Report from the Fermilab Accelerator Advisory Committee Meeting

December 8-10, 2015
FNAL, Batavia Il

AAC Committee:

Present: Wolfram Fischer (BNL), John Galambos (ORNL) (chair), Roland Garoby (ESS), Mark Hogan (SLAC), Jens Knobloch (HZB), Wim Leemans (LBNL), Hasan Padamsee (Cornell), Yoshishige Yamazaki (MSU)

Absent: Frederick Bordry (CERN)

Table of Contents

Introduction and General Remarks

The Accelerator Advisory Committee (AAC) for Fermi National Accelerator Laboratory (FNAL) met Dec. 8-10 2015 at FNAL to review progress of the Accelerator and Technical divisions. The AAC thanks the FNAL staff for the preparation of background materials and presentations, the open engagement during discussions and hospitality during the review. For future AAC meetings, some review of presentation lengths is requested to better preserve discussion periods. There were 14 charge questions presented to the AAC (see Appendix 1) and the presentations during the review focused on these charge questions. The direct linkage between the charge questions and presentation topics is appreciated. This report is organized with alignment along the charge questions.

The breadth of ongoing activities in the Accelerator and Technical divisions is striking. Overall, these activities are guided by and are well aligned with the HEP community priorities, such as the P5 recommendations, the Office of Science programs and International directions. These activities include supporting machine operations, overseeing a short-term (PIP-I) power ramp-up campaign, longer term (PIP-II and PIP-III) upgrade activities, being a major partner in the LCLS-II collaboration, science development (e.g. IOTA), technology development (e.g. SRF, high field magnets, high power targets) and the muon campus construction.

There has been impressive progress since the previous review in Dec. 2014 across many of these areas. In particular, the beam power delivery of 460 kW promised for support of NOvA during 2015 was met, and a short 520 kW operation was demonstrated. Other areas of progress are highlighted in the responses below, and suggested areas of action are highlighted as recommendations in the responses to the charge questions below.

We note that there are many ongoing activities in the AD and TD. A long-range timeline that connects these activities with each other and with other FNAL plans would be useful for understanding the linkages, and for planning purposes. For example it was not clear to the committee whether the planned schedule for advanced Ring R&D (a possible PIP-III technology) is consistent with the LBNF/DUNE needs for higher power beam delivery beyond PIP-II.

1. Have the recommendations from AAC2014 been adequately addressed?

Answer: *Some previous recommendations were not completely addressed, and these are re-enforced below.*

Findings

- Many of the charges were directly responded to.

Comments

- The PIP-II charge/responses were nicely tallied – this effort is appreciated, and this approach is requested for future reviews.

2. Is the goal of 700 kW on target by mid-2016 technically achievable?

Answer: *700 kW in operation by the end of CY16 is at risk if RR collimators are not available on time.*

Findings

- The planning is to demonstrate 700 kW before the summer 2016 and to have it in operation in December 2016.
- Linac:
  - It is being upgraded to improve reliability and it performs satisfyingly.
  - Work is on-going on a new modulator and 200 MHz klystron as back-up solution for the present high power RF tubes.
- Booster:
  - 23 tasks will have been completed at end of CY15. Ten remain, with 7 to be completed during FY16.
  - The proton flux has significantly increased (1.5E17 p/h) and PIP beam characteristics are obtained.
  - 15 Hz operation will be available at the end of FY15 with 20 refurbished cavities installed.
  - Additional actions are in progress against 3 beam loss points (Notch at 750 keV, RF cavities at transition, RF manipulations at extraction + beam studies & simulations).
- RR & MI:
  - Progress has been good during 2015. The planned milestones have been met:
    - 521 kW was demonstrated during 1 h on July 1, 2015 with 4+6 batches and 3.9E12 p/b from the Booster (7.5 Hz) although with excessive beam loss (93.4% eff.).
    - 6+6 batches were tested at reduced power on July 2 (Booster at 15 Hz).
  - Plan:

        - Operation with 4+6 batches at the end of December 2015, starting at 460 kW (Booster at 7.5 Hz -3.4E12 p/b) and aiming at 575 kW before the end of January 2016 with 95% efficiency
        - Operation with 6+6 batches at 575 kW in March 2016 (Booster at 9Hz – 3.6E12 p/b).
        - Demonstration of 700 kW with 6+6 batches in April 2016 (Booster at 9 Hz – 4.3E12 p/b).
        - Operation with 6+6 batches at 700 kW in December 2016.
    - Extensive work is being done on RR aperture and beam studies.
    - Early Synergia simulations seem OK wrt observations.
    - Collimators in RR are mandatory for regular operation at 700 kW. The conceptual design exists but construction is not yet planned.

