster vulnerabilities. The Booster cavities refurbishing plan proceeds well, and is likely on track for July 2015 15 Hz Booster operation with all refurbished cavities (before long shutdown). Booster losses need to be understood in order to support operation at high beam power levels.

In the last decade, FNAL has set up an impressive amount of SRF infrastructure that will benefit both the LCLS-II and PIP-II projects and will enable a flexible SRF program in general. The AAC is highly impressed with the results from the high-Q research. These high-Q activities are highly relevant to LCLS-II, but also will have a major impact on the accelerator community in general.

While the PIP-II R&D goals for the superconducting (SC) linac are well defined, R&D related to modifications of Booster, Recycler Ring and Main Injector are in a conceptual stage. A global WBS of the PIP-II project should be developed to define the entire scope, budget, schedule and resources required for the new construction and upgrades of existing accelerators (Booster, RR and MI). PXIE (PIP-II injector experiment) has made substantial progress since the last AAC Review in February 2013. Beamline and target improvements for transport and utilization of 1.2 MW beam are well understood.

The large scale involvement of FNAL in the LCLS-II project brings a series of benefits for PIP-II, including experience in all stages of design and production of cryomodules, as well as upgrades of the FNAL SRF infrastructure. Potential interferences in realizing the goals of LCLS-II and PIP-II are understood, and plans exist to address them.

Preliminary concepts towards multi-MW beams (>1.2 MW) require R&D to either reduce the cost of SRF or significantly increase the performance of the synchrotrons, and in any scenario to develop high-power targets.

The integrable optics ring approach (IOTA) is an intriguing and novel idea with prospects for a wide range of high intensity rings applications. This approach may lead to a path forward for a PIP-III Rapid Cycling Synchrotron (RCS) option. The AAC strongly endorses pursuing the IOTA development.

More generally, the AAC endorses implementing ASTA as an accelerator test facility with protons and electrons, in support of PIP-III R&D and in support of general accelerator science research and education.

The AAC also endorses the pursuit of SRF performance improvements and cost reduction, and encourages the FNAL team to consider a broader approach towards reducing the overall cryomodule capital and operation costs.

Targetry is a critical development area with impact on the overall neutrino delivery efficiency. The AAC strongly encourages additional support in this area, and the pursuit of overall “target system” optimization, rather than understanding material lifetime limits only. The personnel working on targetry are presently not centralized. Consider consolidating the various target system activities into a common organization within the Accelerator Division.

The FNAL R&D strategy is well aligned with the P5 plan, and the research required for multi-MW beams (PIP-III) overlaps with 4 of the 6 FNAL- recommended GARD thrust areas.

In future meetings, AAC requests the scheduling of a dedicated session to review the responses of the previous review’s recommendations. In addition, explicit linkage between charge questions and the presentations would be helpful.

The committee expresses sincere appreciation to the FNAL directorate for its hospitality during this review.

1. Near-Term Plans for 700 kW

1.1 Main Injector

1. *Is the goal of achieving 460 kW (without the slow-extraction program) in 2015 and 700 kW by mid-2016 technically achievable?*

   460 kW in 2015 is achievable, 700 kW is achievable provided beam physics issues in RR (instabilities and losses) are resolved.

Observations

- 320 kW of beam power were delivered to NuMI target without slip stacking (i.e. 6 Booster batches) and a 1.67 s ramp
- 401 kW beam power were demonstrated for about 1 hour in 2011 with multi-batch slip stacking in the MI.
- The RR is operational in a mode without slip stacking (a significant increase in intensity compared to the pbar operation in the past).

Comments

- The goal of 460 kW beam power without the slow-extraction program is within reach, and can be achieved with slip stacking in the RR (6+2 batches) possibly with reduced batch intensity.
- Since the instability in the RR is presently not well understood, it is difficult to assess if the RR can deliver the needed intensity to the MI for 700 kW operation by mid-2016.

1.2 Recycler Ring

2. *Are the plans in place to overcome beam instabilities and losses during slip-stacking adequate?*

   No. An instability in the recycler has been observed, but a systematic campaign to better understand its cause has not been undertaken yet.

3. *Are beam losses understood sufficiently to minimize machine and tunnel activation?*

   Not entirely. An active campaign must be maintained to understand and mitigate the losses in the RR, including quantitative estimates for the various mitigation measures.

Observations

- A fast (10 turns rise time) horizontal coupled bunch instability has been observed at batch intensities close to those needed for 700 kW MI operation, without slip stacking.

- The vacuum system of the RR will be upgraded and the titanium sublimation pumps (TSPs) will be replaced by ion pumps. The ion pumps do not require that the RR is baked out as is the case for the TSPs.
- RR losses are predominantly in the injection, abort and 303 regions.
- Aperture scans were made in the RR, and some alignment errors corrected.