Comments

- Linac: none.
- Booster:
    - Excellent progress in beam characteristics and overall performance.
    - The implementation of the 750 keV laser notch scheme is delayed, pending a solution to the short lifetime of the present fibers.
- RR & MI:
    - Good progress in beam studies and performance.
    - There is no means to measure beam tails.
    - Little time remains to reach the 700 kW goal in operation.
    - More simulations would help define optimum solutions.
    - The lack of a plan for implementing collimators in the RR is worrying.
    - The possibility of transverse damping during slip stacking in the RR needs further investigation.

Recommendations
- Booster:
  1) Use external laser/optics expertise to bring the laser notch system into an operational capability as soon as possible.
- RR & MI:
  2) Run simulations covering the complete slip stacking process in the RR.
  3) Develop a plan for building and installing collimators in RR as soon as possible and actively monitor progress.
  4) Pursue means to mitigate damper issues during slip stacking.

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

Answer*: Not yet.*

Findings

- A horizontal instability is observed in the RR with 10-20 turn rise time, that strongly depends on the bunch length.
- The existence of electron clouds was established by a microwave transmission measurement, and a measurement of the tune shift along the bunch train.
- A simulation showed that up to 2% of the cloud electrons are trapped in gradient magnets.
- A change of 1/3 of the TSPs to ion pumps without subsequent bakeout of the sections with ion pumps did not visibly change the instability threshold.
- The instabilities are now studied by 2 students and an external visitor.

Comments

- Progress is being made.
- 700 kW operation is not limited by the RR instability, but PIP-II remains vulnerable.
- The understanding of the electron cloud formation and instability detail is still rudimentary with only limited experimentally benchmarked simulations and calculations.
    - The observation that the second batch is more stable than the first batch, untypical for electron cloud driven instabilities, is not yet explained.

Recommendations

5) We repeat our recommendation from the previous two meetings 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. Revisit previous recommendations.

4. Are the MI/RR beam losses understood sufficiently to minimize machine and tunnel activation?

Answer: *Not yet*.

Findings

- A fast activation survey of the whole RR is possible on maintenance days
- Losses in the RR were reduced by realignment and replacement of beam pipes with larger one where possible.
- RR location 421 is presently the limiting vertical aperture, and relocation of the element increased aperture.
- The measured beta-beat reduced the available aperture by up to 2 mm in some locations.
- It was concluded that continuous 700 kW operation will require a new collimation system.

Comments

- The completion of a new collimation system for installation in 2016 appears to be extremely challenging.

- There are presently no diagnostics for beam halo, neither transverse nor longitudinal.
- Losses in the MI are presently not a performance limit as the MI beam pipe is somewhat larger than the RR pipe.

Recommendations

6) Develop a plan for beta-beat correction in the RR.
7) Develop high dynamic range halo diagnostics in the RR and transport lines.

5. Evaluate progress of the Proton Improvement Plan (PIP). Are the plans to increase the beam flux in the Booster adequate and the associated accelerator physics understood?

Answer*: Yes.*

Findings

- PIP goal is to deliver 2.3×10^{17} protons per hour (pph) at a repetition rate of 15 Hz with availability over 85% and residual activity within acceptable levels, anticipating a transition to PIP-II, as stated last year.
- Great progress from 2012, but 1.5×10^{17} (4.3×10^{12} protons per pulse at 10 Hz) at present.
- Beam loss is largest at injection, transition and extraction, as is often the case.
- The beam notch being created at the injection is not sufficient. The proof of principle of the laser notch creation is successfully demonstrated, but the laser notch has not yet been implemented for beam loss reduction.

Comments

- Remarkable progress has been made in Booster performance (e.g.: intensity, stability, loss, beam quality,).
- Continue accelerator physics simulations and mitigations to further reduce beam loss.

Recommendations

1) Use external laser/optics expertise to bring the laser notch system into an operational capability ASAP.

6. Are the plans for new Booster cavities appropriate for future Booster upgrades, to serve at least through PIP-II and potentially through PIP-III?

Answer: *Yes for PIP-II, No for PIP-III.*

Findings

- PIP requires 1 MV (available early CY16) and PIP-II 1.2 MV.
- The refurbished Booster RF cavities will allow reaching 700 kW, but their replacement is necessary before the end of PIP to guarantee long term performance and prepare for PIP-II.
- The required frequency sweep decreases from PIP to PIP-II and PIP-III
- The new cavities shall use the renovated surface equipment.
- 3D modeling of the cavities is in progress.
- Parallel and perpendicular biased ferrite tuners are considered.
- Perpendicular bias gives twice the gradient.
- The temperature rise of the tuner in the perpendicular bias cavity is about twice as high as that of the parallel bias.
- The 2nd harmonic cavity is using perpendicular bias and will serve as demonstrator. Installation in mid-CY16, beam studies and operation after. Decision early in CY17 for the technology of the main accelerating cavities.