Comments

- An unexpected fast beam instability has been observed in the Recycler, and is presently the dominant uncertainty in achieving the 700 kW beam power goal in the MI.
- A number of observations are not understood, e.g. the first batch appears to be more vulnerable than the following batches, overlapping bunches with slip stacking do not appear to cause a problem so far.
- The instability threshold increased after pump firing, i.e. improvements in the vacuum. This and other observations indicate that electron clouds play a role in the instability.
- With the replacement of the TSP by ion pumps, baking of the RR is not necessary anymore. However an unbaked system is likely to have denser electron clouds for the same beam parameters, and may need longer to condition.
- Recycler losses/proton are ~ 5 times higher than losses for the equivalent injection period in the Main Injector. Some Recycler equipment improvements (alignment, magnet shim) have been done, but these may not provide all the desired loss reduction.

Recommendations

1. AAC repeats the past recommendation to simulate the electron cloud formation in the RR, and determine the SEY for electron cloud formation with the RR chamber geometry and a range of beam parameters. Compare the results with simulations of the MI.
2. Perform beam studies to clarify the parametric dependence of the instability (e.g. intensity, vacuum pressure, RF parameters).
3. Simulate instability thresholds for a range of relevant beam parameters, range of electron cloud densities and range of possible machine impedances. Designate a team to develop an instability model that is consistent with the observations.
4. Solicit input from experts available at FNAL and the outside community (e.g. CERN, BNL) on possible causes of the instability and mitigation techniques.
5. Maintain the bake-out capability in the RR until the instability is understood and resolved.
6. Estimate the cost and schedule for a transverse damper that can counteract the observed instability in the RR, in case a damper is needed.
7. Maintain an active campaign to understand the origins of loss in the recycler and mitigate them.
8. As soon as possible begin slip stacking in the Recycler, and transfer to the Main Injector to see if any unforeseen losses occur as a result of this process.

1.3 PIP

4. *Are the goals, deliverables, budget and schedule of the PIP project properly defined, well understood, achievable and self-consistent?*
   Yes.

5. *Are the plans to address the Linac vulnerabilities and reliability adequate?*
   Yes.

6. *Are the plans for the Booster RF cavities sufficient to extend their life at least until 2030?*
   Yes, provided an inventory of 22 cavities is actively maintained.

7. *Are the plans to minimize Booster losses adequate and sufficiently understood to allow for the planned higher beam power levels?*
   The plans are adequate, and we encourage their timely implementation.

Observations

- The PIP goals are (i) delivery of 2×10^{17} protons/hour (at 15 Hz) in 2016 while (ii) maintaining the Linac/Booster availability at >85%, and (iii) maintain the residual activation at acceptable levels
- PIP is organized as a project, has a resource loaded schedule, a defined organization, as well as document and resource controls.
- The 201 MHz RF source and modulator power supplies have properly been identified as critical vulnerabilities, and reasonable response plans are in place for addressing them.
- The modulator contribution to the Linac downtime is 57%, with a MBTF of about 10h.
- A laser notch is under construction for the Linac to reduce the beam losses and associated activation in the Booster. The laser notch is planned to be installed in 2015.
- Reliable 15 Hz Booster operation requires 17 refurbished cavities, and a total of 22 cavities will be refurbished.
- Installed cavities are operated with 15 Hz (without beam in every other cycle).
- The early refurbished cavities showed some weaknesses in the tests and required rework.
- A 15 Hz test of the entire system may be possible as early as 2015.
- The beam losses in the Booster need to be reduced by a factor of two to maintain the present activation level with the doubled repetition rate.

Comments

- System reliability was not presented in detail, making it difficult to assess all subsystems.
- The 200 MHz modulator is the most vulnerable system, with hardware that was discontinued over 10 years ago.
- The strategy for the 200 MHz Final Power Amplifiers (7835 tubes) is to (i) maintain a 4-year inventory, and (ii) test a replacement klystron under order from CPI. The 4-year inventory provides enough buffer time to transition to the klystron technology should the 7835 tube manufacturer stop providing tubes.

- PIP is close to the midpoint in the project, following closely the project schedule of 2012 with some adjustments to labor and funding modifications.
- Experience to date is good guidance for the remaining work, in particular for the Booster RF refurbishment program.
- Management has allocated personnel aligned with the plan, making up for a shortfall early in the project.
- A total of 3 spare cavities, and the ability to repair cavities in the future should be sufficient to provide reliable RF operation until 2030.
- For some components (e.g. tuners) a larger spare inventory is created.
- The campaign to reduce beam loss in the Booster over the past several years has produced significant reductions in beam loss. The creation of a clean "extraction gap" with upstream laser stripping is quite a promising approach to reducing the "notch formation" induced loss presently created at 400-700 MeV. However it is not clear that local losses will be low enough everywhere, even with this implementation.
- A quantitative estimate of all loss reduction measures was not presented, and therefore it was not possible to assess if all measures will lead to the needed reduction by a factor of 2. It was stated that the successful implementation of the laser notch should be close to providing the needed factor of 2.

Recommendations

9. Proceed with the plan to replace the obsolete modulator hardware in the Linac.
10. Develop a plan that itemizes beam loss reduction steps to maintain present levels of beam losses as the intensity doubles. Keep a focus on the laser notching program to demonstrate the feasibility of the system and its reliable operation.

1.4 PIP – PIP-II

8. *In view of PIP-II plans, is the current PIP scope appropriate and well understood?*

   Yes. The PIP scope has been revised as PIP-II plans came along. Particularly, no significant investments will take place to increase the lifetime of the current DTL beyond 2023. Additional comments are included in the *PIP-II and LBNF* section.

1.5 LCLS-II

9. *Is the Fermilab effort on producing the LCLS-II deliverables adequately organized and staffed?*
12. *Are potential interferences in realizing the goals LCLS-II and PIP-II well understood? Are the plans to address these interferences adequate?*

   Qualified yes.

   Staffing: A project organization and a resource loaded schedule for LCLS-II exist and appear to cover relevant aspects for production. The staffing appears reasonable but AAC is unable to evaluate whether the staffing skill set is truly sufficient. In light of planned PIP-II activities, staffing may be tight if PIP-II prototype development is to continue at the planned pace. LCLS-II has been designated to have the highest priority.

LCLS-II Schedule: The presented schedule is ambitious requiring careful and focused management. A prolonged prototyping phase may be useful to retire several risks prior to the production phase.

Infrastructure: FNAL appears to have the necessary type of infrastructure in place or under construction for LCLS-II deliverables. The presented details were insufficient to evaluate whether additional redundancy of some of the infrastructure is needed to meet the production schedule.

Fermilab is aware of potential interferences in realizing the goals of LCLS-II and PIP-II but a PIP-II resource loaded schedule must still be developed.

Observations

In the last decade, FNAL has set up an impressive amount of SRF infrastructure that will benefit LCLS-II production and that of PIP-II in particular and a flexible SRF program in general. The infrastructure includes all equipment necessary for module production, including chemistry, HPR, tuning, vertical and horizontal testing as well as a cleanroom for string assembly. A module test stand is under construction and will be available by end of CY2015. Some infrastructure also exists for basic R&D (thermometry, cavity dissection).

The main activities at present comprise assembly of ILC modules, gearing up for LCLS-II production and basic R&D (nitrogen doping and high Q research) to support cost reduction of LCLS-II. Additionally, design and prototyping work is ongoing for PIP-II.

Presently FNAL has assembled two 1.3 GHz ILC style cryomodules and one 3.9 GHz cryomodule (in operation at FLASH), both for pulsed operation. The last 1.3 GHz module (CM-2) achieved an impressive 31.5 MV/m average gradient with all cavities powered. A 9-mA beam test is not currently planned due to budget and priority shifts.

LCLS-II (current status CD1) is the Fermilab's top priority followed by PIP-II (pre-CD 0).

FNAL main responsibilities for LCLS-II are the design and production of 17 1.3-GHz cryomoules, two 3.9-GHz modules and the cryogenic distribution. The RF coupler production is SLAC's responsibility. Jefferson Lab is responsible for producing the remaining 18 cryomodules and the cryogenic plant.

The presented schedule for LCLS-II and module production is as follows:

- CD1: 8/22/14
- Advance procurement of Nb: Q1FY2015
- Cryoplant procurement: 05/2015
- Prototype string assembly begins: June 2015
- CD2 & 3: Q3FY2015
- Prototype module test: late 2015/early 2016

- Procurement module production components begins: June 2015
- Module production: March 2016 – Q4 2018 at a rate of one module every 45 days.
- Production of 3.9 GHz module to begin at the tail end of 1.3 GHz module production.
- Project completion: 09/2021 (early complete Q4FY2019).

Only half of the production modules are slated for tests at FNAL's module test facility. Discussions are underway with SLAC to test all the Cryomodules. Following LCLS-II production, PIP-II production is currently slated to begin in 2019.

The current PIP-II schedule is:

- CD0: FY2015
- Prototyping phase: FY2015-FY2018
- CD3: Q4FY2018
- Production phase: FY2019+

FNAL's Technical Division (TD) currently has 56.4 FTE's assigned to LCLS-II and PIP-II/PXIE activities. In addition, the Accelerator Division currently has 7 FTE's assigned to LCLS-II. It is planned that ten additional positions will be filled (five new hires, five reassigns). Estimates of personnel requirements for 2015 for both LCLS-II and PIP-II activities total to 70 FTE assuming a PIP-II funding profile commensurate with CD3 in Q1FY19 (due to funding limits PIP-II was reduced to 25, for a total of 61, which reduces the number of new hires and reassignments in FY15 to 5).