Comments

- There are no clear requirements for cavities for PIP-III. It cannot lead to decisions on hardware.
- So far most of the design work seems to have been focused on a parallel bias solution The perpendicular case should be studied further, including the understanding of the temperature rise.
- Sufficient long-term stress powering tests for the prototype and the first series production cavity should be conducted for new cavities.

Recommendations

8) Define during 2016 the criteria for choosing cavity technology.

7. Evaluate the plan for commissioning and operations of the Muon Campus accelerator systems. Is the plan sound?

Answer: *Insufficient detail.*

Findings

- A proposed construction and commissioning plan was presented for providing experimental systems that will enable the P5 endorsed g-2 and Mu2e experiments. Installation for g-2 is expected to be completed by mid 2017 and commissioning through early 2018, with early data taking starting in early 2018. The Mu2e installation phase is expected to continue through 2021 with commissioning for single turn extraction and resonant extraction to commence in 2020 and 2021, respectively.

Comments

- Insufficient context was provided on what the stakeholders require and have been promised, to answer the question.
- A DOE approved schedule for the project phase as well as commissioning/transition plan for experiments should be provided and analyzed.

Recommendations

9) Communicate the proposed operational plan consistent with overall needs and resources with users and DOE.

8. Is the plan and the organization for the LCLS-II cryomodule production and testing sound?

Answer: *Yes, but staffing is very tight and there is no float to react to problems that are likely to occur.*

Findings

- Fermilab's scope for LCLS-II includes (a) the design and production of 17 1.3-GHz cryomodule, (b) the design and production of 2 (+ 1 spare) 3.9 GHz cryomodules (c) the cryogenic distribution (c) installation and commissioning and (d) Assistance with LINAC accelerator physics and LLRF.
- LCLS-II@FNAL is winding down the R&D phase. The main results from the R&D phase are:
  - N-doping/cavity processing recipe established to provide cavities that exceed the LCLS-II design Q = 2.7e10 at 16 MV/m.
  - Integrated horizontal tests of 2 cavities validate the recipe (Avg. Q = 3E10, Emax = 22 MV/m)
  - Cavity processing recipe transferred successfully to first vendor.
  - Recipe for cavity cooldown established to maintain high-Q.
- The main items remaining in the R&D phase are
  - Prototype module test to verify cooldown procedure and high-Q operation at 16 MV/m. The module was to be completed in CY15, however bad plating of the cavity interconnect bellows caused delays.
  - 3.9 GHz cavity and ancillaries development.

  Finalize 3.9 GHz CM design
- FNAL is now transitioning to the production phase. The timeline to meet LCLS II CD4 in Q2FY2020 is as follows:
  - Prototype cryomodule through Q3 2016
  - Cryomodule production and assembly through Q2 2018
  - 3.9 GHz cryomodules production through Q4 2018
- The competition for resources with PIP-II is somewhat ameliorated by the fact that PIP-II funding is currently lower than required. PIP-II plans call for module construction to start in 2020 and CD4 in 2025.
- Several new facilities are or will be coming online to ease the competition for infrastructure resources:
  - LAB2: for cold string/cryomodule assembly and HPR backup, for PIP-II.

- Three vertical test stands are complete, two of which are suitable for LCLS-II cavities.
  - Cryomodule test facility
  - Note: test facilities (including PXIE) are supplied by a central cryoplant, and thus cannot be considered completely independently.
- Nb for the cavities was procured (two vendors). Recent measurements of flux expulsion efficiency with cavities have shown that one batch is less efficient. A 1000 C anneal for 4 hours is being considered as an additional treatment step to cure the problem.
- All cavities are to be vertically tested at FNAL. One cavity out of every two cryomodules will undergo an integrated system test in the HTS.
- To meet a module production rate of one per month, 12 cavities need to be tested vertically per month (assuming 30% reprocess rate). The project is aware of a potential pinch point here and plans on testing 6 cavities per week in two inserts in the early stages to establish a "stock pile."
- The 1.3 GHz cryomodule design is complete. Procurement of cryomodule components is ramping up. Full production will not wait for completion of prototype module tests, unlike suggested by AAC2014. The risk is being accepted by the Project.
- A detailed flow schedule exists for module production which was reviewed by Saclay and JLAB. FNAL staff has spent extensive time at the Saclay XFEL module production site. Cryomodule assembly itself is expected to require 60 days during full production with ca. 3½ months planned during ramp up (3 modules).
- A preliminary design review of the 3.9 GHz cryomodule was held on Nov. 20 (some required changes identified). Responding to an AAC 2014 recommendation, additional resources are being allocated for design and prototyping. Final 3.9 GHz production will not occur until after the 1.3 GHz production run.
- The cryomodule test facility CMTS-1 should be online by the end of CY15. This facility will be used to test all cryomodules for LCLS-II, following a change request that addresses an AAC 2014 recommendation.
- Peaks in LCLS-II and PIP-II staffing requirements are roughly sequential.
- The staff for LCLS-II is currently being ramped up (54 FTE total in Aug and Sept 2015), with a significant number of external technicians planned on being brought on board.
- Staffing needs to be increased in 2017 due to plans to test all cryomodules, which exerts significant demands on the existing staff.