An LCLS-II resource loaded scheduling has been worked out. Through 2018, the project requires from the Technical Division on average about 40 FTEs with a peak around 2017 of 58 FTEs during the phase of peak module production. With LCLS-II in production mode the peak will be addressed by contract hires. A detailed analysis of the PIP-II staffing requirements from Technical Division is still required. FTE estimates commensurate with CD3 in Q4FY2018 are listed in the following table. Typical total numbers for LCLS-II and PIP-II are about 70 FTE with a peak in FY17 of 104. Staff appears fairly heavily matrixed.

Technical Division Staffing	FY15	FY16	FY17	FY18
LCLS-II	36	27	58	35
PIP-II	34 (25)	40	46	35
Total	**70 (61)**	**67**	**104**	**70**
TD Available	56.4+10 (56.4+5)	66.4	66.4	66.4
Difference	-3.6 (+0.4)	-0.6	-37.6	-3.6

Assumptions: FY15 staffing from TD continues at same level in following years. LCLS-II non-TD staffing (7 in FY15) remains unchanged in following years. PIP-II staffing as originally requested to meet CD3 by Q1FY2019. For FY15 the PIP-II request was reduced (number in parentheses) for budgetary reasons.

During LCLS-II production three modules will be "in the system" simultaneously. A preliminary analysis of the individual steps has taken place. A single module requires 45 days for production involving 26 persons at several stations. Not all work stations are staffed simultaneously. A schedule for the flow of the modules (and the staging), as well as the rework of a reasonable estimate of rejected cavities, was not presented.

Following module production, FNAL will assist SLAC in installing and commissioning the modules (presumably 2018/19).

Very impressive results were presented from high-Q research that has direct bearing for LCLS-II. Nitrogen doping appears to reduce the surface resistance (BCS) significantly, while residual losses can be influenced by the cooldown procedure. A reproducible recipe has been developed to benefit from these effects, but a full understanding of the involved mechanisms does not yet exist.

Comments

- The demonstrated RF performance of CM-2 is impressive. AAC suggests FNAL management to consider performing a beam test of CM-2 at ASTA.
- Careful management of the interfaces between systems (couplers, cryoplant, cryo-distribution, module) that are being designed/procured by different labs is required. Interface managers should be designated
- While the (modified TTF-III) coupler is not FNAL's responsibility its long-term CW operation bears some risk that should be retired in the prototyping phase.
- LCLS-II Prototype module testing will certainly not occur prior to the start of production module procurement, and may even occur after scheduled production start. This represents a risk and limits the usefulness of the test. Consider allocating additional resources to expedite the test or delay the start of module production to permit feedback.
- While significant problems are not foreseen, CW operation of the 3.9 GHz modules may bear new surprises. Even the pulsed 3.9 GHz unit produced by FNAL for FLASH encountered many hurdles and production took much longer than expected.
- The cryomodule test stand will be an important facility for PIP-II module development. Careful consideration should be given to the infrastructure requirements at this point to avoid costly/time consuming retrofits later on, once PIP-II modules require testing.
- The current TD staff allocation appears commensurate with the LCLS-II and modified PIP-II communicated project requirements, provided five additional staff members can be hired (primarily engineering disciplines) and five can be reassigned from other departments. An important exception is FY17 when the peak leads to a shortfall of over 35 FTE, which management should address soon if SRF skilled labor is needed. AAC notes, that PIP-II has a significant work load (5 different cavities, 3 types) that must be completed by FY18, incl. oversight of collaboration partners in India.
- At present, the total resource requirements are still fairly poorly defined. While PIP-II has not yet passed CD0, given its high priority for the lab (and within the P5 recommendations) and the long lead times required to find qualified SRF staff one should evaluate soundly the staffing requirements now rather than later.

- To minimize FNAL's time investment for module commissioning at SLAC, consider transferring SLAC personnel to FNAL during some part of the production/testing phase for training and assistance. This may alleviate some of the personnel conflicts with PIP-II.
- The activities for LCLS-II are well aligned with the mid-term strategy of FNAL for PIP-II. FNAL will benefit from augmented infrastructure (module test stand), production experience and proven technology for CW SRF operation. LCLS-II production will ensure that the personnel and management skill set on board will be ideally suited to go into PIP-II production.
- The high-Q activities are highly relevant to LCLS-II, but also will have a major impact on the accelerator community in general. AAC is highly impressed by the accomplishments.
- The interval between discovery of very-high-Q operation (N-doping, cooldown procedure) and its implementation in a production module is very short and bears some risk of unforeseen problems. (Examples in the past include the development of high-purity niobium cavities for quench protection that, once installed in the accelerator, exhibited the unforeseen Q-disease.) In particular, the cryoplant for LCLS-II must be specified in May 2015, which relies on the reproducibility of the high-Q mode in a production cryomodule. AAC believes the high-Q activities should receive high priority in 2015.
- AAC is concerned about excessive matrixing of personnel, SRF in particular. More SRF hires already underway will help to relieve this situation.
- LCLS-II cryomodules are mostly using well established technology except for the innovative nitrogen doping, enhancing Q values. Since long-term Q degradation has been observed in many places, the possibility of Q degradation is properly registered as one of the risks. In order to retire this risk, long-term single cavity powering tests are ongoing. However, in some cases, the degradation is associated with beam, poor vacuum of the neighboring accelerating components and other reasons, rather than isolated cavity case. Thus, long term beam tests shall be planned for this risk mitigation. These tests can be more useful in order to develop remedies (possibly in situ) in case of degradation. AAC encourages FNAL to communicate to LCLS-II project management the danger of possible long term Q degradation.

Recommendations

11. To maximize the feedback of the LCLS-II CW module prototype test, consider allocating additional resources to the prototype test or delay the start of module production.

12. Given the large overhead in shipping modules to SLAC and difficulties in testing individual modules in the SLAC tunnel, AAC urges that plans should accommodate testing of <u>all</u> modules (RF only, no beam) at FNAL prior to installation.

13. AAC encourages an early start of 3.9 GHz CM development to provide ample safety margin in the schedule.

14. AAC urges the FNAL LCLS-II management to work out a flow schedule for the module production that includes a reasonable number of reworks following cavity acceptance

tests and module acceptance tests. A comparison with the XFEL module production should prove useful. This schedule should also help to identify pinch points and necessary redundancy in the production/testing facilities.

15. Develop a PIP-II resource loaded schedule as soon as possible that includes facility availability in combination with LCLS-II to evaluate staffing requirements for 2015+ within TD, assuming PIP-II production begins in 2019. Start planning for the expected peak in personnel in FY17.
16. Assign high priority to the high-Q research in the next six months to feedback results into cryoplant specification and prototype module operation.

2. Longer Term Plans

2.1 PIP-II and LBNF

10. *Please comment on the present progress and plans for PIP-II: Are the R&D goals, deliverables, budget and schedule for PIP-II properly defined, achievable and self-consistent?*

    Yes. R&D goals, deliverables, budget and schedule for the new SC linac are well defined. However, this statement is not valid for the Booster, RR and MI. See comments below.

11. *What accelerator (MI, RR, Booster), beam line and target improvements are likely to be needed to achieve 1.2 MW beam power for LBNF? Are they well understood?*

    Beamline and target improvements for transport and utilization of 1.2 MW beam are well understood. Modifications of the existing accelerators (MI, RR, Booster) required to achieve 1.2 MW beam are known only conceptually. R&D is required to define the scope and cost of all modifications.

13. *Please comment on the upgradability of PIP-II from pulsed to CW.*

    If the design and implementation of the cryomodules, cryogenics distribution system and RF system incorporate the possibility to operate in CW mode, the transition from pulsed to CW would be straightforward.

Observations

The main purpose of PIP-II is to provide 1.2 MW beam power to LBNF by 2023. To achieve this goal, a new higher energy pulsed linac is required to increase the available beam intensity from the booster. A new 800-MeV SC linac has been proposed to replace the aging 400-MeV linac and provide higher beam intensity. In addition, the linac will be built to be compatible for possible future upgrades to CW mode to enable high power experiments at FNAL. There are strong activities at FNAL towards PIP-II:

- A white paper was released;
- Detailed list of R&D work has been created for the linac development. A prototype front end of the linac, PXIE, is being constructed;
- Design work and project preparations are being pursued;
- Activities toward CD0 are under way: Reference Design Report is being prepared; preliminary cost estimate exists and is being continuously updated; the DOE Review of PIP-II is tentatively planned in the spring of 2015;
- International collaboration with India has been established with potential for in-kind contributions of $160M.

PXIE (PIP-II injector experiment) has made substantial progress since the last AAC Review in February 2013. Full commissioning of PXIE is expected in FY18. The ion source and LEBT are operational since 2013 and beam commissioning of the RFQ will start next year. Unfortunately, the brazing of the first RFQ segment revealed vacuum leaks, the repair work can delay the RFQ commissioning with beam. Infrastructure development for PXIE including cryogenic distribution system is aligned to the needs of step-by-step commissioning schedule. There was not clear explanation of required safety procedures to start RFQ beam commissioning.

Significant part of the PIP-II linac R&D is related to SRF technology. The pulsed operation of the 800-MeV SC linac saves ~$80M in cryoplant as compared to CW mode. Due to negligible dynamic load in the cryomodules with HWR and SSR1, they will operate in CW mode. The development of effective, reliable, long lifetime fast tuners is required to manage LFD in the remaining three types of cavities (SSR2, LB650, HB650). Currently there is a research team working on the development of piezoelectric tuners for this purpose.