Comments

- AAC welcomes the fact that two key recommendations from 2014 have been implemented (testing of all cryomodules and prioritization of 3.9 GHz module R&D).
- The development of the cavity processing procedures and transfer to industry have proceeded remarkably well, yielding results not just of importance for LCLS-II but the SRF community as a whole. AAC considers these procedures to be validated.
- The development of cooldown procedures to guarantee high-Q operation appear well in hand. The final validation however requires the prototype module test since here the environment is not identical to that in the HTS. Anticipate the need to have several cool-downs in the pCM test to determine the best gradient for fullest flux expulsion.
- While 1000 C heat treatment of niobium with strong flux pinning appears to improve the flux expulsion, be aware that the heat treatment will also change the metallurgical properties that can impact deep drawing capabilities and the final yield strength. Before

applying the procedure to LCLS-II production, consider producing and testing prototype cavities.
- The completion of the 1.3 GHz cryomodule design is a major milestone.
- Close attention should be paid to magnetic hygiene, and residual magnetic field achieved to maintain high Q. Consider designating a person responsible for magnetic hygiene so magnetized objects don't slip through the cracks.
- The transition from R&D to mass production is often a bumpy road that requires a "culture change" in the involved teams (see Saclay/XFEL and FRIB). Schedule constraints no longer can be easily brushed aside, work flow planning and clear documentation is required etc. and must become routine to the staff. The project should not underestimate the time required to go through this transition. Communication with XFEL and projects like FRIB should help to smoothen the transition.
- Technical validation and resource planning really cannot be considered complete until the prototype module has been assembled and tested successfully.
- Given the limited redundancy of facilities and interdependency with other projects for testing (and processing), risk and single point of failure analyses should be performed to identify mitigation schemes.
- An ambitious testing and assembly schedule is being implemented that requires a flawless supply chain. AAC welcomes the fact that a supply chain manager has been appointed. A scheme for RATS (receiving, acceptance, tests, storage) should be developed if not already done. Down the road it must be possible to track which components were incorporated in which module.
- The time for staff training for module production and testing should not be underestimated and should begin now. XFEL is ideal for resource analyses and training. From what AAC understands, extended visits at Saclay have already taken place. In addition, module testing and tunnel installation is currently going on at DESY. Consider sending key personnel to participate in both.
- Long term testing of the CW TTF-III coupler has not yet been performed. Try to do so soon to retire the risk of failure.
- For the ramp up of module production (first two or three modules) consider performing horizontal integrated tests on all cavities to correlate performance in the module with that prior to assembly to pinpoint potential problems in the assembly sequence. If these modules perform well, the number of tests can be reduced as planned.
- The 3.9 GHz development effort will strain resources. Consider outsourcing some of this activity to other labs.

Recommendations

10) Start training staff for module testing. Consider sending staff to DESY to participate in the module tests.
11) Magnetic hygiene is essential to maintain the exceptionally high Q values: designate a person responsible for this aspect.

9. The PIP-II R&D program and the cryoplant design effort are being jointly executed with India. Evaluate these joint plans and comment on the split between Fermilab and India. Is the split appropriate and is the effort likely to reduce the project risk and/or costs?

Answer*: The split is appropriate. Technical risk is reduced by the CW option, other risks are reduced provided that the Indian partners remain committed through the end of the project.*

Findings

- Congratulations to PIP-II for acquiring CD-0.
- Now that the project has CD-0, preparation of project documentation and a resource loaded schedule is planned for the R&D phase.
- Construction start is aimed for 2020.
- Continued limited funding levels will limit the initiation of important prototypes for PIP-II.
- In the R&D phase, The PIP-II development program will focus on PIXIE, SRF development and modifications to the Booster/Recycler/Main Injector.
- Collaboration with laboratories from India (IIFC) will increase resources to advance the PIP-II R&D program in several key areas.
- Seven engineers from India are now at Fermilab for two years.