The cost estimate includes detailed list of R&D related to the SC linac and project preparation. The developments related to upgrades of the booster, recycler and MI for PIP-II are in conceptual stage only.

Large scale involvement of FNAL in LCLS-II project brings a series of benefits for PIP-II. The FNAL team has an opportunity to gain experience in all stages of design and construction of SC cryomodules. In addition, FNAL will obtain additional upgrades of SRF infrastructure.

The decision to proceed with PIP-II impacts the scope of current PIP, specifically the linac and booster. For example, as a consequence of PIP-II plans, the production of 200 MHz klystrons will not be pursued. Booster modifications within the scope of PIP are relevant and necessary investment for PIP-II project. Booster machine should continue to run up to 2028-2030 (PIP-III plan to replace the booster would not come before). Booster must operate at 15 Hz to reach 700 kW; transition to 20 Hz operation for PIP-II may require additional booster upgrades within the scope of PIP-II. Systems and parameters required to reach 20 Hz operation are being developed. A list of required studies will then be used to create a schedule for hardware and operational tests that need to be done. Any results will be used to guide implementation and resource requirements.

Resources for LCLS-II and PIP-II are similar in scale. Resource loaded schedules for both LCLS-II and PIP-II are being developed.

Comments

- The scope of PIP-II is primarily associated with the new SC linac, however the rings appeared somewhat detached. A global WBS of the PIP-II project that will define the scope, budget, schedule and resources for the new construction and upgrades of existing accelerators (Booster, RR and MI) should be developed.
- While R&D tasks for the PIP-II linac are well identified, R&D related to modifications of Booster, Recycler and MI are in conceptual stage only. R&D is required to define all necessary hardware upgrades for 1.2 MW operations and define the cost of these upgrades with better accuracy. Therefore, the current budget allocation of $30M for upgrades of these machines seems unreliable. Estimates for most of the known Booster hardware changes/additions have been obtained. However, final numbers will depend upon the chosen hardware design. The present estimate for Booster, not including RF, is approximately 8 to 9 million dollars.
- The PIP-II SC linac will be built for CW operation. Therefore it is essential to establish R&D work towards high performance of all three types of cavities (SSR2, LB650 and HB650) to minimize dynamic cryogenics load.
- Existing high power linacs had issues with the performance of the RFQ after prolonged operation. Therefore, long term operation of the RFQ and PXIE is desirable to reveal possible performance degradation.
- The brazing of the copper RFQ segment for PXIE was not successful and revealed vacuum leaks. There is a plan to repair these leaks by repeating the high temperature brazing. This is a high risk procedure and can introduce delay in the schedule of the RFQ assembly and testing which is currently planned to start in April 2015.
- At the present time, safety procedures and approval for the commissioning of the PXIE RFQ are not fully clear.
- Expedite the development of resource loaded schedule for PIP-II to identify conflicts with LCLS-II and resolve them in advance.
- Horn and production target are very challenging objects but their design improvements are well defined for LBNF at 1.2 MW. Similarly, the design of the beamline to the target is well developed.
- PXIE should be fully utilized in order to validate the design of PIP-II. The committee heard that PXIE LEBT has been operated a few thousand hours. This effort should be continued with the remaining PXIE components such as RFQ and cryomodules.

Recommendations

17. Develop global WBS of the PIP-II project to define scope, budget, schedule and resources for new construction and upgrades of existing accelerators (booster, RR and MI).
18. Identify a list of R&D tasks and funding sources related to the modifications of the booster, recycler and main injector required for 1.2 MW upgrade for PIP-II.

19. Develop a risk registry for all the chain of accelerators required for PIP-II.
20. Vigorously pursue activities for formal approval of CD0 for PIP-II in FY15.
21. Start safety approval process for the beam commissioning of the PXIE RFQ.
22. Develop a global resource-loaded planning for both LCLS-II and PIP-II projects to see the interferences between the projects. Make sure that the key competences are provided for both projects, especially during the peak periods (2017-2019).
23. Plan for long term operation of PXIE to address possible performance degradation issues of accelerator components, particularly, RFQ and SC resonators. The PXIE should be operated beyond a few thousand hours in order to test the reliability of all the accelerator components.
24. Launch more detailed beam simulation, incorporating mechanical detailing of the Booster, RR and MI in support of PIP-II. In particular, the injection to the Booster is a critical system due to highly congested area.

2.2 PIP-III

14. Please comment on presented goals and options for PIP-III (beyond 1.2 MW), including high-power targets and other affected beamline components.
15. Does the proposed R&D program address the most critical technical issues?
16. Please advise Fermilab on an R&D path towards achieving the PIP-III goals.