Comments

- The 200 M$ in kind contribution will be a major contribution to the success for PIP-II. The commitment and engineering effort discussed will provide important leverage.
- 7 engineers residing at FNAL for 2 years is a major demonstration of that commitment.
- The PIP-2 budget is constrained for the next couple of years with major goals to accomplish, in particular HWR CM and SSR1 CM.

Recommendations

12) Ensure that sufficient resources are made available by FNAL in the R&D phase to leverage the Indian resources.

10. Are the plans for the first experiments at FAST and IOTA appropriate? Is the organization of this Fermilab effort sound and appropriate?

Answer: *See recommendation.*

Findings

- These activities were explained to be encompassed within Nigel's priority list (#10) "R&D (a core competency) accelerators and detectors".
- FAST and IOTA leverage ~$100M infrastructure that has been built up over last few years (NML, ASTA…).
- There has been steady progress bringing the facilities online since the last AAC: notably 20MeV e- beam through the injector, modest but successful first experiments (transfer matrix, bunch shaping) and an IOTA Workshop in April 2015.
- Commissioning with electrons is underway and expected to evolve from 20MeV (FY15) to 150MeV (FY17) with IOTA experiments in FY18 (electrons in Phase I) and eventually Phase II with protons in FY20
- A PIP-III R&D plan is expected to be developed within approximately 1 year and this may inform IOTA priorities, i.e. for RCS feasibility in space charge limit with non-linear integrable optics or electron lens, 0.06% beam losses.

Comments

- The first experiments at FAST/IOTA are certainly appropriate from a standpoint of doing interesting beam physics and education, but were not specified with enough detail to understand the impact on PIP-III options.
- The schedule as presented is not consistent – develop one based on expected funding and stick to it. Note that the benefits of increased funding and the corresponding speedup of the program are not clearly articulated nor justified.
- The proton injector for IOTA (HINS RFQ) requires $1M of unfunded M&S and unspecified labor to resurrect, characterize and move, yet the presented priorities are 1. IOTA protons, 2. IOTA electrons, 3. FAST electrons; which begs the question: why are timeline and priorities backwards?
- The committee is concerned that 'Significant effort and resources are needed to establish experiments with protons', i.e. profile monitors, loss monitors, electron lens, etc.
- Fermilab should encourage collaborations to develop instrumentation capable of providing insight into halo formation and phase space dynamics on turn by turn basis and carry out studies to bench mark/validate simulations.

Recommendation

13) Develop a plan that transparently defines: 1) define how priorities will be decided between various parties with different funding (LDRD, HEP, DHS, DOE Early Career Awards, NSF, etc.), 2) the transition to operations and prioritization of first experiments and 3) how a comprehensive suite of diagnostics, will be selected and acquired..

11. Evaluate the program for development of high power target systems. Are the activities likely to result in a conceptual design of a multi-megawatt target in time for PIP-II/DUNE?

Answer: Yes

Findings:

- A consolidated Target department was created in Feb. 2015 to take care of all targets/horns at Fermilab (9 technicians, 8 engineers, 3 physicists).
- A wide range of target "systems" is being supported (BNB, NuMI) and developed (g-2, Mu2e, LBNF).
- Many of the original design NuMI targets had early failures
- A new NuMI target design (TA01) is complete and has demonstrated the highest exposure to date.
- There is a huge workload: experience exploiting/repairing/and diagnosing existing devices.
- The preliminary design of PIP-II target and horns is ready (scaled to 1.2 MW from NuMI). Development is interrupted in F16 and FY17 (lower priority).
- R&D in collaboration with international partners to prepare for future needs.
- Conceptual design of >2 MW target system needs R&D.

Comments:

- The re-organization of target staff into a new centralized AD group is a positive move, and should pay dividends.
- New NuMI target system optimizations have been undertaken, showing promise of 30% improvement in neutrino yield. This effort is commendable, and likely a cost effective means of increasing useful neutrino yield.
- Attention to the "shelf-consumable" inventory of target system components is important, as these have long fabrication times.
- Participation in the RaDIATE collaboration is a cost effective means to understanding radiation damage end-of-life limits.
- R&D is essential for future devices (e.g. PIP-III) and can benefit from world-wide test facilities and competences.

Recommendations:

- None

12. Evaluate the Fermilab High-field magnet program: Is it sound and aligned well with the P5 recommendation to "continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs" for present and future hadron colliders (e.g. LHC upgrades)? Are the allocated resources adequate for the proposed plan and schedule?

Answer :

Given the resources allocated, the HFM program is aligned with P5 goal of increasing performance toward 15 T, for accelerator class magnets. However the resources allocated for development of 15T (and higher) magnets are insufficient. Conductor procurement is at risk and HTS work has stopped.

Findings

- The 11 Tesla Nb3Sn dipole R&D for LHC upgrades is complete, a major accomplishment.
- R&D has started on a 15 T Nb3Sn dipole demonstrator for a future Hadron Collider.
- A magnet design has been put forward.
- A first test is planned for 2016
- Cable samples for the inner coils have been fabricated and tested.
- Nb3Sn conductor procurement needs additional funding.
- HTS work has come to a halt.

Comments

- Given the resources allocated, the HFM program is reasonable and aligned with P5 goal of increasing performance toward 15 T, for accelerator class magnets. The issues related to cost reduction are not fully explored, however. Processes used are very similar to previous ones and it is not clear how this approach leads to cost reduction.
- A balanced effort between conductor R&D (Nb3Sn) and demonstration magnets in a national context is important.
- Exploring reduction of the number of training quenches is needed.
- Pay attention to costs.

Recommendation

14) A national coordinated program is important. Pursue the collaborative paths laid out in the White Paper with other partner labs *to ensure that the US high field magnet program continues to play a leadership role..*

13. Evaluate the SRF science and technology program: Is the plan sound? Does it address all major SRF-related issues relevant to future HEP Intensity-Frontier CW linacs at Fermilab? How well is it aligned with needs of future HEP Energy-Frontier machines?

***Answer**: The R&D is sound. Its main thrust is minimizing refrigeration cost, thus addressing intensity frontier CW LINACs. To a lesser extent it addresses (LINAC-based) Energy Frontier machines that require highest accelerating fields. Cost effective SRF R&D will help address the options for PIP-III.*

Findings

- The FNAL SRF program is organized in two branches: one branch for research one branch for facilities management (including upgrades).
- In the past year, a strong emphasis has been placed on SRF R&D for a two prong approach: (a) to directly address the LCLS-II high-Q effort and (b) broader R&D to impact the cost of SRF in general. The program addresses the AAC 2014 recommendation to assign priority to high-Q research.
- In addressing AAC 2014 recommendation 26, an analysis of the cost drivers for SRF systems has been performed. It was found that cavity material and manufacturing, followed by coupler technology are the main drivers. In general, it is claimed that Q/Eacc performance potentially plays an even more important role, since improvements directly translate into a reduction of required modules. A concrete cost driver analysis for the PIP-II LINAC (or similar) was not performed.
- To address material and production costs, FNAL is investigating several schemes: Nb/Cu clad sheets, hydroforming cavities, and Nb on Cu thin films using HiPIMS. These activities appear to be at a lower priority than those subsequently discussed.
- The main R&D activities concentrate(d) on Q-improvement strategies:
  - Nitrogen doping: a recipe has been developed to maximize the Q gain while maintaining a high quench field and ensuring low sensitivity to trapped flux. This recipe was validated in fully dressed LCLS-II cavities and was successfully transferred to industry. The same procedure has been transferred to PIP-II cavities, achieving an impressive Q = 7E10 at 17 MV/m. To better understand the science of N-doping material analyses are now being performed.
  - Magnetic flux management: Extensive R&D was conducted to better understand the impact of trapped flux on the cavity Q. Two aspects were investigated: (a) the efficiency of flux expulsion during cooldown (b) the impact of the surface treatment/nitrogen doping recipe on the sensitivity of the surface resistance on trapped flux. This insight permitted an optimization of the N-doping procedure. Cooldown procedures for fully dressed cavities have been developed that maintain a high Q in a realistic cryomodule like environment.
  - Development of new superconductors (Nb3Sn + others perhaps in the future): Given the promising results obtained at Cornell, their Nb3Sn production recipe is planned to be adopted at FNAL. The goal is to extend this to production scale cavities (down to 650 MHz). The development of thin films (currently Nb on Cu) may be extended in the future to other superconductors (such as NbTixN, MgB2) to improve Q or Emax.
- Recognizing that availability of processing, testing and analysis facilities are key to enabling the SRF research, a separate branch for the operation and development of facilities has been established. Noteworthy is the new construction of the Lab2 facility (module assembly/HPR), cryomodule test facility and 3 VTS sites that reduce pinch points for module production and testing. Further facilities for material QC, cavity tuning, cavity processing (chemistry, heat treatment, doping) exist. Analytical instruments for material analyses, e.g. SEM/EDX, AFM also exist.

Comments

- FNAL is to be congratulated on its young, enthusiastic team! In the last years, FNAL basic R&D has had a significant impact on the SRF community as a whole.
- The research directly targets LCLS-II and PIP-II, leveraging the resources very well. At the same time it is sufficiently generic to address many other projects, especially

intensity frontier LINACs. A more technically oriented R&D program would probably not do this as well.