Specific proposals to reach proton beam power greater than 1.2 MW (beyond PIP-II) were not presented. The following comments are on the general directions being pursued which impact long-term operation at beam power > ~ 2 MW.

Observations

The 1.2 MW power level delivered by PIP-II is believed to be the upper limit possible using the present Booster. Higher power levels will require either increasing the linac energy to ~ 8 GeV, or providing a new RCS to boost the power beyond PIP-II levels.

Either of these options need cost reductions to fit into presently envisioned cost constraints.

Two general development paths were discussed, towards possible lower cost options beyond PIP-II for > 1.2 MW beam. One path is to reduce the superconducting RF cost, and the other is to develop a “super” RCS option.

Target system developments will be needed for a multi-MW application, and include targets, collection optics, remote handling etc.

Understanding material radiation damage effects is important, but expensive to do in prototypical conditions. Alternative approaches are being examined, and a collaborative effort (RADIATE) to understand radiation damage effects has been formed.

The FNAL R&D strategy is defined in alignment with the P5 plan, and the PIP-III required research overlaps with 4 of the 6 GARD thrust areas recommended by FNAL.

Comments

- The recent N-doping shows exciting improvements in the fundamental SRF properties, and new cool-down recipes result in more efficient flux expulsion. Both of these developments are exciting, and already offer cost reductions.

- It is important to maintain good communication between LBNF and PIP-II for strategic planning beyond 1.2 MW operations.

Recommendations

25. Pursue the IOTA development, as an intriguing and novel idea with prospects for providing a new path for a wide range of high intensity rings. This approach may lead to a path forward for a PIP-III RCS option.
26. Pursue SRF performance improvements, with emphasis on cost reduction. Consider a broader approach to reducing the overall cryomodule cost, in addition to concentrating on the cavity material and cavity fabrication.
27. Target development is a critical area that requires additional support. In addition to helping understand material lifetime limits of existing and near-term target components, this area of development has promise to impact the overall neutrino delivery efficiency. Pursuing overall "target system" optimization is encouraged.
28. Personnel working on targetry are not centralized. Consider consolidating the various target system activities into a common organization within the Accelerator Division.

Charge

Fermilab Accelerator Advisory Committee Meeting

October 14-16, 2014

Fermilab's goal is to deliver the highest power neutrino beams in the world. To this end, the number of protons delivered for the production of our neutrino beams must be increased to the NOvA experiment in the near term and to LBNF in the longer term. The goal of the Proton Improvement Plan (PIP) is to enable proton beams of up to 700 kW to the NOvA target. The goal of PIP-II is to deliver proton beams of 1.2 MW to the LBNF target. PIP-II will replace the existing Linac and must interface with the Booster after the PIP upgrades are completed. Additional upgrades to the Booster and Main Injector may be required to realize the 1.2 MW goal. Fermilab has also agreed to collaborate in the production of Superconducting RF (SRF) accelerating modules and the cryogenic distribution system for LCLS-II. This task relies on the Fermilab expertise and experience in SRF and cryogenics and may present a production challenge for PIP-II modules.

Finally, the delivery of multi-MW beams for the future program will require additional upgrades beyond PIP-II such as the replacement of the Booster, and R&D, for example, in high power targets. These preliminary ideas may be described as PIP-III.

The Fermilab Accelerator Advisory Committee is asked to assess and provide advice on the following topics with a concentration on the accelerator physics and engineering:

Near-Term Plans for 700 kW:

Main Injector:

1. Is the goal of achieving 460 kW (without the slow-extraction program) in 2015 and 700 kW by mid-2016 technically achievable?

Recycler:

2. Are the plans in place to overcome beam instabilities and losses during slip-stacking adequate?
3. Are beam losses understood sufficiently to minimize machine and tunnel activation?

PIP:

4. Are the goals, deliverables, budget and schedule of the PIP project properly defined, well understood, achievable and self-consistent?

5. Are the plans to address the Linac vulnerabilities and reliability adequate?

6. Are the plans for the Booster RF cavities sufficient to extend their life at least until 2030?

7. Are the plans to minimize Booster losses adequate and sufficiently understood to allow for the planned higher beam power levels?

PIP – PIP-II:

8. In view of PIP-II plans, is the current PIP scope appropriate and well understood?

LCLS-II:

9. Is the Fermilab effort on producing the LCLS-II deliverables adequately organized and staffed?

Longer Term Plans:

PIP-II and LBNF:

10. Please comment on the present progress and plans for PIP-II: Are the R&D goals, deliverables, budget and schedule for PIP-II properly defined, achievable and self-consistent?

11. What accelerator (MI, RR, Booster), beam line and target improvements are likely to be needed to achieve 1.2 MW beam power for LBNF? Are they well understood?