- Excellent results were obtained in taking the high Q program from the lab to applying it to production systems, including vendor qualification.
- Extending the studies of cooldown procedures to full cryomodules would be useful.
- The team appears to have identified high-leverage R&D items that are of direct relevance to PIP-II. To underscore this and put in relation to other options, a useful exercise would be to make a cost estimate for a 2.5 MW SRF linac using present cavity and cryomodule costs, and show how much reduction can be expected by cost-effective R&D results.
- High-Q is of use only if it can be maintained for longer periods in accelerators. Investigating the longevity of the Q and degradation due to field emission needs to be pursued. Consider investing R&D effort in module recovery (e.g., Ar-discharge cleaning, snow cleaning, high pulsed power processing for medium gradient).
- To complete the picture of magnetic flux hygiene, consider a program to better understand the cause of flux pinning and how this may be avoided.
- The current R&D thrust seems less targeted to energy frontier activities due to lower quench fields of N-doped cavities. Nb_3Sn may address this in future.

Recommendations

15) Consider in-situ (in module) Q recovery schemes in R&D.
16) Analyze the cost of a high intensity LINAC driving a multi-MW facility with state-of-the-art technology (including high-Q) and identify additional cost reduction paths to guide the future R&D program.

14. Comment on Fermilab's analysis of the proton beam power options beyond the PIP- II goal of 1.2 MW and on the possible R&D scope for these options.

Answer:

- *The present analysis is very preliminary.*
- *A search for a global optimum including the experiment(s) would be worthwhile conducting.*
- *The creation of a PIP-III R&D plan is an essential preliminary step.*
  - *It should cover the subject of charge exchange injection at 8 GeV in collaboration with external partners.*
  - *The precise goals of IOTA for PIP-III should be defined and given adequate priorities to contribute early enough to be useful.*

Findings

- P5 recommendation in favor of a high energy ν program needing 600 kT x MW x years (rather 900) requires a multi-MW beam at 60-120 GeV.
- For that purpose, PIP-III aims at a beam power of 2.5 – 5 MW after ~5 years of operation at 1.2 MW (PIP-II).
- Status of PIP-III analysis:
  - The 8 GeV proton source is identified as the main bottleneck.

    - Possible options: 8 GeV SC linac, New RCS, New RCS with >800 MeV injector.
    - The main issues (on-going work) are the following:
        - SC linac: cost (SRF R&D) and charge exchange injection at 8 GeV.
        - RCS: space charge (IOTA experiments), instabilities, RF etc.
        - MI: new RF system, transition, e-cloud, impedances/instabilities etc.
        - Target: new target (R&D for material selection and design).
        - In all cases, the budget for beam loss is very small.
- The plan is to involve all partners interested in neutrino research (LBNF/DUNE).

Comments

- The analysis is still preliminary.
- The proton energy is considered fixed at 60/120 GeV (MI).
- The spectrum of challenging questions is very wide. Although a number of them have started to be addressed, the involvement of international partners is mandatory.
- IOTA is envisaged as the source of valuable insight on potential solutions.
- For PIP-III, the additional cost/benefit of a CW linac extension needs to be understood.

Appendix 1: Charge

Fermilab Accelerator Advisory Committee Meeting

December 8-10, 2015

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 in support of 15 Hz Booster operations and to provide the proton flux sufficient 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 are be required to realize the 1.2 MW goal. Fermilab is also collaborating 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.

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.

It is planned to commission the Muon Campus facilities, providing muon beams to the Muon g-2 experiment in 2017 and later to the Mu2e experiment.

Finally, we request your consideration of the R&D activities for FAST, IOTA, SRF, and High Field Magnets.

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:

1. Have the recommendations from AAC2014 been adequately addressed?
2. Is the goal of 700 kW on target by mid-2016 technically achievable?
3. Are the plans in place to overcome beam instabilities and losses in the Recycler during slip-sacking adequate? (presentations from the Recycler Instability task force and the Loss mitigation task force)
4. Are the MI/RR beam losses understood sufficiently to minimize machine and tunnel activation? (the Loss Mitigation task force)

5. Evaluate progress of the Proton Improvement Plan (PIP). Are the plans to increase the beam flux in the Booster adequate and the associated accelerator physics understood?

6. Are the plans for new Booster cavities appropriate for future Booster upgrades, to serve at least through PIP-II and potentially through PIP-III? (see report on Cavity Upgrade review).
7. Evaluate the plan for commissioning and operations of the Muon Campus accelerator systems. Is the plan sound?
8. Is the plan and the organization for the LCLS-II cryomodule production and testing sound?
9. The PIP-II R&D program and the cryoplant design effort are being jointly executed with India. Evaluate these joint plans and comment on the split between Fermilab and India. Is the split appropriate and is the effort likely to reduce the project risk and/or costs?
10. Are the plans for the first experiments at FAST and IOTA appropriate? Is the organization of this Fermilab effort sound and appropriate?
11. Evaluate the program for development of high power target systems. Are the activities likely to result in a conceptual design of a multi-megawatt target in time for PIP-II/DUNE.
12. Evaluate the Fermilab High-field magnet program: Is it sound and aligned well with the P5 recommendation to "continue to play a leadership role in superconducting magnet technology focused on the dual goals of increasing performance and decreasing costs" for present and future hadron colliders (e.g. LHC upgrades)? Are the allocated resources adequate for the proposed plan and schedule?
13. Evaluate the SRF science and technology program: Is the plan sound? Does it address all major SRF-related issues relevant to future HEP Intensity-Frontier CW linacs at Fermilab? How well is it aligned with needs of future HEP Energy-Frontier machines?
14. Comment on Fermilab's analysis of the proton beam power options beyond the PIP- II goal of 1.2 MW and on the possible R&D scope for these options.

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

In addition to a verbal closeout with the management of the Accelerator and Technical Divisions on the final day of the meeting, the AAC is requested to submit a written report of their findings, comments, and recommendations to Sergei Nagaitsev by February 1, 2016.

Appendix 2: Agenda

Tuesday 08 December 2015

AAC Executive Session - (08:30-09:15)

Welcome from Fermilab Chief Operating Officer Tim Meyer - (09:15-09:20)

Accelerator Overview: Programs, Parameters, Requirements vs. Time, R, Acronyms - (09:20-09:59)

- Presenters: NAGAITSEV, Sergei

PIP, Booster, Recycler, Main Injector: Address Questions 2, 3, 4, 5

Q5: PIP - Proton Improvement Plan Progress, Increasing Booseter Beam, & Associated Accelerator Physics - (10:00-10:30)

- Presenters: Mr. PELLICO, William

Q2: Technical Feasibility of 700 KW by mid-2016 - (10:30-11:00)

- Presenters: Dr. KOURBANIS, Ioanis

Q4: Mitigation of Losses in MI/RR to Minimize Activation - (11:00-11:30)

- Presenters: Dr. ADAMSON, Phil

Q3: Beam Instabilities and Losses in the Recycler during Slip-Stacking - (11:30-12:00)

- Presenters: ALEXAHIN, Yuri

Discussion - (12:00-13:00)

Light Lunch - WH 2X (13:00-14:00)
Q6: Future Booster Cavities - (14:00-14:30)

- Presenters: Mr. KROC, Thomas

Q7: Commissioning Plan for Muon Campus Beams - (14:30-15:00)

- Presenters: ANNALA, Jerry

Q9: PIP-II R and Cryoplant - Connection with India - (15:00-15:30)

- Presenters: HOLMES, Stephen

Discussion - (15:30-16:30)

AAC Executive Session - (16:30-18:30)

Drinks - Chez Leon (18:30-19:00) Dinner - Chez Leon (19:00-20:30)

Wednesday 09 December 2015

AAC to Meet with Fermilab Director Nigel Lockyer - (08:30-08:45)

Q8: Plan and Organization for LCLS-II Cryomodule Production and Testing - Remote Presenation? - (08:45-10:00)

- Presenters: STANEK, Richard

Q From Day 1 - (10:00-11:00)

Strategy of the Accelerator R Program toward Multi-MW Beams at Fermilab and Role and Major Objectives of IOTA/FAST and PIP-III - (11:00-11:40)

- Presenters: Dr. SHILTSEV, Vladimir

Q10: IOTA Progress, Plans and Initial Experiments at FAST - (11:40-12:30)

- Presenters: VALISHEV, Alexander

Discussion - (12:30-13:30)

Working Box Lunch for AAC - (13:30-14:00)

Q11: High Power Target Systems for PIP-II/DUNE and Beyond - (14:00-14:40)

- Presenters: Dr. ZWASKA, Bob

Q13: SRF Science and Technology Program - (14:40-15:20)

- Presenters: Dr. ROMANENKO, Alexander

Q12: High Field Magnet Program - (15:20-16:00)

- Presenters: Dr. ZLOBIN, Alexander

Discussion - (16:00-17:00)

AAC Executive Session - (17:00-18:30)

Committee on their own for Dinner - (18:30-20:00)

Thursday 10 December 2015 Q From Day 2 - (08:30-09:30)

Preparation for Close-Out - (09:30-11:00)

Closeout - (11:00-12:00)