12. Are potential interferences in realizing the goals LCLS-II and PIP-II well understood? Are the plans to address these interferences adequate?

13. Please comment on the upgradability of PIP-II from pulsed to CW.

PIP-III

14. Please comment on presented goals and options for PIP-III (beyond 1.2 MW), including high-power targets and other affected beamline components.

15. Does the proposed R&D program address the most critical technical issues?

16. Please advise Fermilab on an R&D path towards achieving the PIP-III goals.

The Director would welcome any other comments the AAC has on any of the topics presented, or on other issues beyond the topics presented.

Agenda

Tuesday, October 14, 2014

08:00 - 08:30 Continental Breakfast

08:30 - 08:40 Welcome from Nigel Lockyer *10'*

08:40 - 09:00 Executive Session 20’

09:00 - 12:00 Proton Improvement Plan

- 09:00 **PIP Overview** *30'*

  Speaker: Mr. William Pellico (FNAL)

- 09:30 **Linac** *20'*

  Speaker: Fernanda Gallinucci Garcia (Fermilab)

- 09:50 **Booster Cavities** *20'*

  Speaker: Dr. Cheng-Yang Tan (Fermilab)

- 10:10 Coffee Break *30'*

- 10:40 **Booster Losses** *20'*

  Speaker: Dr. Keith Gollwitzer (Fermilab)

- 11:00 **PIP Discussion Time** *1h0'*

12:00 - 13:00 Lunch

AAC, Sr. Management & Tuesday Presenters

13:00 - 15:00 Main Injector & Recycler

- 13:00 **The 700-kW Plan** *30'*

  Speaker: Dr. Ioanis Kourbanis (Fermilab)

- 13:30 **Recycler Losses and Instabilities** *30'*

  Speaker: Dr. Phil Adamson (FNAL)

- 14:00 **MI & RR - 700 kW Discussion Time** *1h0'*

15:00 - 15:30 Coffee Break

15:30 - 18:15 Fermilab Participation in LCLS-II

- 15:30 **Fermilab SRF Strategy** *10'*

  Speaker: Hasan Padamsee (Fermi National Accelerator Lab)

- 15:40 **LCLS-II at Fermilab** *30'*

  Speaker: Richard Stanek (Fermilab)

- 16:10 Executive Session *20'*

- 16:30 AAC Only *1h15'*

- 17:45 LCLS-II Discussion *30'*

18:30 - 19:00 Cocktail Hour - Chez Leon

19:00 - 20:30 Dinner - Chez Leon

Wednesday, October 15, 2014

08:00 - 08:30 Continental Breakfast

08:30 - 09:00 Executive Session *30'*

09:00 - 12:00 PIP-II

- 09:00 **PIP - II Goals, Strategy, and Status** *30'*

  Speaker: Stephen Holmes (Fermilab)

- 09:30 **PXIE** *30'*

  Speaker: Paul Derwent (Fermilab)

- 10:00 Coffee Break *30'*

- 10:30 **PIP - II SRF** *30'*

  Speaker: Dr. Vyacheslav Yakovlev (FNAL)

- 11:00 **Booster Impact** *15'*

  Speaker: Dr. Cheng-Yang Tan (Fermilab)

- 11:15 **MI & Recycler Impact** *15'*

  Speaker: Dr. Ioanis Kourbanis (Fermilab)

- 11:30 **LBNF Beamline** *15'*

  Speaker: Dr. Vaia Papadimitriou (Fermilab)

- 11:45 **LBNF Target** *15'*

  Speaker: Dr. Bob Zwaska (Fermilab)

12:00 - 13:00 Lunch

AAC, Sr. Management & Wednesday Presenters

13:00 - 14:30 Q&A From Day 1, PIP-II Discussion

14:30 - 17:00 PIP-III

- 14:30 **Approaches to Multi-MW Complex Upgrade: Options and R&D** *20'*

  Speaker: Dr. Vladimir Shiltsev (FNAL)

- 14:50 Coffee Break *30'*

- 15:20 **SRF Cost Reduction R&D** *20'*

  Speaker: Dr. Alexander Romanenko (Fermilab)

- 15:40 **Target R&D** *20'*

  Speaker: Dr. Bob Zwaska (Fermilab)

- 16:00 **PIP-III Discussion** *1h0'*

17:00 - 17:30 Executive Session and/or AAC Only *30'*

17:30 - 18:00 AAC Only *30'*

18:00 - 19:30 Dinner - On Your Own

Thursday, October 16, 2014

08:00 - 08:30 Continental Breakfast

08:30 - 09:30 Q&A From Day 2

09:30 - 10:00 Preparations for Close-Out *30'*

10:00 - 10:15 Coffee Break

10:15 - 11:00 Continued Preparation for Close-Out *45'*

11:00 - 12:00 Close-Out *1h0'*

12:00 - 13:00 Box Lunch

AAC Only